Automatic Detection of B-lines in In-Vivo Lung Ultrasound

This paper proposes an automatic method for accurate detection and visualization of B-lines in ultrasound lung scans, which provides a quantitative measure for the number of B-lines present. All the scans used in this study were acquired using a BK3000 ultrasound scanner (BK Ultrasound, Denmark) driving a 5.5 MHz linear transducer (BK Ultrasound). Four healthy subjects and four patients after major surgery with pulmonary edema, were scanned at four locations on each lung for B-line examination. Eight sequences of 50 frames were acquired for each subject yielding 64 sequences in total. The proposed algorithm was applied to all 3200 in-vivo lung ultrasound images. The results showed that the average number of B-lines was 0.28±0.06 (Mean±Std) in scans belonging to the patients compared to 0.03±0.06 (Mean±Std) in the healthy subjects. Also, the Mann-Whitney test showed a significant difference between the two groups with p-value of 0.015, and indicating that the proposed algorithm was able to differentiate between the healthy volunteers and the patients. In conclusion, the method can be used to automatically and to quantitatively characterize the distribution of B-lines for diagnosing pulmonary edema.

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CMUT Electrode Resistance Design: Modelling and Experimental Verification by a Row-Column Array

This paper addresses the importance of having control over the resistivity of the electrodes for capacitive micromachined ultrasonic transducers (CMUT) devices. The electrode resistivity can vary depending on the fabrication technology used, and resistivity control becomes especially important in the cases where metal electrodes can not be used. This raises the question: When is the resistivity of an electrode sufficiently low? To answer this question we have developed a simple design criterion. The criterion describes the attenuation of AC signals along a CMUT element. It is shown that the non-dimensional product between angular excitation frequency, resistance, and capacitance $\omega R C$ of an element has to be smaller than 0.35 to ensure an AC potential drop along the element of less than 1%. The optimal magnitude and directionality of the transmit pressure will be achieved if CMUT elements are designed according to the developed criteria. Hence, the model can be used to estimate device parameters that will ensure the CMUT is suitable for generating ultrasound images. An example is given where the model is used to predict the required electrode thickness for structured electrodes made of Gold, Aluminium, and Indium-Tin-Oxide, respectively. To verify the model, two Row-Column addressed (RCA) CMUT transducers were used to illustrate the effect of high and low electrode resistivity. One transducer had a sufficient electrode resistivity, and the other had an insufficient electrode resistivity. The RCA CMUT transducers were fabricated using fusion bonding, where the top electrode is made of aluminium and the bottom electrode is made of doped silicon. The resistivity of the aluminium top electrode is 2×10-6 $\Omega$cm for both transducers, whereas the resistivity for the bottom electrode is 0.1 $\Omega$cm for the first transducer and 0.005 $\Omega$cm for the second transducer. The transducer with low resistivity emits pressure uniformly along both the rows and columns, whereas the transmit pressure field from the other transducer has a uniformly distributed pressure field along the rows, but a decreasing pressure field along the columns due to the high resistivity in the bottom electrode. The pressure drop, along the columns is frequency dependent and has been observed to be 63%, 74%, and 82% for the excitation frequencies 2 MHz, 4.5 MHz, and 7 MHz, respectively.

General information
Development of Super-resolution Sharpness-based Axial Localization for Ultrasound Imaging

Super-resolution ultrasound mostly uses image-based methods for the localization of single scatterers. These methods are largely based on the centre of mass (COM) calculation. Sharpness-based localization is an alternative to COM for scatterer localization in the axial direction. Simulated ultrasound point scatterer data (centre frequency f0 = 7 MHz, wavelength λ = 220 μm) showed that the normalized sharpness method can provide scatterer axial localization with an accuracy down to 2 μm (< 0.01λ), which is a two-order of magnitude improvement compared to that achievable by conventional imaging (≈λ), and a 5-fold improvement compared to the COM estimate (≈10 μm or 0.05λ). Similar results were obtained experimentally using wire-target data acquired by the Synthetic Aperture Real-time Ultrasound System (SARUS). The performance of the proposed method was also found to be consistent across different types of ultrasound transmission. The localization precision deteriorates in the presence of noise, but even in very low signal-to-noise-ratio (SNR = 0 dB) the uncertainty was not higher than 6 μm, which outperforms the COM estimate. The method can be implemented in image data as well as using the raw signals. It is proposed that signal derived localization should replace the image-based equivalent, as it provides at least a 10 times improved accuracy.
Estimation of High Velocities in Synthetic Aperture Imaging: II: Experimental Investigation

The paper describes the performance of a new pulse sequence design and estimation approach for increasing the maximum detectable velocity in synthetic aperture (SA) velocity imaging. Measurements are conducted for conventional imaging for comparing the velocity range detectable by a directional Transverse Oscillation (TO) autocorrelation estimator to a new cross-correlation estimator. For conventional focused emissions a 192-elements, 3 MHz convex array transducer is used together with the SARUS experimental scanner on a flow rig at beam-to-flow angles of 60°, 70° and 90°. Here the new estimator always yields a higher precision, and the aliasing limit is increased by a factor 3. The new SA inter-spaced scheme was investigated using Field II simulations and SARUS measurements. A 3 MHz, 128-elements phased array was employed with a 5 virtual source emissions scheme for flow estimation and 15 emissions for B-mode imaging. The scheme was interleaved three times for a positive, negative, and positive transmission, so that nonlinear pulse inversion also could be made. The experiments were conducted at three angles and for 4 different pulse repetition frequencies. A peak transverse velocity of 0.51 m/s could be estimated at fprf=450 Hz, translating to 5.6 m/s at fprf=5 kHz showing the theoretical increase of a factor 10 predicted in the accompanying theory paper.

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Estimation of High Velocities in Synthetic Aperture Imaging: I: Theory

The paper describes a new pulse sequence design and estimation approach, which can increase the maximum detectable velocity in synthetic aperture (SA) velocity imaging. In SA N spherical or plane waves are emitted, and the sequence is repeated continuously. The N emissions are combined to form a High Resolution Image (HRI). Correlation of HRIs is employed to estimate velocity, and the combination of N emissions lowers the effective pulse repetition frequency by N. Inter-leaving emission sequences can increase the effective pulse repetition frequency to the actual pulse repetition frequency, thereby increasing the maximum detectable velocity by a factor of N. This makes it possible to use longer sequences with better focusing properties. It can also increase the possible interrogation depth for vessels with large velocities. A new cross-correlation vector flow estimator is also presented, which can further increase the maximum detectable velocity by a factor of three. It is based on Transverse Oscillation (TO), a pre-processing stage, and cross-correlation of signals beamformed orthogonal to the ultrasound propagation direction. The estimator is self-calibrating without estimating the lateral TO wavelength. This paper develops the theory behind the two methods. The performance is demonstrated in the accompanying paper for convex and phased array probes connected to the SARUS scanner for parabolic flow for both conventional and SA imaging.

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Non-Invasive Assessment of Intravascular Pressure Gradients: A Review of Current and Proposed Novel Methods

Invasive catheterization is associated with a low risk of serious complications. However, although it is the gold standard for measuring pressure gradients, it induces changes to blood flow and requires significant resources. Therefore, non-invasive alternatives are urgently needed. Pressure gradients are routinely estimated non-invasively in clinical settings using ultrasound and calculated with the simplified Bernoulli equation, a method with several limitations. A PubMed literature search on validation of non-invasive techniques was conducted, and studies were included if non-invasively estimated pressure gradients were compared with invasively measured pressure gradients in vivo. Pressure gradients were mainly estimated from velocities obtained with Doppler ultrasound or magnetic resonance imaging. Most studies used the simplified Bernoulli equation, but more recent studies have employed the expanded Bernoulli and Navier–Stokes equations. Overall, the studies reported good correlation between non-invasive estimation of pressure gradients and catheterization. Despite having strong correlations, several studies reported the non-invasive techniques to either overestimate or underestimate the invasive measurements, thus questioning the accuracy of the non-invasive methods. In conclusion, more advanced imaging techniques may be needed to overcome the shortcomings of current methods.

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Pediatric Transthoracic Cardiac Vector Flow Imaging - A Preliminary Pictorial Study

Purpose Conventional pediatric echocardiography is crucial for diagnosing congenital heart disease (CHD), but the technique is impaired by angle dependency. Vector flow imaging (VFI) is an angle-independent noninvasive ultrasound alternative for blood flow assessment and can assess complex flow patterns not visible on conventional Doppler ultrasound. Materials and Methods 12 healthy newborns and 3 infants with CHD were examined with transthoracic cardiac VFI using a conventional ultrasound scanner and a linear array. Results VFI examinations revealed common cardiac flow patterns among the healthy newborns, and flow changes among the infants with CHD not previously reported with conventional echocardiography. Conclusion For assessment of cardiac flow in the normal and diseased pediatric heart, VFI may provide additional information compared to conventional echocardiography and become a useful diagnostic tool.

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Resolving Ultrasound Contrast Microbubbles using Minimum Variance Beamforming

Minimum Variance (MV) beamforming is known to improve the lateral resolution of ultrasound images and enhance the separation of isolated point scatterers. This paper aims to evaluate the adaptive beamformer’s performance with flowing microbubbles (MBs), which are relevant to super-resolution ultrasound imaging. Simulations using point scatterer data from single emissions were complemented by an experimental investigation performed using a capillary tube phantom and the Synthetic Aperture Real-time Ultrasound System (SARUS). The MV performance was assessed by the minimum distance that allows the display of two scatterers positioned side-by-side, the lateral Full-Width-Half-Maximum (FWHM), and the Peak-Side-lobe-Level (PSL). In the tube, scatterer responses separated by down to 196 μm (or 1.05λ) were distinguished by the MV method, while the standard Delay-and-Sum (DAS) beamformers were unable to achieve such separation. Up to 9-fold FWHM decrease was also measured in favour of the MV beamformer, for individual echoes from MBs. The lateral distance between two scatterers impacted on their FWHM value, and additional differences in the scatterers’ axial or out-of-plane position also impacted on their size and appearance. The simulation and experimental results were in agreement in terms of lateral resolution. The point scatterer study showed that the proposed MV imaging scheme provided clear resolution benefits compared to DAS. Current super-resolution methods mainly depend on DAS beamformers. Instead, the use of the MV method may provide a larger number of detected, and potentially better localized, MB scatterers.

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Row-Column Beamforming with Dynamic Apodizations on a GPU
A delay-and-sum beamformer implementation for 3D imaging with row-column arrays is presented. It is written entirely in the MATLAB programming language for flexible use and fast modifications for research use, and all parts can run on either the CPU or GPU. Dynamic apodization with row-column arrays is presented and is supported in both transmit and receive. Delay calculations are simplified compared to previous beamformers, and 3D delay and apodization calculations are reduced to 2D problems for faster calculations. The performance is evaluated on an Intel Xeon E5-2630 v4 CPU with 64 GB RAM and a NVIDIA GeForce GTX 1080 Ti GPU with 11 GB RAM. A 192+192 array is simulated to image a volume of 96-by-96-by-45 wavelengths sampled at 0.3 wavelength in the axial direction and 0.5 wavelength in the lateral and elevation directions giving 5.53 million sample points. A single-element synthetic aperture sequence with 192 emissions is used. The 192 volumes are beamformed in approximately 1 hour on the CPU and 5 minutes on the GPU corresponding to a speed-up of up to 12.2 times. For a smaller beamforming problem consisting of the three center planes in the volume, a speed-up of 4.6 times is found from 109 to 24 seconds. The GPU utilization is around 5.0% of the possible floating point calculations indicating a trade-off between the easy programming approach and high performance.

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Vector Flow Imaging Compared with Digital Subtraction Angiography for Stenosis Assessment in the Superficial Femoral Artery - A Study of Vector Concentration, Velocity Ratio and Stenosis Degree Percentage
Stenosis of the superficial femoral artery (SFA) induces complex blood flow with increased velocities. Disease assessment is performed with Doppler ultrasound and digital subtraction angiography (DSA), but Doppler ultrasound is limited by angle dependency and DSA by ionizing radiation. An alternative is the vector flow imaging method based on transverse oscillation (TO), an angle-independent vector velocity technique using ultrasound. In this study, flow complexity and velocity measured with TO were compared with DSA for the assessment of stenosis in the SFA. The vector concentration, a measure of flow complexity, and the velocity ratio obtained from the stenosis and a disease-free adjacent vessel segment, were estimated with TO in 11 patients with a total of 16 stenoses of the SFA. TO data were compared with the corresponding stenosis degree percentage obtained with DSA. The correlation between the vector concentration and DSA was very strong (R=0.93; p

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3D Printed Flow Phantoms With Fiducial Markers for Super-Resolution Ultrasound Imaging

The improved resolution provided by ultrasound super-resolution imaging (SRI) sets new demands on the fabrication of phantoms for the validation and verification of the technique. Phantoms should resemble tissue and replicate the 3D nature of tissue vasculature at the microvascular scale. This paper presents a potential method for creating complex 3D phantoms, via 3D printing of water-filled polymer networks. By using a custom-built stereolithographic printer, projected light of the desired patterns converts an aqueous poly(ethylene glycol) diacrylate (PEGDA) solution into a hydrogel, a material capable of containing 75 wt% of water. Due to the hydrogel mainly consisting of water, it will, from an acoustical point of view, respond very similar to tissue. A method for printing cavities as small as (100 μm)³ is demonstrated, and a 3D printed flow phantom containing channels with cross sections of (200 μm)² is presented. The designed structures are geometrically manufactured with a 2% increase in dimensions. The potential for further reduction of the flow phantom channels size, makes 3D printing a promising method for obtaining microvascular-like structures.

Accuracy and Precision of a Plane Wave Vector Flow Imaging Method in the Healthy Carotid Artery

The objective of the study described here was to investigate the accuracy and precision of a plane wave 2-D vector flow imaging (VFI) method in laminar and complex blood flow conditions in the healthy carotid artery. The approach was to study (i) the accuracy for complex flow by comparing the velocity field from a computational fluid dynamics (CFD) simulation to VFI estimates obtained from the scan of an anthropomorphic flow phantom and from an in vivo scan; (ii) the accuracy for laminar unidirectional flow in vivo by comparing peak systolic velocities from VFI with magnetic resonance angiography (MRA); (iii) the precision of VFI estimation in vivo at several evaluation points in the vessels. The carotid artery at the bifurcation was scanned using both fast plane wave ultrasound and MRA in 10 healthy volunteers. The MRA geometry acquired from one of the volunteers was used to fabricate an anthropomorphic flow phantom, which was also scanned using the fast plane wave sequence. The same geometry was used in a CFD simulation to calculate the velocity field. Results indicated that similar flow patterns and vortices were estimated with CFD and VFI in the phantom for the carotid bifurcation. The root-mean-square difference between CFD and VFI was within 0.12 m/s for velocity estimates in the common carotid artery and the internal branch. The root-mean-square difference was 0.17 m/s in the external branch. For the 10 volunteers, the mean difference between VFI and MRA was -0.17 m/s for peak systolic velocities of laminar flow in vivo. The precision in vivo was calculated as the mean standard deviation (SD) of estimates aligned to the heart cycle and was highest in the center of the common carotid artery (SD = 3.6% for velocity magnitudes and 4.5° for angles) and lowest in the external branch and for vortices (SD = 10.2% for velocity magnitudes and 39° for angles). The results indicate that plane wave VFI measures flow precisely and that estimates are in good agreement with a CFD simulation and MRA.
A Comparison Study of Vector Velocity, Spectral Doppler and Magnetic Resonance of Blood Flow in the Common Carotid Artery

Magnetic resonance phase contrast angiography (MRA) is the gold standard for blood flow evaluation. Spectral Doppler ultrasound (SDU) is the first clinical choice, although the method is angle dependent. Vector flow imaging (VFI) is an angle-independent ultrasound method. The aim of the study was to compare VFI- and SDU-estimated peak systolic velocities (PSV) of the common carotid artery (CCA) with PSV obtained by MRA. Furthermore, intra- and inter-observer agreement was determined. MRA estimates were significantly different from SDU estimates (left CCA: p

A Row–Column-Addressed 2D Probe with an Integrated Compound Diverging Lens

Planar 2D row–column-addressed (RCA) arrays can be an attractive alternative to fully-populated arrays due to their significantly lower channel count. However, these arrays can only look straight forward, which limits their utility. One way to increase their field of view is by applying a diverging lens. However, when common lens materials are used for a single-layer diverging lens, they exhibit deficiencies in performance or form factor. A compound lens solution was integrated into a fully functioning probe to achieve a 30° field-of-view (FOV) while retaining clinically-acceptable patient contact characteristics. The compound lens was fabricated of a Bi$_2$O$_3$ loaded RTV and an urethane, Hapflex 541. Two similar developed probes were compared one with lens and one without. A curvilinear FOV of 28.5° was obtained, which was slightly lower than the designed and was caused by small deformation of the lens during assembly. The output pressure was lowered a factor 6 and the center frequency decreased from 8.5 MHz to 4.9 MHz due to the lens. This was
caused by the lens thickness, resulting in an increased attenuation of the transmitted signal. The difference between the two dB compressed frequency responses was observed to follow a linear tendency with a fitted slope of ~4 dB/MHz, which was in agreement with the estimated attenuation of the lens.

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**Atherosclerotic Lesions in the Superficial Femoral Artery (SFA) Characterized with Velocity Ratios using Vector Velocity Ultrasound**

Atherosclerotic arteries are challenging to evaluate quantitatively using spectral Doppler ultrasound because of the turbulent flow conditions that occur in relation to the atherosclerotic stenoses. Vector velocity ultrasound is angle independent and provides flow information, which could potentially improve the diagnosis of arterial stenoses. The purpose of the study is to distinguish significant stenoses in the superficial femoral artery (> 50% diameter reduction) from non-significant stenoses based on velocity ratios derived from the commercially available vector velocity ultrasound technique Vector Flow Imaging (VFI). Velocity ratios (intrastenotic blood flow velocity divided by pre- or poststenotic velocity) from a total of 16 atherosclerotic stenoses and plaques in the superficial femoral artery of 11 patients were obtained using VFI. The stenosis degree, expressed as percentage diameter reduction of the artery, was determined from digital subtraction angiography and compared to the velocity ratios. A velocity ratio of 2.5 was found to distinguish clinically relevant stenoses with >50% diameter reduction from clinically non-relevant stenoses with

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Characterization of medical ultrasound transducers

Optimal use of multi-element ultrasound transducers requires knowledge of the performance of their individual elements, for realistic simulation and optimized beamforming. When developing transducers, it is critical to characterize the performance of the transducer material itself, removing the effect of the transducer element size and geometry. To provide that level of knowledge, a measurement and characterization algorithm was developed and applied on several transducers. The individual elements were characterized consistently along the transducer length, and element spatial deviations were measured with μm precision, confirming the precision of the method.

Curvilinear 3-D Imaging Using Row–Column Addressed 2-D Arrays with a Diverging Lens: Phantom Study

A double-curved diverging lens over the flat row–column-addressed (RCA) 2-D array can extend its inherent rectilinear 3-D imaging field-of-view (FOV) to a curvilinear volume region, which is necessary for applications such as abdominal and cardiac imaging. Two concave lenses with radii of 12.7mm and 25.4mm were manufactured using RTV664 silicone. The diverging properties of the lenses were evaluated based on simulations and measurements on several phantoms. The measured FOV for both lenses in contact with tissue mimicking phantom were less than 15% different from the theoretical predictions, i.e., a curvilinear FOV of 32°×32° and 24°×24° for the 12.7mm and 25.4mm radii lenses. A synthetic aperture imaging sequence with single element transmissions was designed for imaging down to 140mm at a volume rate of 88 Hz. The performance was evaluated in terms of signal-to-noise ratio (SNR), FOV, and full-width-at-half-maximum (FWHM) of a focused beam. The penetration depths in a tissue mimicking phantom with 0.5 dB/(cm MHz) attenuation were 100mm and 125mm for the lenses with radii of 12.7mm and 25.4 mm. The azimuth, elevation, and radial FWHM at 43mm depth were (5.8, 5.8, 1)λ and (6, 6, 1)λ. The results of this study confirm that the proposed lens approach is an effective method for increasing the FOV, when imaging with RCA 2-D arrays.

Super resolution imaging (SRI) can benefit greatly from full 3D imaging to compensate for vessel structures moving out of the image plane. Row Column Addressed (RCA) arrays can provide such 3D imaging with low-complexity probe design. A RCA probe is being designed for a rat kidney with 192 + 192 elements to ensure low sidelobes and an imaging volume of 15x15x15 mm^3. The design space of such a transducer is investigated with this in mind. Capacitive micromachined ultrasonic transducer (CMUT) technology allows for new geometric shapes, including a near kerf-less zig-zag interwoven structure, which provides flexibility in the design process of new RCA. This work compares the image quality of a straight element RCA array with an RCA array with an interwoven zig-zag structure by simulations, to assess the image quality of a zigzag structured RCA. The Point Spread Function (PSF) showed symmetry in both the azimuth and elevation direction. Both the straight and interwoven design had a lateral Full Width Half Maximum (FWHM) of approximately 0.6 λ, close to the ideal FWHM without apodization. The interwoven design showed a slight contrast loss over the straight design, which was quantified with the Cystic Resolution (CR). The CR at 20 dB for the straight design was 1.3 λ, compared to 1.4 λ of the interwoven design. The interwoven zig-zag structure is therefore a viable solution to meet the requirements of the rodent experiments and provides a new level of design flexibility for manufacturing RCA transducer arrays.

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Flow Changes after Biological and Mechanical Aortic Valve Implantation Measured with VFI

Aortic valve stenosis increases peak systolic velocity (PSV) and flow complexity in the ascending aorta, and is treated with either biological or mechanical implants. Vector flow imaging (VFI) is an angle independent ultrasound method for flow assessment. In contrast to conventional ultrasound, VFI can quantify complex flow patterns, e.g. the flow complexity called vector concentration (VC) in long axis and the secondary rotation (SR) in short axis view. Study aim was to evaluate flow changes only visible with VFI before and after valve implantation in patients with aortic valve stenosis. VFI on a commercial scanner (Pro Focus 2202 Ultra View, BK Medical) with a linear transducer (8670, BK Medical) was applied intraoperatively on the ascending aorta. Four patients scheduled for biological valve implants and 4 patients for mechanical valve implants were scanned before and after surgery. Four patients with normal aortic valve were scanned for comparison. VFI data of the ascending aorta were obtained in long and short axis view during the systolic phase for assessment of VC and SR. VC ranges from 0 to 1 (complex to laminar flow), and SR is measured in Hz. PSV was obtained with conventional spectral Doppler. Before surgery, patients with aortic valve stenosis scheduled for mechanical (PSV: 356.3 (64.3) cm/s; SR: 15.3 (7.8) Hz; VC: 0.18 (0.03)) and biological implants (PSV: 350.0 (80.8) cm/s; SR: 17.9 (2.6) Hz; VC: 0.26 (0.07)) had more complex flow with higher velocities compared with patients with normal aortic valve (PSV: 124.8 (16.7) cm/s; SR: 2.9 (1.1) Hz; VC: 0.83 (0.09)). After surgery, velocities were lower for mechanical (PSV: 214.5 (47.5) cm/s; SR: 5.6 (3.0) Hz) compared with biological implants (PSV: 241.5 (39.1) cm/s; SR: 13.2 (1.8) Hz). However, VC was higher for biological (0.68 (0.05)) compared with mechanical implants (0.56 (0.09)) indicating a more laminar and less complex flow despite higher systolic velocities in patients treated with biological implants. The mechanical valve has a larger opening with cusps attached centrally in the lumen opposed to the biological valve, which may explain the differences found. Normal flow was neither found for biological nor mechanical implants. VFI can provide new parameters for flow evaluation and be useful for aortic flow assessment before and after valve implantation and in the development of mechanical valves.

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Increasing the field-of-view of row–column-addressed ultrasound transducers: implementation of a diverging compound lens
The purpose of this work is to investigate compound lenses for row-column-addressed (RCA) ultrasound transducers for increasing the field-of-view (FOV) to a curvilinear volume region, while retaining a flat sole to avoid trapping air between the transducer sole and the patient, which would otherwise lead to unwanted reflections. The primary motivation behind this research is to develop a RCA ultrasound transducer for abdominal or cardiac imaging, where a curvilinear volume region is a necessity. RCA transducers provide 3-D ultrasound imaging with fewer channels than fully-addressed 2-D arrays (2N instead of N2), but they have inherently limited FOV. By increasing the RCA FOV, these transducers can be used for the same applications as fully-addressed transducers while retaining the same price range as conventional 2-D imaging due to the lower channel count. Analytical and finite element method (FEM) models were employed to evaluate design options. Composite materials were developed by loading polymers with inorganic powders to satisfy the corresponding speed of sound and specific acoustical impedance requirements. A Bi2O3 powder with a density of 8.9 g/cm3 was used to decrease the speed of sound of a room temperature vulcanizing (RTV) silicone, RTV615, from 1.03 m=μs to 0.792 m=μs. Using micro-balloons in RTV615 and a urethane, Hapflex 541, their speeds of sound were increased from 1.03 m=μs to 1.50 m=μs and from 1.52 m=μs to 1.93 m=μs, respectively. A diverging add-on lens was fabricated of a Bi2O3 loaded RTV615 and an unloaded Hapflex 541. The lens was tested using a RCA probe, and a FOV of 32.2° was measured from water tank tests, while the FEM model yielded 33.4°. A wire phantom with 0.15 mm diameter wires was imaged at 3 MHz down to a depth of 14 cm using a synthetic aperture imaging sequence with single element transmissions. The beamformed image showed that wires outside the array footprint were visible, demonstrating the increased FOV.

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Non-invasive Estimation of Pressure Changes using 2-D Vector Velocity Ultrasound: An Experimental Study with In-Vivo Examples
A non-invasive method for estimating intravascular pressure changes using 2-D vector velocity is presented. The method was first validated on computational fluid dynamics (CFD) data, and with catheter measurements on phantoms. Hereafter, the method was tested in-vivo at the carotid bifurcation and at the aortic valve of two healthy volunteers. Ultrasound measurements were performed using the experimental scanner SARUS, in combination with an 8MHz linear array transducer for experimental scans and a carotid scan, whereas a 3.5MHz phased array probe was employed for a scan of an aortic valve. Measured 2-D fields of angle-independent vector velocities were obtained using synthetic aperture imaging. Pressure drops from simulated steady flow through six vessel geometries spanning different degrees of diameter narrowing, running from 20% – 70 %, showed relative biases from 0.35% to 12.06 %, depending on the degree of constriction. Phantom measurements were performed on a vessel with the same geometry as the 70% constricted CFD model. The derived pressure drops were compared to pressure drops measured by a clinically used 4F catheter and to a finite element model. The proposed method showed peak systolic pressure drops of -3.0kPa±57 Pa, while the catheter and the simulation model showed -5.4kPa±52 Pa and -2.9 kPa, respectively. An in-vivo acquisition of 10 s was made at the carotid bifurcation. This produced eight cardiac cycles from where pressure gradients of -227Pa±15 Pa were found. Lastly, the aortic valve measurement showed a peak pressure drop of -2.1 kPa over one cardiac cycle. In conclusion, pressure gradients from convective flow changes are detectable using 2-D vector velocity ultrasound.

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Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging, Technical University of Denmark, Copenhagen University Hospital
Portable Vector Flow Imaging Compared with Spectral Doppler Ultrasonography

In this study, a vector flow imaging (VFI) method developed for a portable ultrasound scanner was used for estimating peak velocity values and variation in beam-to-flow angle over the cardiac cycle in vivo on healthy volunteers. Peak-systolic velocity (PSV), end-diastolic velocity (EDV), and resistive index (RI) measured with VFI were compared to spectral Doppler ultrasonography (SDU). Seventeen healthy volunteers were scanned on the left and right common carotid arteries (CCAs). The standard deviation (SD) of VFI measurements averaged over the cardiac cycle was 7.3% for the magnitude and 3.84° for the angle. Bland-Altman plots showed a positive bias for the PSV measured with SDU (mean difference: 0.31 ms\(^{-1}\)), and Pearson correlation analysis showed a highly significant correlation (\(r = 0.6; p < 0.001\)). A slightly positive bias was found for EDV and RI measured with SDU (mean difference: 0.08 ms/1 and -0.01 ms\(^{-1}\), respectively). However, the correlation was low and not significant. The beam-to-flow angle was estimated over the systolic part of the cardiac cycle, and its variations were for all measurements larger than the precision of the angle estimation. The range spanned deviations from -25.2° to 23.7° with an average deviation from -15.5° to 9.7°. This can significantly affect PSV values measured by SDU as the beam-to-flow angle is not constant and not aligned with the vessel surface. The study demonstrates that the proposed VFI method can be used in vivo for the measurement of PSV in the CCAs, and that angle variations across the cardiac cycle can lead to significant errors in SDU velocity estimates.

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Research output: Contribution to journal » Journal article – Annual report year: 2018 » Research » peer-review
Probe development of CMUT and PZT row-column-addressed 2-D arrays
This paper presents the characterization of two prototyped fully integrated 62 × 62 row-column-addressed (RCA) 2-D transducer array probes, which are based on capacitive micromachined ultrasonic transducer (CMUT) and on piezoelectric transducer (PZT) technology, respectively. Both transducers have integrated apodization to reduce ghost echoes and were designed with similar acoustical features i.e. 3 MHz center frequency, λ/2-pitch and 24.8 mm² × 24.8 mm² active footprint. The transducer arrays were assembled in a 3-D printed probe handle with electromagnetic shield and integrated electronics for driving the 128-channel coaxial cable to the scanner. The electronics were designed to allow all elements, both rows and columns, to be used interchangeably as either transmitters or receivers. The transducer characterization i.e. bandwidth, phase delay, surface pressure, sensitivity, insertion loss, and acoustical crosstalk, were based on several single element measurements, including pressure and pulse-echo, and were evaluated quantitatively and comparatively. The weighted center frequency was 3.0 MHz for both probes and the measured -6 dB fractional bandwidth was 109 ± 4% and 80 ± 3% for the CMUT and the PZT probe, respectively. The surface pressures of the CMUT and PZT were 0.55 ± 0.06 MPa and 1.68 ± 0.09 MPa, respectively, and the receive sensitivities of the rows (receiving elements) were 12.9 ± 0.7 μV/Pa and 13.7 ± 2.1 μV/Pa.

Real-time 2-D Phased Array Vector Flow Imaging
Echocardiography examination of the blood flow is currently either restricted to 1-D techniques in real-time or experimental off-line 2-D methods. This paper presents an implementation of transverse oscillation for real-time 2-D vector flow imaging (VFI) on a commercial BK Ultrasound scanner. A large field-of-view (FOV) sequence for studying flow dynamics at 11 frames per second (fps) and a sequence for studying peak systolic velocities (PSV) with a narrow FOV at 36 fps were validated. The VFI sequences were validated in a flow-rig with continuous laminar parabolic flow and in a pulsating flow pump system before being tested in vivo, where measurements were obtained on two healthy volunteers. Mean PSV from 11 cycles was 155 cm s⁻¹ with a precision of ± 9.0% for the pulsating flow pump. In vivo, PSV estimated in the ascending aorta was 135 cm s⁻¹ ± 16.9% for 8 cardiac cycles. Furthermore, in vivo flow dynamics of the left ventricle and in the ascending aorta were visualized. In conclusion, angle independent 2-D VFI on a phased array has been implemented in real-time, and it is capable of providing quantitative and qualitative flow evaluations of both complex and fully transverse flow.
Respiratory variability of peak velocities in the common femoral vein estimated with vector flow imaging and Doppler ultrasound

Respiratory variability of peak velocities (RVPV) in the common femoral vein measured with ultrasound can reveal venous outflow obstruction. Pulse wave (PW) Doppler is the gold standard for venous velocity estimation of the lower extremities. PW Doppler measurements are angle dependent, whereas vector flow imaging (VFI) can yield angle-independent measures. The hypothesis of the present study was that VFI can provide RVPV estimations without the angle dependency of PW Doppler for an improved venous disease assessment. Sixty-seven patients with symptomatic chronic venous disease were included in the study. On average, VFI measured a lower RVPV than PW Doppler (VFI: 14.11 cm/s; PW: 17.32 cm/s, p=0.002) with a non-significant improved precision compared with PW Doppler (VFI: 21.09%; PW: 26.49%, p=0.08). In a flow phantom, VFI had improved accuracy (p < 0.01) and equal precision compared with PW Doppler. The study indicated that VFI can characterize the hemodynamic fluctuations in the common femoral vein.

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SA-VFI: the IEEE IUS challenge on Synthetic Aperture Vector Flow Imaging

High frame rate vector flow imaging represents the future way to implement velocity estimation modes on clinical systems. Several approaches to obtain such imaging modes are possible especially using plane or diverging waves. The SAVFI (Synthetic Aperture-Vector Flow Imaging) challenge is a competition organized during the IEEE International Ultrasonics Symposium 2018 in Kobe that aimed at bringing together all groups willing to work on synthetic aperture based high frame rate vector flow imaging. This document describes the framework and objectives of the challenge as well as the data-sets and metrics used in the competition. The paper concludes with a discussion of the experiences from organizing this challenge.

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Organisations: Department of Electrical Engineering, Biomedical Engineering, Université Claude Bernard Lyon 1
Contributors: Jensen, J. A., Liebgott, H., Cervenansky, F., Villagómez Hoyos, C. A.
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Spatiotemporal filtering for synthetic aperture slow flow imaging

In this study, power Doppler images (PD) are obtained using a duplex synthetic aperture (SA) sequence with continuous data. Focused spherical waves are emitted in human in-vivo tissue with a handheld probe. To overcome the effects of motion blur, microvascular flow detection is enhanced by using a spatiotemporal higher order singular value decomposition (HOSVD) filter. Images of testicular parenchyma and vasculature in the carotid region were acquired from healthy volunteers. The data were acquired with an effective fPRF of 2.08 kHz and beamformed using Synthetic Transmit Aperture beamforming. A second temporal axis was obtained by grouping the received signals in Doppler frames of 32 consecutive acquisitions. The time between Doppler frames is 15 ms (65 Hz), giving a sampling interval that represents the slow flow variation. Doppler frames were processed using a HOSVD filter, taking into account the 2 temporal dimensions and the spatial dimension. Power Doppler images were obtained for the soft tissue in proximity to the common carotid artery and the testicular parenchyma. In the latter case the imaged vessels are under 1 mm in diameter and the velocity of the flow within them is below 0.5 cm/s. This preliminary study with in-vivo data supports the use of sparse synthetic aperture sequences combined with eigen-filtering for slow flow imaging in human tissue.

General information

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Number of pages: 4
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Ultrasound Open Platforms for Next-Generation Imaging Technique Development

Open platform (OP) ultrasound systems are aimed primarily at the research community. They have been at the forefront of the development of synthetic aperture, plane wave, shear wave elastography and vector flow imaging. Such platforms are driven by a need for broad flexibility of parameters that are normally pre-set or fixed within clinical scanners. OP ultrasound scanners are defined to have three key features including customization of the transmit waveform, access to the pre-beamformed receive data and the ability to implement real-time imaging. In this paper, a formative discussion is given on the development of OPs from both the research community and the commercial sector. Both software and hardware based architectures are considered, and their specifications are compared in terms of resources and programmability. Software based platforms capable of real-time beamforming generally make use of scalable graphics processing unit (GPU) architectures, whereas a common feature of hardware based platforms is the use of fieldprogrammable gate array (FPGA) and digital signal processor (DSP) devices to provide additional on-board processing capacity. OPs with extended number of channels (>256) are also discussed in relation to their role in supporting 3-D imaging technique development. With the increasing maturity of OP ultrasound scanners, the pace of advancement in ultrasound imaging algorithms is poised to be accelerated.
Vector Flow Imaging Compared with Pulse Wave Doppler for Estimation of Peak Velocity in the Portal Vein

The study described here investigated whether angle-independent vector flow imaging (VFI) technique estimates peak velocities in the portal vein comparably to pulsed wave Doppler (PWD). Furthermore, intra- and inter-observer agreement was assessed in a substudy. VFI and PWD peak velocities were estimated from intercostal and subcostal views for 32 healthy volunteers, and precision analyses were conducted. Blinded to estimates, three physicians rescanned 10 volunteers for intra- and inter-observer agreement analyses. The precision of VFI and PWD was 18% and 28% from an intercostal view and 23% and 77% from a subcostal view, respectively. Bias between VFI and PWD was 0.57 cm/s (p = 0.38) with an intercostal view and 9.89 cm/s (p
Vector velocity ultrasound—a new ultrasound technique

• Vector flow techniques, with their many advantages over conventional Doppler techniques, are powerful alternatives for blood flow evaluation.
• Vector flow imaging can visualise complex flow; refine the classic flow parameters; and introduce new flow parameters and insonation windows.
• These factors will reduce operator dependency, improve the logistical work flow for users and the diagnostic accuracy for patients.

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Volumetric Color Flow Map using Row Column Transducer array - Simulation study
Volumetric Color Flow Mapping (CFM) is typically performed using matrix probes with up to 9,000 elements. The many elements necessitate the use of highly specialized and expensive probes with dedicated electronics. This paper demonstrates how Row Column Addressed (RCA) transducer arrays can provide volumetric CFM using only 1/72 times the number of elements used for conventional matrix probes without ECG gating. A simulation study is carried out and a constant parabolic vessel flow beneath a 62 × 62 flat surfaced RCA transducer with a center frequency of 3.5 MHz is simulated. A Synthetic Aperture Focusing Technique (SAFT) is used to construct volumetric images covering a region of 13.2×13.2×48.4 mm3 from eight focused emissions. The image lines in the volume are beamformed in parallel, and the axial velocity estimation is performed using eight consecutive realisations of the volumetric image. A volume rate of ~ 234 Hz is reached, with a pulse repetition frequency (fprf) of 15 kHz. From eight center line velocity profiles, the relative mean bias and standard deviation were calculated to be ~0.60% and 2.93%, respectively.

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Contributors: Jørgensen, L. T., Schou, M., Stuart, M. B., Jensen, J. A.
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3-D Imaging using Row–Column-Addressed 2-D Arrays with a Diverging Lens: Phantom Study
A double-curved diverging lens over a flat row–column-addressed (RCA) 2-D array can extend its inherent rectilinear 3-D imaging field-of-view (FOV) to a curvilinear volume region, which is necessary for applications such as abdominal and cardiac imaging. A concave lens with radius of 12.7 mm was manufactured using RTV664 silicone. The diverging properties of the lens were evaluated based on measurements on several phantoms. The measured 6 dB FOV in contact with a material similar to human soft tissue was less than 15% different from the theoretical predictions, i.e., a curvilinear FOV of 32°×32°. A synthetic aperture imaging sequence with single element transmissions was designed for imaging down to 14 cm at a volume rate of 88 Hz. The performance was evaluated in terms of signal-to-noise ratio (SNR), FOV,
and full-width-half-maximum (FWHM). The penetration depth in a tissue mimicking phantom with 0.5 dB/(cm MHz) attenuation was 13 cm. The results of this study confirm that the proposed lens approach is an effective method for increasing the FOV, when imaging with RCA 2-D arrays.

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Contributors: Bouzari, H., Engholm, M., Beers, C., Stuart, M. B., Nikolov, S. I., Thomsen, E. V., Jensen, J. A.
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**Accuracy and Precision of Plane Wave Vector Flow Imaging for Laminar and Complex Flow In Vivo**
In this study, a comparison between velocity fields for a plane wave 2-D vector flow imaging (VFI) method and a computational fluid dynamics (CFD) simulation is made. VFI estimates are obtained from the scan of a flow phantom, which mimics the complex flow conditions in the carotid artery. Furthermore, the precision of the VFI method is investigated under laminar and complex flow conditions in vivo. The carotid bifurcation of a healthy volunteer was scanned using both fast plane wave ultrasound and magnetic resonance imaging (MRI). The acquired MRI geometry of the bifurcation was used for fabricating an anthropomorphic flow phantom, which was also ultrasound scanned. The same geometry was used in a CFD simulation to calculate the velocity field. Results showed that similar flow patterns and vortices were estimated using CFD and VFI in the phantom. Velocity magnitudes were estimated with a mean difference within 15 %, however, it was 23 % in the external branch. For the in vivo scan, the precision in terms of mean standard deviation (SD) of estimates aligned to the cardiac cycle was highest in the center of the common carotid artery (SD 4.7° for angles) and lowest in the external branch and close to the vessel wall (SD 15.0° for angles).

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**A Methodology for Anatomic Ultrasound Image Diagnostic Quality Assessment**
This paper discusses methods for assessment of ultrasound image quality based on our experiences with evaluating new methods for anatomic imaging. It presents a methodology to ensure a fair assessment between competing imaging methods using clinically relevant evaluations. The methodology is valuable in the continuing process of method optimization and guided development of new imaging methods. It includes a three phased study plan covering from initial prototype development to clinical assessment. Recommendations to the clinical assessment protocol, software, and statistical analysis are presented. Earlier uses of the methodology has shown that it ensures validity of the assessment, as it separates the influences between developer, investigator, and assessor once a research protocol has been established.
This separation reduces confounding influences on the result from the developer to properly reveal the clinical value. The paper exemplifies the methodology using recent studies of Synthetic Aperture Sequential Beamforming tissue harmonic imaging.

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**Aortic Valve Stenosis Increases Helical Flow and Flow Complexity: A Study of Intra-operative Cardiac Vector Flow Imaging**
Aortic valve stenosis alters blood flow in the ascending aorta. Using intra-operative vector flow imaging on the ascending aorta, secondary helical flow during peak systole and diastole, as well as flow complexity of primary flow during systole, were investigated in patients with normal, stenotic and replaced aortic valves. Peak systolic helical flow, diastolic helical flow and flow complexity during systole differed between the groups (p<0.0001), and correlated to peak systolic velocity (R 0.94, 0.87 and 0.88, respectively). The study indicates that aortic valve stenosis increases helical flow and flow complexity, which are measurable with vector flow imaging. For assessment of aortic stenosis and optimization of valve surgery, vector flow imaging may be useful.

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Automatic Segmentation of Vessels in In-Vivo Ultrasound Scans
Ultrasound has become highly popular to monitor atherosclerosis, by scanning the carotid artery. The screening involves measuring the thickness of the vessel wall and diameter of the lumen. An automatic segmentation of the vessel lumen, can enable the determination of lumen diameter. This paper presents a fully automatic segmentation algorithm, for robustly segmenting the vessel lumen in longitudinal B-mode ultrasound images. The automatic segmentation is performed using a combination of B-mode and power Doppler images. The proposed algorithm includes a series of preprocessing steps, and performs a vessel segmentation by use of the marker-controlled watershed transform. The ultrasound images used in the study were acquired using the bk3000 ultrasound scanner (BK Ultrasound, Herlev, Denmark) with two transducers "8L2 Linear" and "10L2w Wide Linear" (BK Ultrasound, Herlev, Denmark). The algorithm was evaluated empirically and applied to a dataset of in-vivo 1770 images recorded from 8 healthy subjects. The segmentation results were compared to manual delineation performed by two experienced users. The results showed a sensitivity and specificity of 90.41 ± 11.2 % and 97.93 ± 5.7 % (mean ± standard deviation), respectively. The amount of overlap of segmentation and manual segmentation, was measured by the Dice similarity coefficient, which was 91.25 ± 11.6 %. The empirical results demonstrated the feasibility of segmenting the vessel lumen in ultrasound scans using a fully automatic algorithm.

A Vector Flow Imaging Method for Portable Ultrasound Using Synthetic Aperture Sequential Beamforming
This paper presents a vector flow imaging method for the integration of quantitative blood flow imaging in portable ultrasound systems. The method combines directional transverse oscillation (TO) and synthetic aperture sequential beamforming to yield continuous velocity estimation in the whole imaging region. Six focused emissions are used to create a high-resolution image (HRI), and a dual-stage beamforming approach is used to lower the data throughput between the probe and the processing unit. The transmit/receive focal points are laterally separated to obtain a TO in the HRI that allows for the velocity estimation along the lateral and axial directions using a phase-shift estimator. The performance of
the method was investigated with constant flow measurements in a flow rig system using the SARUS scanner and a 4.1-
MHz linear array. A sequence was designed with interleaved B-mode and flow emissions to obtain continuous data
acquisition. A parametric study was carried out to evaluate the effect of critical parameters. The vessel was placed at
depths from 20 to 40 mm, with beam-to-flow angles of 65°, 75°, and 90°. For the lateral velocities at 20 mm, a bias
between -5% and -6.2% was obtained, and the standard deviation (SD) was between 6% and 9.6%. The axial bias was
lower than 1% with an SD around 2%. The mean estimated angles were 66.70° ± 2.86°, 72.65° ± 2.48°, and 89.13° ±
0.79° for the three cases. A proof-of-concept demonstration of the real-time processing and wireless transmission was
tested in a commercial tablet obtaining a frame rate of 27 frames/s and a data rate of 14 MB/s. An in vivo measurement of
a common carotid artery of a healthy volunteer was finally performed to show the potential of the method in a realistic
setting. The relative SD averaged over a cardiac cycle was 4.33%.

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BCB polymer based row-column addressed CMUT
This paper presents an inexpensive, low temperature and rapid fabrication method for capacitive micromachined
ultrasonic transducers (CMUT). The fabrication utilizes the bonding and dielectric properties of the photosensitive polymer
Benzocyclobutene (BCB). A BCB based row-column addressed CMUT with integrated apodization has been fabricated
and characterized with initial impedance measurement. Furthermore, two linear BCB CMUT arrays have been fabricated
with different bottom electrode designs and characterized acoustically. All the fabricated arrays have a center frequency of
2.5 MHz when immersed into water and a pull-in voltage of 75 V. Stability tests have showed a stable coupling coefficient
of approximately 0.1 during 10 hours of biased operation. Acoustic measurements, with a hydrophone positioned 1 cm
from the CMUTs, have showed a peak-to-peak pressure of 14 kPa.

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Common Carotid Artery Flow Measured by 3-D Ultrasonic Vector Flow Imaging and Validated with Magnetic Resonance Imaging

Ultrasound (US) examination of the common carotid artery was compared with a through-plane magnetic resonance imaging (MRI) sequence to validate a recently proposed technique for 3-D US vector flow imaging. Data from the first volunteer examined were used as the training set, before volume flow and peak velocities were calculated for the remaining eight volunteers. Peak systolic velocities (PSVs) and volume flow obtained with 3-D US were, on average, 34% higher and 24% lower than those obtained with MRI, respectively. A high correlation was observed for PSV ($r = 0.79$), whereas a lower correlation was observed for volume flow ($r = 0.43$). The overall standard deviations were ±5.7% and ±5.7% for volume flow and PSV with 3-D US, compared with ±2.7% and ±3.2% for MRI. Finally, the data were re-processed with a change in the parameter settings for the echo-canceling filter to investigate its influence on overall performance. PSV was less affected by the re-processing, whereas the difference in volume flow between 3-D vector flow imaging and MRI was reduced to -9%, and with an improved overall standard deviation of ±4.7%. The results illustrate the feasibility of using 3-D US for precise and angle-independent volume flow and PSV estimation in vivo.

Curvilinear 3-D Imaging Using Row–Column-Addressed 2-D Arrays with a Diverging Lens: Feasibility Study

Constructing a double-curved row–column-addressed (RCA) 2-D array or applying a diverging lens over the flat RCA 2-D array can extend the imaging field-of-view (FOV) to a curvilinear volume without increasing the aperture size, which is necessary for applications such as abdominal and cardiac imaging. Extended FOV and low channel count of double-curved RCA 2-D arrays make 3-D imaging possible with equipment in the price range of conventional 2-D imaging. This study proposes a delay-and-sum beamformation scheme specific to double-curved RCA 2-D arrays and validates its focusing ability based on simulations. A synthetic aperture imaging sequence with single element transmissions is designed for imaging down to 14 cm at a volume rate of 88 Hz. Using a diverging lens with f-number of -1 circumscribing the underlying RCA array, the imaging quality of a double-curved λ/2-pitch 3 MHz 62+62 RCA 2-D array is investigated as a function of depth within a curvilinear FOV of 60°×60°. The simulated double-curved 2-D array exhibits the same full-width-at-halfmaximum values for a point scatterer within its curvilinear FOV at a fixed radial distance compared with a flat 2-D array within its rectilinear FOV. The results of this study demonstrate that the proposed beamforming approach is accurate for achieving correct time-of-flight calculations, and hence avoids geometrical distortions.
Directional Transverse Oscillation Vector Flow Estimation

A method for estimating vector velocities using transverse oscillation (TO) combined with directional beamforming is presented. In Directional Transverse Oscillation (DTO) a normal focused field is emitted and the received signals are beamformed in the lateral direction transverse to the ultrasound beam to increase the amount of data for vector velocity estimation. The approach is self-calibrating as the lateral oscillation period is estimated from the directional signal through a Fourier transform to yield quantitative velocity results over a large range of depths. The approach was extensively simulated using Field IIpro and implemented on the experimental SARUS scanner in connection with a BK Medical 8820e convex array transducer. Velocity estimates for DTO are found for beam-to-flow angles of 60, 75, and 90, and vessel depths from 24 to 156 mm. Using 16 emissions the Standard Deviation (SD) for angle estimation at depths ranging from 24 to 104 mm are between 6.01 and 0.93 with a mean SD of 2.8. The mean relative SD for the lateral velocity component is 9.2% and the mean relative bias -3.4% or 4 times lower than for traditional TO. The approach also works for deeper lying vessels with a slight increase in SD to 15.7%, but a maintained bias of -3.5% from 126 to 156 mm. Data for a pulsating flow has also been acquired for 15 cardiac cycles using a CompuFlow 1000 pump. The relative SD was here 7.4% for a femoral artery waveform.
Energy Based Clutter Filtering for Vector Flow Imaging
To obtain accurate blood flow velocity estimates it is important to remove the clutter signal originating from tissue. Conventionally, the clutter signal has been separated from the blood signal based on the difference of their spectral frequencies. However, this approach is not enough for obtaining vector flow measurements, since the spectra overlap at high beam-to-flow angles. In this work a distinct approach is proposed, where the energy of the velocity spectrum is used to differentiate among the two signals. The energy based method is applied by limiting the amplitude of the velocity spectrum function to a predetermined threshold. The effect of the clutter filtering is evaluated on a plane wave (PW) scan sequence in combination with transverse oscillation (TO) and directional beamforming (DB) for velocity estimation. The performance of the filter is assessed by comparison of the velocity estimates of the proposed filter against a conventional moving average clutter filter. The effect of tissue motion is investigated using a Field II simulation of a straight vessel with moving wall, while the direct effect of the filter on the velocity estimates is evaluated on a CFD model of a carotid bifurcation with a fixed vessel wall. The results show that the proposed filter outperformed the moving average during moving vessel wall conditions, where standard deviations from the velocity magnitudes and angles were kept consistently below 6% and 6° compared to 63% and 48° on the moving average filter. The results on the CFD showed that on non-moving conditions the velocity estimates had minor statistical differences with errors on the magnitude of -7.95±10.1% and angles of 0.15±6.65° for the proposed filter compared to -5.83±9.08% and -0.12±4.48°.

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Evaluation of New Ultrasound Techniques for Clinical Imaging in selected Liver and Vascular Applications
This Ph.D. project is based on a longstanding collaboration between physicists and engineers from the Center of Fast Ultrasound Imaging (CFU) at the Technical University of Denmark and medical doctors from the department of Radiology at Rigshospitalet. The intent of this cooperation is to validate new ultrasonic methods for future clinical use. Study I compares two B-mode ultrasound methods: the new experimental technique Synthetic Aperture Sequential Beamforming combined with Tissue Harmonic Imaging (SASB-THI), and a conventional technique combined with THI. While SASB reduces the amount of data transformation, thus enabling wireless transmission, THI can improve resolution and image contrast, and creates fewer artifacts. Thirty-one patients with verified liver tumors were scanned and recordings with and without visible pathology were performed. Subsequently, eight radiologists evaluated blinded to information about the technique, which B-mode images they preferred, as well as detection of pathology. Evaluation showed that the techniques were preferred equally and tumor could be detected equally well.
Study II deals with the ability of vector flow imaging (VFI) to monitor patients with arteriovenous fistulas for hemodialysis.
for upcoming stenosis. VFI is an angle-independent method for determining blood flow direction and velocity. Volume can be determined by integrating the velocity profile multiplied by the cross-sectional area. Nineteen patients were monitored monthly over a period of six months, and VFI estimates were compared with the reference ultrasound dilution technique (UDT). VFI volume flow values were not significantly different from UDT and had a better precision. Concordance between VFI and UDT was high when large volume flow changes (greater than 25%) occurred between dialysis sessions. However, the methods could not be regarded as interchangeable. Study III deals with VFI’s ability to determine peak velocity in the portal vein. The commonly used ultrasound method for this is spectral Doppler, which is known to overestimate peak velocity when the angle between the blood vessel and the beam is more than 70 degrees; this overestimation becomes even larger when the angle becomes larger. VFI can determine the peak velocity angle independently. Thirty-two healthy volunteers were scanned with spectral Doppler and VFI with two portal vein scan positions (intercostal and subcostal). The study showed that VFI estimates the same peak velocity as spectral Doppler. Furthermore, VFI has better precision and can estimate the same peak velocity with a scan position, where spectral Doppler cannot. Finally, inter- and intraobserver agreement is higher for VFI. All three studies indicate that the techniques can be used in the clinic and probably will be part of everyday practice in the near future.

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Experimental performance assessment of the sub-band minimum variance beamformer for ultrasound imaging
Recent progress in adaptive beamforming techniques for medical ultrasound has shown that current resolution limits can be surpassed. One method of obtaining improved lateral resolution is the Minimum Variance (MV) beamformer. The frequency domain implementation of this method effectively divides the broadband ultrasound signals into sub-bands (MVS) to conform with the narrow-band assumption of the original MV theory. This approach is investigated here using experimental Synthetic Aperture (SA) data from wire and cyst phantoms. A 7 MHz linear array transducer is used with the SARUS experimental ultrasound scanner for the data acquisition. The lateral resolution and the contrast obtained, are evaluated and compared with those from the conventional Delay-and-Sum (DAS) beamformer and the MV temporal implementation (MVT). From the wire phantom the Full-Width-at-Half-Maximum (FWHM) measured at a depth of 52 mm, is 16.7 μm (0.08λ) for both MV methods, while the corresponding values for the DAS case are at least 24 times higher. The measured Peak-Side-lobe-Level (PSL) may reach ~41 dB using the MVS approach, while the values from the DAS and MVT beamforming are above ~24 dB and ~33 dB, respectively. From the cyst phantom, the power ratio (PR), the contrast-to-noise ratio (CNR), and the speckle signal-to-noise ratio (sSNR) measured at a depth of 30 mm are at best similar for MVS and DAS, with values ranging between ~29 dB and ~30 dB, 1.94 and 2.05, and 2.16 and 2.27 respectively. In conclusion the MVS beamformer is not suitable for imaging continuous targets, and significant resolution gains were obtained only for isolated targets.

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Fast Plane Wave 2-D Vector Flow Imaging Using Transverse Oscillation and Directional Beamforming

Several techniques can estimate the 2-D velocity vector in ultrasound. Directional beamforming (DB) estimates blood flow velocities with a higher precision and accuracy than transverse oscillation (TO), but at the cost of a high beamforming load when estimating the flow angle. In this paper, it is proposed to use TO to estimate an initial flow angle, which is then refined in a DB step. Velocity magnitude is estimated along the flow direction using cross-correlation. It is shown that the suggested TO-DB method can improve the performance of velocity estimates compared to TO, and with a beamforming load, which is 4.6 times larger than for TO and seven times smaller than for conventional DB. Steered plane wave transmissions are employed for high frame rate imaging, and parabolic flow with a peak velocity of 0.5 m/s is simulated in straight vessels at beamto-flow angles from 45 to 90. The TO-DB method estimates the angle with a bias and standard deviation (SD) less than 2, and the SD of the velocity magnitude is less than 2%. When using only TO, the SD of the angle ranges from 2 to 17 and for the velocity magnitude up to 7%. Bias of the velocity magnitude is within 2% for TO and slightly larger but within 4% for TO-DB. The same trends are observed in measurements although with a slightly larger bias. Simulations of realistic flow in a carotid bifurcation model provide visualization of complex flow, and the spread of velocity magnitude estimates is 7.1 cm/s for TO-DB, while it is 11.8 cm/s using only TO. However, velocities for TO-DB are underestimated at peak systole as indicated by a regression value of 0.97 for TO and 0.85 for TO-DB. An in vivo scanning of the carotid bifurcation is used for vector velocity estimations using TO and TO-DB. The SD of the velocity profile over a cardiac cycle is 4.2% for TO and 3.2% for TO-DB.

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High-frame-rate Imaging of a Carotid Bifurcation using a Low-complexity Velocity Estimation Approach
In this paper, a 2-D vector flow imaging (VFI) method developed by combining synthetic aperture sequential beamforming and directional transverse oscillation is used to image a carotid bifurcation. Ninety-six beamformed lines are sent from the probe to the host system for each VFI frame, enabling the possibility of wireless transmission. The velocity is estimated using a relatively inexpensive 2-D phase-shift approach, and real-time performance can be achieved in mobile devices. However, high-frame-rate velocities can be obtained by sending the data to a cluster of computers. The objective of this study is to demonstrate the scalability of the method’s performance according to the needs of the user and the processing capabilities of the host system. In vivo measurements of a carotid bifurcation of a 54-year-old volunteer were conducted using a linear array transducer connected to the SARUS scanner. The velocities were estimated at a rate of 134 independent frames per second (FPS) to reveal complex flow patterns. A peak frame rate of 2140 FPS can be obtained by generating the images recursively. VFI images are shown during the systolic phase revealing the formation of a vortex in the internal carotid artery. The peak systolic velocity from a range gate in the common tract was 0.76 m s⁻¹ with a standard deviation (SD) of 6.1%. The mean velocity profile was calculated from the same range gate with an average SD of 7.86%.

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Improved Focusing Method for 3-D Imaging using Row–Column-Addressed 2-D Arrays
A row–column-addressed (RCA) 2-D array can be interpreted as two orthogonal 1-D arrays. By transmitting with row elements and receiving the echoes through column elements or vice versa, a rectilinear volume in front of the array can be beamformed. Since the transmit and receive 1-D arrays are orthogonal to each other, only one-way focusing is possible in each transmit or receive plane. For applications, where the scatterers are sparse, e.g., in micro-bubble tracking, this study suggests to multiply the envelope data received by the row elements when transmitting with columns as well as the data received by the column elements when transmitting with rows, to improve the focusing. In this way, at each point a two-way focused profile in both transmit and receive directions can be produced. This paper investigates the performance of the new focusing scheme based on simulations and phantom measurements with a PZT λ/2-pitch 3 MHz 62×62 RCA 2-D transducer probe. A synthetic aperture imaging sequence with single element transmissions at a time, is designed for imaging down to 14 cm at a volume rate of 44 Hz.

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Output Pressure and Pulse-Echo Characteristics of CMUTs as Function of Plate Dimensions

This paper presents an experimental study of the acoustic performance of Capacitive Micromachined Ultrasonic Transducers (CMUTs) as function of plate dimensions. The objective is to increase the output pressure without decreasing the pulse-echo signal. The CMUTs are fabricated with a LOCOS process, followed by direct wafer fusion bonding to a Silicon-On-Insulator (SOI) wafer. In this way, the plate thickness is determined by the SOI wafer device layer thickness, resulting in CMUTs with plate thicknesses of 2, 9.3 and 15 μm. The corresponding radii and gap heights resulting in an immersion frequency of 5MHz and a pull-in voltage of 200V are obtained using finite element analysis.

Hydrophone and plane reflector measurements are used to assess the acoustic performance. Increasing the plate thickness from 2μm to 15μm decreases the pulse-echo bandwidth from >100% to 30%. A maximum in both peak-to-peak output pressure and pulse-echo signal is obtained for the 9.3μm plate, which still has a moderate pulse-echo bandwidth of 60%. The 9.3μm plate results in a 1.9 times higher peak-to-peak output pressure and a 3.6 times higher pulse-echo signal compared to the 2μm plate. By adjusting the plate dimensions of a CMUT it is possible to optimize its acoustic performance for medical imaging applications, including visualization of deeper structures in the body, as well as nonlinear imaging such as tissue harmonic imaging.

Real-time Implementation of Synthetic Aperture Vector Flow Imaging on a Consumer-level Tablet

In this work, a 2-D vector flow imaging (VFI) method based on synthetic aperture sequential beamforming (SASB) and directional transverse oscillation is implemented on a commercially available tablet. The SASB technique divides the beamforming process in two parts, whereby the required data rate between the probe and back-end can be reduced by a factor of 64 compared to conventional delay-and-sum focusing. The lowered data rate enables real-time wireless transfer for both B-mode and VFI data. In the present setup, element data were acquired from a straight vessel with the SARUS research scanner and processed by a first-stage beamformer in a fixed focus. The data were subsequently transferred to an HTC Nexus 9 tablet through an ASUS RT-AC68U Wi-Fi router to simulate a wireless probe. The second-stage beamforming of the B-mode and flow data and the velocity estimation were implemented on the tablet’s built-in GPU (Nvidia Tegra K1) through the OpenGL ES 3.1 API. Real-time performance was achieved with rates up to 26 VFI frames per second (38 ms/frame) for concurrent processing and Wi-Fi transmission.
Simulating CMUT Arrays Using Time Domain FEA

PZFlex is a commercial FEA software that has been optimized for the ultrasound industry and is commonly used to design piezoelectric ultrasound transducers. However, PZFlex is not commonly used within the CMUT research field. Nevertheless, it has an explicit modeling approach allowing large structures like CMUT arrays to be modeled and its transient analysis intrinsically supplies non-linear and broadband results from a single run. A 3-D model of a CMUT array is developed with multiple cells in each element and one active element surrounded by N passive elements. It is demonstrated that the electro-mechanics can precisely be predicted, within 3%, including the pull-in voltage and the spring softening effect. The transmit impulse response is simulated by deconvolving the extrapolated pressure with the excitation pulse, and it is in excellent agreement with the measured. It is shown that the impulse response can directly be used in Field II to assess the image quality of the transducer using the lateral, axial and cystic resolution for two different CMUT designs.

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Stenosis of the superficial femoral artery evaluated in-vivo with vector concentration - a novel ultrasound vector velocity derived flow parameter for measurement of flow complexity

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Super-resolution Axial Localization of Ultrasound Scatter Using Multi-focal Imaging

This paper aims to develop a method for achieving micrometre axial scatterer localization for medical ultrasound, surpassing the inherent, pulse length dependence limiting ultrasound imaging. Methods: The method, directly translated from cellular microscopy, is based on multi-focal imaging and the simple, aberration dependent, image sharpness metric of a single point scatterer. The localization of a point scatterer relies on the generation of multiple overlapping sharpness curves, created by deploying three foci during receive processing, and by assessing the sharpness values after each acquisition as a function of depth. Each derived curve peaks around the receive focus and the unique position of the scatterer is identified by combining the data from all curves using a maximum likelihood algorithm with a calibration standard. Results: Simulated and experimental ultrasound point scatter data show that the sharpness method can provide scatterer axial localization with an average accuracy down to 10.21 µm (≈ λ/21) and with up to 11.4 times increased precision compared to conventional localization. The improvements depend on the rate of change of sharpness using each focus, and the signal to noise ratio in each image. Conclusion: Super-resolution axial imaging from optical microscopy has been successfully translated into ultrasound imaging by using raw ultrasound data and standard beamforming. Significance: The normalized sharpness method has the potential to be used in scatterer localization applications and contribute in current super-resolution ultrasound imaging techniques.

Synthetic Aperture Sequential Beamforming using Spatial Matched Filtering

Synthetic Aperture Sequential Beamforming (SASB) has shown to achieve a good resolution and high penetration depth. The low complexity at the transducer level of the beamformer makes it ideal for use with a handheld device. SASB with a low F# (≤ 0.5) can achieve even better resolution at the cost of high grating lobes, which causes loss of contrast in the final image. In this paper, Spatial Matched Filtering (SMF) was used instead the second stage of beamformer, in an attempt to suppress the grating lobes. The advantage of SMF over SASB was investigated by pushing the limits of F#, from 1.5 to 0.5. The effect of the number of emissions used in first stage was also investigated. A 3.3 MHz BK Ultrasound
9040 convex array was simulated in Field II on a point scatter phantom and a cyst phantom. The resolution was quantified with the full-width-half-max (FWHM), and the contrast was measured with the 20 dB cystic resolution. The contrast-to-noise ratio (CNR) was calculated for the cyst mimicking phantom. The results showed that SMF achieved similar resolution as SASB and improved grating lobe suppression leading to an increase in contrast. The grating lobes caused by an F# of 0.5 are dominant in the SASB images, but not as much in SMF images. The CNR for a cyst mimicking phantom was improved 7 dB and 6 dB for SMF over SASB at depth 20 mm and 30 mm, with an F# of 0.5 and 256 emissions. The FWHM for SMF was slightly higher than SASB across all depth and parameter settings, with a maximum difference of 0.3 mm. It was demonstrated that SMF can achieve similar resolution to SASB and for certain parameter settings improve the contrast by suppressing the grating lobe artifacts.

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Transmitting Performance Evaluation of ASICs for CMUT-Based Portable Ultrasound Scanners
Portable ultrasound scanners (PUS) have, in recent years, raised a lot of attention, as they can potentially overcome some of the limitations of static scanners. However, PUS have a lot of design limitations including size and power consumption. These restrictions can compromise the image quality of the scanner. In order to overcome these restrictions, application specific integrated circuits (ASICs) are needed to implement the electronics. In this work, a comparative study of the transmitting performance of a capacitive micromachined ultrasonic transducer (CMUT) driven by a commercial generic ultrasound transmitter and an ASIC optimized for CMUT-based PUS is presented. A single CMUT element is pulsed with a 1% dutycycle at a frequency of 5 MHz. The DC bias voltage is 80 V and the pulsing voltage is 20 V. The acoustic performance is assessed by comparing the ultrasonic signals measured with a hydrophone both in the time and frequency domains. The difference in normalized signal amplitude evaluated at the center frequency of the CMUT is −1.9 dB and the measured bandwidth is equivalent. The ASIC consumes only 1.3% of the total power consumption used by the commercial transmitter.

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Ultrasonic 3-D Vector Flow Method for Quantitative In Vivo Peak Velocity and Flow Rate Estimation
Current clinical ultrasound (US) systems are limited to show blood flow movement in either 1-D or 2-D. In this paper, a method for estimating 3-D vector velocities in a plane using the transverse oscillation method, a 32×32 element matrix
array, and the experimental US scanner SARUS is presented. The aim of this paper is to estimate precise flow rates and peak velocities derived from 3-D vector flow estimates. The emission sequence provides 3-D vector flow estimates at up to 1.145 frames/s in a plane, and was used to estimate 3-D vector flow in a cross-sectional image plane. The method is validated in two phantom studies, where flow rates are measured in a flow-rig, providing a constant parabolic flow, and in a straight-vessel phantom (Ø=8 mm) connected to a flow pump capable of generating time varying waveforms. Flow rates are estimated to be 82.1 ± 2.8 L/min in the flow-rig compared with the expected 79.8 L/min, and to 2.68 ± 0.04 mL/stroke in the pulsating environment compared with the expected 2.57 ± 0.08 mL/stroke. Flow rates estimated in the common carotid artery of a healthy volunteer are compared with magnetic resonance imaging (MRI) measured flow rates using a 1-D through-plane velocity sequence. Mean flow rates were 333 ± 31 mL/min for the presented method and 346 ± 2 mL/min for the MRI measurements.

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Vector and Doppler Ultrasound Velocities Evaluated in a Flow Phantom and the Femoropopliteal Vein
Ultrasound is used for evaluating the veins of the lower extremities. Operator and angle dependency limit spectral Doppler ultrasound (SDUS). The aim of the study was to compare peak velocity measurements in a flow phantom and the femoropopliteal vein of 20 volunteers with the angle-independent vector velocity technique vector flow imaging (VFI) and SDUS. In the flow phantom, VFI underestimated velocity (p = 0.01), with a lower accuracy of 5.5% (p = 0.01) and with no difference in precision, that is, error factor, compared with SDUS (VFI: 1.02 vs. SDUS: 1.02, p = 0.58). In vivo, VFI estimated lower velocities (femoral: p = 0.001; popliteal: p = 0.001) with no difference in precision compared with SDUS (femoral: VFI 1.09 vs. SDUS 1.14, p = 0.37; popliteal: VFI 1.13 vs. SDUS 1.06, p = 0.09). In conclusion, the precise VFI technique can be used to characterize venous hemodynamics of the lower extremities despite its underestimation of velocities.

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Vector Flow Imaging Compared with Conventional Doppler Ultrasound and Thermodilution for Estimation of Blood Flow in the Ascending Aorta

Transverse oscillation (TO) is a real-time ultrasound vector flow method implemented on a commercial scanner. The TO setup was examined on a flowrig with constant and pulsatile flow. Subsequently, 25 patients undergoing cardiac bypass surgery were scanned intraoperatively with TO on the ascending aorta and compared to transthoracic echocardiography (TEE) and pulmonary artery catheter thermodilution (PACTD). On the flowrig, TO had a precision of 5.5%, 9.4% and 14.7%, a percentage error of 18.2%, 14.6% and 40.7%, and a mean bias of 0.4 cm/s, 36.8 ml/min and 32.4 ml/min for velocity and flow rate (constant and pulsatile) estimation. The correlation coefficients for all flowrig evaluations were 0.99 indicating systematic bias. After bias correction, the percentage error was reduced to 11.5%, 12.6% and 15.9% for velocity and flow rate (constant and pulsatile) estimation. In the in vivo setup, TO, TEE, and PACTD had a precision of 21.9%, 13.7%, and 12.0%. TO compared with TEE and PACTD had a mean bias of 12.6 cm/s and −0.08 l/min, and a percentage error of 23.4% and 36.7%, respectively. The percentage error was reduced to 22.9% for the TEE comparison, but increased to 43.8% for the PACTD comparison, after correction for the systematic bias found in the flowrig. TO is a reliable and precise method for velocity and flow rate estimation on a flowrig. However, TO with the present setup, is not interchangeable with PACTD for cardiac volume flow estimation, but is a reliable and precise angle-independent ultrasound alternative for velocity estimation of cardiac flow.

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Vector velocity estimation of blood flow – A new application in medical ultrasound

Vector flow techniques in the field of ultrasound encompass different pulse emission and estimation strategies. Numerous techniques have been introduced over the years, and recently commercial implementations usable in the clinic have been made. A number of clinical papers using different vector velocity approaches have been published. This review will give an overview of the most significant in vivo results achieved with ultrasound vector flow techniques, and will outline some of the possible clinical applications for vector velocity estimation in the future.

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Velocity Estimation in Medical Ultrasound

This article describes the application of signal processing in medical ultrasound velocity estimation. Special emphasis is on the relation among acquisition methods, signal processing, and estimators employed. The description spans from current clinical systems for one-and two-dimensional (1-D and 2-D) velocity estimation to the experimental systems for three-dimensional (3-D) estimation and advanced imaging sequences, which can yield thousands of images or volumes per second with fully quantitative flow estimates. Here, spherical and plane wave emissions are employed to insonify the whole region of interest, and full images are reconstructed after each pulse emission for use in velocity estimation.

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Volumetric 3-D Vector Flow Measurements using a 62+62 Row-Column Addressed Array

Experimental results from volumetric 3-D vector flow measurements using a 62+62 row-column addressed (RCA) array are presented. A plane-by-plane steered transmit sequence and its post processing steps are described for obtaining 3-D vector flow in a volume. A modified version of the transverse oscillation (TO) velocity estimator is used, which exploits the focal lines generated with the tall elements of a RCA array. Validation of the method is made in a flow-rig system where circulating blood mimicking fluid produced a steady parabolic flow profile with a flow rate of 13.7 mL/s, translating to a peak velocity of 24.1 cm/s. A volume rate of 16.4 volumes per second is obtained, and estimated flow rates based on nine steered planes within the volume are investigated. A positive bias is found for all investigated planes lying in the range from 6.5% to 21.2% with the standard deviation being less than 4% for all cases. It is concluded that volumetric 3-D vector flow estimation is feasible with an RCA array with only 124 elements.

3-D Imaging using Row--Column-Addressed 2-D Arrays with a Diverging Lens

It has been shown that row–column-addressed (RCA) 2-D arrays can be an inexpensive alternative to fully addressed 2-D arrays. Generally imaging with an RCA 2-D array is limited to its forward-looking volume region. Constructing a double-curved RCA 2-D array or applying a diverging lens over the flat RCA 2-D array, can extend the imaging field-of-view (FOV) to a curvilinear volume without increasing the aperture size, which is necessary for applications such as abdominal and cardiac imaging. Extended FOV and low channel count of doublecurved RCA 2-D arrays make it possible to have 3-D imaging with equipment in the price range of conventional 2-D imaging. This study proposes a delay-and-sum (DAS) beamformation scheme specific to double-curved RCA 2-D arrays and validates its focusing ability based on simulations. A synthetic aperture imaging (SAI) sequence with single element transmissions at a time, is designed for imaging down to 14 cm at a volume rate of 88 Hz. The curvilinear imaging performance of a λ/2-pitch 3 MHz 62×62 RCA 2-D array is investigated as a function of depth, using a diverging lens with f-number of -1. The results of this study demonstrate that the proposed beamforming approach is accurate for achieving correct time-of-flight calculations, and hence avoids geometrical distortions.
Bouzari et al. IUS2016.pdf

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3-D Vector Flow Estimation With Row–Column-Addressed Arrays

Simulation and experimental results from 3-D vector flow estimations for a 62 × 62 2-D row–column (RC) array with integrated apodization are presented. A method for implementing a 3-D transverse oscillation (TO) velocity estimator on a 3-MHz RC array is developed and validated. First, a parametric simulation study is conducted, where flow direction, ensemble length, number of pulse cycles, steering angles, transmit/receive apodization, and TO apodization profiles and spacing are varied, to find the optimal parameter configuration. The performance of the estimator is evaluated with respect to relative mean bias $\hat{B}$ and mean standard deviation $\hat{\sigma}$. Second, the optimal parameter configuration is implemented on the prototype RC probe connected to the experimental ultrasound scanner SARUS. Results from measurements conducted in a flow-rig system containing a constant laminar flow and a straight-vessel phantom with a pulsating flow are presented. Both an M-mode and a steered transmit sequence are applied. The 3-D vector flow is estimated in the flow rig for four representative flow directions. In the setup with 90° beam-to-flow angle, the relative mean bias across the entire velocity profile is $\pm 4.7\%$ with a relative standard deviation of $\pm 0.4\%$ for $(v_x, v_y, v_z)$. The estimated peak velocity is $48.5 \pm 3$ cm/s giving a $\pm 3\%$ bias. The out-of-plane velocity component perpendicular to the cross section is used to estimate volumetric flow rates in the flow rig at a 90° beam-to-flow angle. The estimated mean flow rate in this setup is $91.2 \pm 3.1$ L/h corresponding to a bias of $\pm 11.1\%$. In a pulsating flow setup, flow rate measured during five cycles is $2.3 \pm 0.1$ mL/stroke giving a negative $9.7\%$ bias. It is concluded that accurate 3-D vector flow estimation can be obtained using a 2-D RC-addressed array.

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3-D Vector Flow Using a Row-Column Addressed CMUT Array

This paper presents an in-house developed 2-D capacitive micromachined ultrasonic transducer (CMUT) applied for 3-D blood flow estimation. The probe breaks with conventional transducers in two ways; first, the ultrasonic pressure field is generated from thousands of small vibrating micromachined cells, and second, elements are accessed by row and/or column indices. The 62×62 2-D row-column addressed prototype CMUT probe was used for vector flow estimation by transmitting focused ultrasound into a flow-rig with a fully developed parabolic flow. The beam-to-flow angle was 90°. The received data was beamformed and processed offline. A transverse oscillation (TO) velocity estimator was used to estimate the 3-D vector flow along a line originating from the center of the transducer. The estimated velocities in the lateral and axial direction were close to zero as expected. In the transverse direction a characteristic parabolic velocity
profile was estimated with a peak velocity of 0.48 m/s ± 0.02 m/s in reference to the expected 0.54 m/s. The results presented are the first 3-D vector flow estimates obtained with a row-column CMUT probe, which demonstrates that the CMUT technology is feasible for 3-D flow estimation.

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**Accurate Angle Estimator for High-Frame-rate 2-D Vector Flow Imaging**

This paper presents a novel approach for estimating 2-D flow angles using a high-frame-rate ultrasound method. The angle estimator features high accuracy and low standard deviation (SD) over the full 360° range. The method is validated on Field II simulations and phantom measurements using the experimental ultrasound scanner SARUS and a flow rig before being tested in vivo. An 8-MHz linear array transducer is used with defocused beam emissions. In the simulations of a spinning disk phantom, a 360° uniform behavior on the angle estimation is observed with a median angle bias of 1.01° and a median angle SD of 1.8°. Similar results are obtained on a straight vessel for both simulations and measurements, where the obtained angle biases are below 1.5° with SDs around 1°. Estimated velocity magnitudes are also kept under 10% bias and 5% relative SD in both simulations and measurements. An in vivo measurement is performed on a carotid bifurcation of a healthy individual. A 3-s acquisition during three heart cycles is captured. A consistent and repetitive vortex is observed in the carotid bulb during systoles.

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A framework for simulating ultrasound imaging based on first order nonlinear pressure–velocity relations.

An ultrasound imaging framework modeled with the first order nonlinear pressure–velocity relations (NPVR) based simulation and implemented by a half-time staggered solution and pseudospectral method is presented in this paper. The framework is capable of simulating linear and nonlinear ultrasound propagation and reflections in a heterogeneous medium with different sound speeds and densities. It can be initialized with arbitrary focus, excitation and apodization for multiple individual channels in both 2D and 3D spatial fields. The simulated channel data can be generated using this framework, and ultrasound image can be obtained by beamforming the simulated channel data. Various results simulated by different algorithms are illustrated for comparisons. The root mean square (RMS) errors for each compared pulses are calculated. The linear propagation is validated by an angular spectrum approach (ASA) with a RMS error of 3% at the focal point for a 2D field, and Field II with RMS errors of 0.8% and 1.5% at the electronic and the elevation focuses for 3D fields, respectively. The accuracy for the NPVR based nonlinear propagation is investigated by comparing with the Abersim simulation for pulsed fields and with the nonlinear ASA for monochromatic fields. The RMS errors of the nonlinear pulses calculated by the NPVR and Abersim are respectively 2.4%, 7.4%, 17.6% and 36.6% corresponding to initial pressure amplitudes of 50 kPa, 200 kPa, 500 kPa and 1 MPa at the transducer. By increasing the sampling frequency for the strong nonlinearity, the RMS error for 1 MPa initial pressure amplitude is reduced from 36.6% to 27.3%.

Analog Gradient Beamformer for a Wireless Ultrasound Scanner.

This paper presents a novel beamformer architecture for a low-cost receiver front-end, and investigates if the image quality can be maintained. The system is oriented to the development of a hand-held wireless ultrasound probe based on Synthetic Aperture Sequential Beamforming, and has the advantage of effectively reducing circuit complexity and power dissipation. The array of transducers is divided into sub-apertures, in which the signals from the single channels are aligned through a network of cascaded gradient delays, and summed in the analog domain before A/D conversion. The delay values are quantized to simplify the shifting unit, and a single A/D converter is needed for each sub-aperture yielding a compact, low-power architecture that can be integrated in a single chip. A simulation study was performed using a 3.75 MHz convex array, and the point spread function (PSF) for different configurations was evaluated in terms of lateral full-width-at-half-maximum (FWHM) and −20 dB cystic resolution (CR). Several setups were simulated varying the sub-aperture size N and the quantization step, and design constraints were obtained comparing the PSF to that of an ideal non-quantized system. The PSF is shown for N = 32 with a quantization step of 12 ns. For this configuration, the FWHM is degraded by 0.25% and the CR is 8.70% lower compared to the ideal situation. The results demonstrate that the gradient beamformer provides an adequate image quality, and open the way to a fully-integrated chip for a compact, low-cost, wireless ultrasound probe.
Analysis of Systolic Backflow and Secondary Helical Blood Flow in the Ascending Aorta Using Vector Flow Imaging

Secondary rotational flow and systolic backflow are seen in the ascending aorta and, in this study, were analyzed with the vector velocity method transverse oscillation. Twenty-five patients were scanned intra-operatively, and the vector velocities were related to estimates of transesophageal echocardiography and pulmonary artery catheter thermodilution, and associated with gender, age, aortic diameter, atherosclerotic plaques, left ventricular ejection fraction and previous myocardial infarctions. Secondary flow was present for all patients. The duration and rotational frequency (p <0.001) and the duration and flow direction of the secondary flow (p <0.002) were associated. Systolic backflow was present in 40% of the patients and associated with systolic velocities (p <0.002) and the presence of atherosclerotic plaques (p <0.001). No other significant associations were observed. The study indicates that backflow is injurious and that secondary flow is a normal flow phenomenon. The study also shows that transverse oscillation can provide new information on blood flow in the ascending aorta.

An improved minimum variance beamforming applied to plane-wave imaging in medical ultrasound

Minimum variance beamformer (MVB) is an adaptive beamformer which provides images with higher resolution and contrast in comparison with non-adaptive beamformers like delay and sum (DAS). It finds weight vector of beamformer by minimizing output power while keeping the desired signal unchanged. We used the eigen-based MVB and
generalized coherence factor (GCF) to further improve the quality of MVB beamformed images. The eigen-based MVB projects the weight vector with a transformation matrix constructed from eigen-decomposing of the array covariance matrix that increases resolution and contrast. GCF is used to emphasis on coherence part of images that improves the resolution. Four different datasets provided by IUS 2016 beamforming challenge are used to evaluate the proposed method. In comparison with DAS with rectangular weight vector, our method improved contrast about 8.52 dB and 6.20 dB for simulation and experimental contrast phantoms, respectively. It also enhanced lateral (axial) resolution about 87% (40%) and 73% (21%) for simulated and experimental resolution phantoms, respectively.

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A novel array processing method for precise depth detection of ultrasound point scatter
A signal based algorithm resulting in increased depth resolution is presented for medical ultrasound. It relies on multiple foci beamforming that is enabled by current ultrasound imaging systems. The concept stems from optical microscopy and is translated here into ultrasound using the Field II simulation software. A 7 MHz linear transducer is used to scan a single point scatterer phantom that can move in the axial direction. Individual beamformer outputs from 3 different foci are post-processed using the highly-dependent on focusing errors, metric of sharpness to estimate the position of the point scatter. A 37.8 μm uncertainty in depth estimation is achieved, which attains an almost 3-fold improvement compared to conventional ultrasound imaging axial resolution. Future work on the development of this algorithm requires experimental validation in tissue-like materials that provide strong aberrations.

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Blood flow velocity in the Popliteal Vein using Transverse Oscillation Ultrasound.
Chronic venous disease is a common condition leading to varicose veins, leg edema, post-thrombotic syndrome and venous ulcerations. Ultrasound (US) is the main modality for examination of venous disease. Color Doppler and occasionally spectral Doppler US (SDUS) are used for evaluation of the venous flow. Peak velocities measured by SDUS
are rarely used in a clinical setting for evaluating chronic venous disease due to inadequate reproducibility mainly caused by the angle dependency of the estimate. However, estimations of blood velocities are of importance in characterizing venous disease. Transverse Oscillation US (TOUS), a non-invasive angle independent method, has been implemented on a commercial scanner. TOUS’s advantage compared to SDUS is a more elaborate visualization of complex flow. The aim of this study was to evaluate, whether TOUS perform equal to SDUS for recording velocities in the veins of the lower limbs. Four volunteers were recruited for the study. A standardized flow was provoked with a cuff compression-decompression system placed around the lower leg. The average peak velocity in the popliteal vein of the four volunteers was 151.5 cm/s for SDUS and 105.9 cm/s for TOUS (p <0.001). The average of the peak velocity standard deviations (SD) were 17.0 cm/s for SDUS and 13.1 cm/s for TOUS (p <0.005). The study indicates that TOUS estimates lower peak velocity with improved SD when compared to SDUS. TOUS may be a tool for evaluation of venous disease providing quantitative measures for the evaluation of venous blood flow.

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**Capacitive Substrate Coupling of Row–Column-Addressed 2-D CMUT Arrays**
Row–column-addressed CMUT arrays suffer from low receive sensitivity of the bottom elements due to a capacitive coupling to the substrate. The capacitive coupling increases the parasitic capacitance. A simple approach to reduce the parasitic capacitance is presented, which is based on depleting the semiconductor substrate. To reduce the parasitic capacitance by 80% the bulk doping concentration should be at most $10^{12}$ cm$^{-3}$. Experimental results show that the parasitic capacitance can be reduced by 87% by applying a substrate potential of 6V relative to the bottom electrodes. The depletion of the semiconductor substrate can be sustained for at least 10 minutes making it applicable for row–column-addressed CMUT arrays for ultrasonic imaging. Theoretically the reduced parasitic capacitance indicates that the receive sensitivity of the bottom elements can be increased by a factor of 2:1.

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Elimination of Second-Harmonics in CMUTs using Square Pulse Excitation

The harmonic imaging mode is today a fundamental part of ultrasound imaging; it is not only used for suppressing the grating lobe artifact, but also to reduce many other acoustical artifacts in the ultrasound image. A vital performance parameter for accepting CMUT probes as a clinical usable transducer technology is, that it can support harmonic imaging. The large bandwidth of the CMUT is a clear advantage for harmonic imaging, but the inherent nonlinear behavior of the CMUT poses an issue as it is difficult to dissociate the harmonics generated in the tissue from the harmonic content of the transmitted signal. This work presents how proper pulse coding of a bipolar pulser, which is present in most commercial ultrasound scanners, can reduce the intrinsic generated harmonic to fundamental pressure amplitude ratio to below −35 dB, making CMUT probes usable for clinical applications.

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Evaluation of healthy muscle tissue by strain and shear wave elastography – Dependency on depth and ROI position in relation to underlying bone

Purpose: The aim of this study was to evaluate the influence of depth and underlying bone on strain ratios and shear wave speeds for three different muscles in healthy volunteers. For strain ratios the influence from different reference region-of-interest positions was also evaluated. Material and methods: Ten healthy volunteers (five males and five females) had their biceps brachii, gastrocnemius, and quadriceps muscle examined with strain- and shear wave elastography at three different depths and in regions located above bone and beside bone. Strain ratios were averaged from cine-loops of 10 s length, and shear wave speeds were measured 10 times at each target point. The distance from the skin surface to the centre of each region-of-interest was measured. Measurements were evaluated with descriptive statistics and linear regression. Results: Linear regression showed a significant influence on strain ratio measurements from the reference region-of-interest position, i.e. being above the same structures as the target region-of-interest or not (means: 1.65 and 0.78; (P < 0.001)). For shear wave speeds, there was a significant influence from depth and location above or beside bone (P = 0.011 and P = 0.031). Conclusion: Strain ratio values depend significantly on reference and target region-of-interest being above the same tissue, for instance bone. Strain ratios were not influenced by depth in this study. Shear wave speeds decreased with increasing scanning depth and if there was bone below the region-of-interest.

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Experimental 3-D Vector Flow Estimation with Row-Column Addressed Arrays

Experimental 3-D vector flow estimates obtained with a 62+62 2-D row-column (RC) array with integrated apodization are presented. A transverse oscillation (TO) velocity estimator is implemented on a 3.0 MHz RC array, to yield real-time 3-D vector flow in a cross-sectional scan plane at 750 frames per second. The method is validated in a straight-vessel phantom (Ø = 8 mm) connected to a flow pump capable of generating time-varying carotid waveforms. The out-of-plane velocity component perpendicular to the cross section of the vessel and the cross-sectional area is used to estimate volumetric flow rates. The flow rate measured from five cycles is 2.3 mL/stroke ± 0.1 mL/stroke giving a negative 9.7% bias compared to the pump settings. It is concluded that 124 elements are sufficient to estimate 3-D vector flow, if they are positioned in a row-column wise manner.

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Fabrication of Capacitive Micromachined Ultrasonic Transducers Using a Boron Etch-Stop Method

Capacitive Micromachined Ultrasonic Transducers (CMUTs) fabricated using Silicon-On-Insulator (SOI) wafers often have large thickness variation of the flexible plate, which causes variation in both pull-in voltage and resonant frequency across the CMUT array. This work presents a bond and boron etch-stop scheme for fabricating the flexible plate of a CMUT. The proposed fabrication method enables precise control of the plate thickness variation and is a low cost alternative to the SOI-based process. N-type silicon wafers are doped with boron to a surface concentration of > 10^{20} cm^{-3} using solid planar diffusion predeposition at 1125 °C for 30, 60, and 90 min. Process simulations are used to predict the boron doping profiles and validated with secondary ion mass spectrometry measurements. The doped wafers are fusion-bonded to a silicon dioxide surface and thinned down using an 80 °C, 20 wt% potassium hydroxide solution with isopropyl alcohol added to increase the etch selectivity to the highly doped boron layer. The resulting plate thickness uniformity is estimated from scanning electron micrographs to a mean value of 2.00um±2.5%. The resonant frequency in air for a 1-D linear CMUT array is measured to 12MHz±2.5%. Furthermore, hydrophone measurements show that the fabricated devices can be used to emit sound pressure in the ultrasonic frequency domain.

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Contributors: Diederichsen, S. E., Sandborg-Olsen, F., Engholm, M., Lei, A., Jensen, J. A., Thomsen, E. V.
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High Frame Rate Synthetic Aperture 3D Vector Flow Imaging

3-D blood flow quantification with high spatial and temporal resolution would strongly benefit clinical research on cardiovascular pathologies. Ultrasonic velocity techniques are known for their ability to measure blood flow with high precision at high spatial and temporal resolution. However, current volumetric ultrasonic flow methods are limited to one velocity component or restricted to a reduced field of view (FOV), e.g., fixed imaging planes, in exchange for higher temporal resolutions. To solve these problems, a previously proposed accurate 2-D high frame rate vector flow imaging (VFI) technique is extended to estimate the 3-D velocity components inside a volume at high temporal resolutions (< 1 ms). The full 3-D vector velocities are obtained from beamformed volumetric data using synthetic aperture (SA) techniques combined with a 2-D matrix array. The method is validated using Field II simulations of flow along a straight vessel phantom and with complex flow from a 3-D computational fluid dynamics (CFD) model of a carotid bifurcation. Results from the simulations show that the 3-D velocity components are estimated with a mean relative bias of -12.8%, -10% and 1.42% for the Vx, Vy and Vz respectively; each presented a mean relative standard deviation of 11.8%, 12.3% and 1.11%.

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High frame rate synthetic aperture vector flow imaging for transthoracic echocardiography.

This work presents the first in vivo results of 2-D high frame rate vector velocity imaging for transthoracic cardiac imaging. Measurements are made on a healthy volunteer using the SARUS experimental ultrasound scanner connected to an intercostal phased-array probe. Two parasternal long-axis view (PLAX) are obtained, one centred at the aortic valve and another centred at the left ventricle. The acquisition sequence was composed of 3 diverging waves for high frame rate synthetic aperture flow imaging. For verification a phantom measurement is performed on a transverse straight 5 mm diameter vessel at a depth of 100 mm in a tissue-mimicking phantom. A flow pump produced a 2 ml/s constant flow with a peak velocity of 0.2 m/s. The average estimated flow angle in the ROI was 86.2±6.6 with a true flow angle of 90°. A relative velocity bias of ~39% with a standard deviation of 13% was found. In-vivo acquisitions show complex flow patterns in the heart. In the aortic valve view, blood is seen exiting the left ventricle cavity through the aortic valve into the aorta during the systolic phase of the cardiac cycle. In the left ventricle view, blood flow is seen entering the left ventricle cavity through the mitral valve and splitting in two ways when approximating the left ventricle wall. The work presents 2-D velocity estimates on the heart from a non-invasive transthoracic scan. The ability of the method detecting flow regardless of the beam angle could potentially reveal a more complete view of the flow patterns presented on the heart.
Hybrid Segmentation of Vessels and Automated Flow Measures in In-Vivo Ultrasound Imaging

Vector Flow Imaging (VFI) has received an increasing attention in the scientific field of ultrasound, as it enables angle independent visualization of blood flow. VFI can be used in volume flow estimation, but a vessel segmentation is needed to make it fully automatic. A novel vessel segmentation procedure is crucial for wall-to-wall visualization, automation of adjustments, and quantification of flow in state-of-the-art ultrasound scanners. We propose and discuss a method for accurate vessel segmentation that fuses VFI data and B-mode for robustly detecting and delineating vessels. The proposed method implements automated VFI flow measures such as peak systolic velocity (PSV) and volume flow. An evaluation of the performance of the segmentation algorithm relative to expert manual segmentation of 60 frames randomly chosen from 6 ultrasound sequences (10 frame randomly chosen from each sequence) is also presented. Dice coefficient denoting the similarity between segmentations is used for the evaluation. The coefficient ranges between 0 and 1, where 1 indicates perfect agreement and 0 indicates no agreement. The Dice coefficient was 0.91 indicating a very agreement between automated and manual expert segmentations. The flowrig results also demonstrated that the PSVs measured from VFI had a mean relative error of 14.5% in comparison with the actual PSVs. The error for the PSVs measured from spectral Doppler was 29.5%, indicating that VFI is 15% more precise than spectral Doppler in PSV measurement.

Intra-operative Vector Flow Imaging Using Ultrasound of the Ascending Aorta among 40 Patients with Normal, Stenotic and Replaced Aortic Valves

Stenosis of the aortic valve gives rise to more complex blood flows with increased velocities. The angle-independent vector flow ultrasound technique transverse oscillation was employed intra-operatively on the ascending aorta of (I) 20 patients with a healthy aortic valve and 20 patients with aortic stenosis before (IIa) and after (IIb) valve replacement. The results indicate that aortic stenosis increased flow complexity (p < 0.0001), induced systolic backflow (p < 0.003) and reduced systolic jet width (p < 0.0001). After valve replacement, the systolic backflow and jet width were normalized (p, 0.52 and p,....
but flow complexity was not \( p < 0.0001 \). Flow complexity \( p < 0.0001 \), systolic jet width \( p < 0.0001 \) and systolic backflow \( p < 0.001 \) were associated with peak systolic velocity. The study found that aortic stenosis changes blood flow in the ascending aorta and valve replacement corrects some of these changes. Transverse oscillation may be useful for assessment of aortic stenosis and optimization of valve surgery. (E-mail: lindskov@gmail.com) 2016 World Federation for Ultrasound in Medicine & Biology

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**In Vivo High Frame Rate Vector Flow Imaging Using Plane Waves and Directional Beamforming**

Directional beamforming (DB) estimates blood flow velocities accurately when the flow angle is known. However, for automatically finding the flow angle a computationally expensive approach is used. This work presents a method for estimating the flow angle using a combination of inexpensive transverse oscillation (TO) estimators and only 3 directional beamformed lines. The suggested DB vector flow estimator is employed with steered plane wave transmissions for high frame rate imaging. Two distinct plane wave sequences are used: a short sequence (3 angles) for fast flow and an interleaved long sequence (21 angles) for both slow flow and B-mode. Parabolic flow with a peak velocity of 0.5 m/s is measured at beam-to-flow angles of 60° and 90°. The DB method estimates the angle with a bias and standard deviation (STD) less than 2° and the STD of the velocity magnitude is 2.5%. This is 7-8.5% when using TO. The long sequence has a higher sensitivity, and when used for estimation of slow flow with a peak velocity of 0.04 m/s, the STD is 2.5% and bias is 0.1%. This is a factor of 4 better than if the short sequence is used. The carotid bifurcation was scanned on a healthy volunteer, and the short sequence was used with TO and DB to estimate velocity vectors. The STD of the velocity profile over a cardiac cycle was 6.1% for TO and 4.9% for DB.

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Novel Automatic Detection of Pleura and B-lines (Comet-Tail Artifacts) on In-Vivo Lung Ultrasound Scans.

This paper presents a novel automatic method for detection of B-lines (comet-tail artifacts) in lung ultrasound scans. B-lines are the most commonly used artifacts for analyzing the pulmonary edema. They appear as laser-like vertical beams, which arise from the pleural line and spread down without fading to the edge of the screen. An increase in their number is associated with presence of edema. All the scans used in this study were acquired using a BK3000 ultrasound scanner (BK Ultrasound, Denmark) driving a 192-element 5.5 MHz wide linear transducer (10L2W, BK Ultrasound). The dynamic received focus technique was employed to generate the sequences. Six subjects, among those three patients after major surgery and three normal subjects, were scanned once and Six ultrasound sequences each containing 50 frames were acquired. The proposed algorithm was applied to all 300 in-vivo lung ultrasound images. The pleural line is first segmented on each image and then the B-line artifacts spreading down from the pleural line are detected and overlayed on the image. The resulting 300 images showed that the mean lateral distance between B-lines detected on images acquired from patients decreased by 20% in compare with that of normal subjects. Therefore, the method can be used as the basis of a method of automatically and qualitatively characterizing the distribution of B-lines.

Optimization of Synthetic Aperture Image Quality

Synthetic Aperture (SA) imaging produces high-quality images and velocity estimates of both slow and fast flow at high frame rates. However, grating lobe artifacts can appear both in transmission and reception. These affect the image quality and the frame rate. Therefore optimization of parameters effecting the image quality of SA is of great importance, and this paper proposes an advanced procedure for optimizing the parameters essential for acquiring an optimal image quality, while generating high resolution SA images. Optimization of the image quality is mainly performed based on measures such as F-number, number of emissions and the aperture size. They are considered to be the most contributing acquisition factors in the quality of the high resolution images in SA. Therefore, the performance of image quality is quantified in terms of full-width at half maximum (FWHM) and the cystic resolution (CTR). The results of the study showed that SA imaging with only 32 emissions and maximum sweep angle of 22 degrees yields a very good image quality compared with using 256 emissions and the full aperture size. Therefore the number of emissions and the maximum sweep angle in the SA can be optimized to reach a reasonably good performance, and to increase the frame rate by lowering the required number of emissions. All the measurements are performed using the experimental SARUS scanner connected to a λ/2-pitch transducer. A wire phantom and a tissue mimicking phantom containing anechoic cysts are scanned using the optimized parameters for the transducer. Measurements coincide with simulations.
Optimized Plane Wave Imaging for Fast and High-Quality Ultrasound Imaging

This paper presents a method for optimizing parameters affecting the image quality in plane wave imaging. More specifically, the number of emissions and steering angles is optimized to attain the best images with the highest frame rate possible. The method is applied to a specific problem, where image quality for a λ-pitch transducer is compared with a λ/2-pitch transducer. Grating lobe artifacts for λ-pitch transducers degrade the contrast in plane wave images, and the impact on frame rate is studied. Field II simulations of plane wave images are made for all combinations of the parameters, and the optimal setup is selected based on Pareto optimality. The optimal setup for a simulated 4.1-MHz λ-pitch transducer uses 61 emissions and a maximum steering angle of 20° for depths from 0 to 60 mm. The achieved lateral full-width at half-maximum (FWHM) is 1.5λ and the contrast is −29 dB for a scatterer at 9 mm (24λ). Using a λ/2-pitch transducer and only 21 emissions within the same angle range, the image quality is improved in terms of contrast, which is −37 dB. For imaging in regions deeper than 25 mm (66λ), only 21 emissions are optimal for both the transducers, resulting in a −36 dB contrast at 34 mm (90λ). Measurements are performed using the experimental SARUS scanner connected to a λ-pitch and λ/2-pitch transducer. A wire phantom and a tissue mimicking phantom containing anechoic cysts are scanned and show the performance using the optimized sequences for the transducers. FWHM is 1.6λ and contrast is −25 dB for a wire at 9 mm using the λ-pitch transducer. For the λ/2-pitch transducer, contrast is −29 dB. In vivo scans of the carotid artery of a healthy volunteer show improved contrast and present fewer artifacts, when using the λ/2-pitch transducer compared with the λ-pitch. It is demonstrated with a frame rate, which is three times higher for the λ/2-pitch transducer.
Plane-Wave Imaging Challenge in Medical Ultrasound

Plane-Wave imaging enables very high frame rates, up to several thousand frames per second. Unfortunately the lack of transmit focusing leads to reduced image quality, both in terms of resolution and contrast. Recently, numerous beamforming techniques have been proposed to compensate for this effect, but comparing the different methods is difficult due to the lack of appropriate tools. PICMUS, the Plane-Wave Imaging Challenge in Medical Ultrasound aims to provide these tools. This paper describes the PICMUS challenge, its motivation, implementation, and metrics.

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Preliminary investigation of an ultrasound method for estimating pressure changes in deep-positioned vessels.

This paper presents a method for measuring pressure changes in deep-tissue vessels using vector velocity ultrasound data. The large penetration depth is ensured by acquiring data using a low frequency phased array transducer. Vascular pressure changes are then calculated from 2-D angle-independent vector velocity fields using a model based on the Navier-Stokes equations. Experimental scans are performed on a fabricated flow phantom having a constriction of 36% at a depth of 100 mm. Scans are carried out using a phased array transducer connected to the experimental scanner, SARUS. 2-D fields of angle-independent vector velocities are acquired using directional synthetic aperture vector flow imaging. The obtained results are evaluated by comparison to a 3-D numerical simulation model with equivalent geometry as the designed phantom. The study showed pressure drops across the constricted phantom varying from -40 Pa to 15 Pa with a standard deviation of 32%, and a bias of 25% found relative to the peak simulated pressure drop. This preliminary study shows that pressure can be estimated non-invasively to a depth that enables cardiac scans, and thereby, the possibility of detecting the pressure drops across the mitral valve.

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Quantitative Measurements using Ultrasound Vector Flow Imaging

Duplex Vector Flow Imaging (VFI) imaging is introduced as a replacement for spectral Doppler, as it automatically can yield fully quantitative flow estimates without angle correction. Continuous VFI data over 9 s for 10 pulse cycles were acquired by a 3 MHz convex probe connected to the SARUS scanner for pulsating flow mimicking the femoral artery from a CompuFlow 1000 pump (Shelley Medical). Data were used in four estimators based on directional transverse oscillation for velocity, flow angle, volume flow, and turbulence estimation and their respective precisions. An adaptive lag scheme gave the ability to estimate a large velocity range, or alternatively measure at two sites to find e.g. stenosis degree in a vessel. The mean angle at the vessel center was estimated to 90.9° ±8.2° indicating a laminar flow from a turbulence index being close to zero (0.1 ±0.1). Volume flow was 1.29 ±0.26 mL/stroke (true: 1.15 mL/stroke, bias: 12.2%). Measurements down to 160 mm were obtained with a relative standard deviation and bias of less than 10% for the lateral component for stationary, parabolic flow. The method can, thus, find quantitative velocities, angles, and volume flows at sites currently inaccessible to spectral systems, and at much larger velocities and ranges than conventional systems without any angle correction making measurements less time-consuming and more correct.

Robust microbubble tracking for super resolution imaging in ultrasound

Currently ultrasound resolution is limited by diffraction to approximately half the wavelength of the sound wave employed. In recent years, super resolution imaging techniques have overcome the diffraction limit through the localization and tracking of a sparse set of microbubbles through the vasculature. However, this has only been performed on fixated tissue, limiting its clinical application. This paper proposes a technique for making super resolution images on non-fixated tissue by first compensating for tissue movement and then tracking the individual microbubbles. The experiment is performed on the kidney of an anesthetized Sprague-Dawley rat by infusing SonoVue at 0.1× original concentration. The algorithm demonstrated in vivo that the motion compensation was capable of removing the movement caused by the mechanical ventilator. The results shows that microbubbles were localized with a higher precision, reducing the standard deviation of the super localizations from 22μm to 8 μm. The paper proves that the restriction of completely fixated tissue can be eliminated, when making super resolution imaging with microbubbles.
An automatic approach for simulating the emitted pressure, intensity, and MI of advanced ultrasound imaging sequences is presented. It is based on a linear simulation of pressure fields using Field II, and it is hypothesized that linear simulation can attain the needed accuracy for predicting Mechanical Index (MI) and Ispta.3 as required by FDA. The method is performed on four different imaging schemes and compared to measurements conducted using the SARUS experimental scanner. The sequences include focused emissions with an F-number of 2 with 64 elements that generate highly non-linear fields. The simulation time is between 0.67 ms to 2.8 ms per emission and imaging point, making it possible to simulate even complex emission sequences in less than 1 s for a single spatial position. The linear simulations yield a relative accuracy on MI between -12.1% to 52.3% and for Ispta.3 between -38.6% to 62.6%, when using the impulse response of the probe estimated from an independent measurement. The accuracy is increased to between -22% to 24.5% for MI and between -33.2% to 27.0% for Ispta.3, when using the pressure response measured at a single point to scale the simulation. The spatial distribution of MI and Ita.3 closely matches that for the measurement, and simulations can therefore be used to select the region for measuring the intensities, resulting in a significant reduction in measurement time. It can validate emission sequences by showing symmetry of emitted pressure fields, focal position, and intensity distribution.

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Safety Assessment of Advanced Imaging Sequences I: Measurements

A method for rapid measurement of intensities (Ispta), mechanical index (MI), and probe surface temperature for any ultrasound scanning sequence is presented. It uses the scanner’s sampling capability to give an accurate measurement of the whole imaging sequence for all emissions to yield the true distributions. The method is several orders of magnitude faster than approaches using an oscilloscope, and it also facilitates validating the emitted pressure field and the scanner’s emission sequence software. It has been implemented using the experimental SARUS scanner and the Onda AIMS III intensity measurement system (Onda Corporation, Sunnyvale, CA, USA). Four different sequences have been measured: a fixed focus emission, a duplex sequence containing B-mode and flow emissions, a vector flow sequence with B-mode and flow emissions in 17 directions, and finally a synthetic aperture (SA) duplex flow sequence. A BK8820e (BK Medical, Herlev, Denmark) convex array probe is used for the first three sequences and a BK8670 linear array probe for the SA sequence. The method is shown to give the same intensity values within 0.24% of the AIMS III Soniq 5.0 (Onda, Corporation, Sunnyvale, CA, USA) commercial intensity measurement program. The approach can measure and store data for a full imaging sequence in 3.8 to 8.2 s per spatial position. Based on Ispta, MI, and probe surface temperature, the method gives the ability to determine whether a sequence is within US FDA limits, or alternatively indicate how to scale it to be within limits.

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Surveillance for hemodialysis access stenosis: usefulness of ultrasound vector volume flow

Purpose:
To investigate if ultrasound vector-flow imaging (VFI) is equal to the reference method ultrasound dilution technique (UDT) in estimating volume flow and changes over time in arteriovenous fistulas (AVFs) for hemodialysis.

Materials and methods:
From January 2014 to January 2015, patients with end-stage renal disease and matured functional AVFs were consecutively solicited to participate in this prospective study. All patients were included after written informed consent and approval by the National Committee on Biomedical Research Ethics and the local Ethics Committee (journal no. H-4-2014-FSP). VFI and UDT measurements were performed monthly over a six-month period. Nineteen patients were included in the study. VFI measurements were performed before dialysis, and UDT measurements after. Statistical analyses were performed with Bland-Altman plot, Student’s t-test, four-quadrant plot, and regression analysis. Repeated measurements and precision analysis were used for reproducibility determination.

Results:
Precision measurements for UDT and VFI were 32% and 20%, respectively (p = 0.33). Average volume flow measured with UDT and VFI were 1161 mL/min (±778 mL/min) and 1213 mL/min (±980 mL/min), respectively (p = 0.3). The mean difference was -51 mL/min (CI: -150 mL/min to 46 mL/min) with limits of agreement from -35% to 54%, with a strong
A large change in volume flow between dialysis sessions detected by UDT was confirmed by VFI (p = 0.0001), but the concordance rate was poor (0.72).

Conclusions:
VFI is an acceptable method for volume flow estimation and volume flow changes over time in AVFs.

Synthetic aperture ultrasound Fourier beamformation using virtual sources
An efficient Fourier beamformation algorithm is presented for multistatic synthetic aperture ultrasound imaging using virtual sources (FBV). The concept is based on the frequency domain wavenumber algorithm from radar and sonar and is extended to a multi-element transmit/receive configuration using virtual sources. Window functions are used to extract the azimuth processing bandwidths and weight the data to reduce sidelobes in the final image. Field II simulated data and SARUS measured data are used to evaluate the results in terms of point spread function, resolution, contrast, SNR, and processing time. Lateral resolutions of 0.53 mm and 0.66 mm are obtained for FBV and DAS on point target simulated data. Corresponding axial resolutions are 0.21 mm for FBV and 0.20 mm for DAS. The results are also consistent over different depths evaluated using a simulated phantom containing several point targets at different depths. FBV shows a better lateral resolution at all depths, and the axial and cystic resolutions of -6 dB, -12 dB and -20 dB are almost the same for FBV and DAS. To evaluate the cyst phantom metrics, three different criteria of Power Ratio (PR), Contrast Ratio (CR), and contrast to noise ratio (CNR) have been used. Results show that the algorithms have a different performance in the cyst center and near the boundary. FBV has a better performance near the boundary, however, DAS is better in the more central area of the cyst. Measured data from phantoms are also used for evaluation. The results confirm the applicability of FBV in ultrasound and 20 times less processing time in comparison with DAS is attained. Evaluating the results over a wide variety of parameters and having almost the same results for simulated and measured data demonstrates the ability of FBV in preserving the quality of image as DAS, while providing a more efficient algorithm with 20 times less computations.
System-Level Design of an Integrated Receiver Front End for a Wireless Ultrasound Probe

In this paper, a system-level design is presented for an integrated receive circuit for a wireless ultrasound probe, which includes analog front ends and beamformation modules. This paper focuses on the investigation of the effects of architectural design choices on the image quality. The point spread function is simulated in Field II from 10 to 160 mm using a convex array transducer. A noise analysis is performed, and the minimum signal-to-noise ratio (SNR) requirements are derived for the low-noise amplifiers (LNAs) and A/D converters (ADCs) to fulfill the design specifications of a dynamic range of 60 dB and a penetration depth of 160 mm in the B-mode image. Six front-end implementations are compared using Nyquist-rate and modulator ADCs. The image quality is evaluated as a function of the depth in terms of lateral full-width at halfmaximum (FWHM) and −12-dB cystic resolution (CR). The designs that minimally satisfy the specifications are based on an 8-b 30-MSPS Nyquist converter and a single-bit third-order 240-MSPS modulator, with an SNR for the LNA in both cases equal to 64 dB. The mean lateral FWHM and CR are 2.4% and 7.1% lower for the architecture compared with the Nyquist-rate one. However, the results generally show minimal differences between equivalent architectures. Advantages and drawbacks are finally discussed for the two families of converters.

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Ultrasound Vector Flow Imaging: Part II: Parallel Systems

The paper gives a review of the current state-of-the-art in ultrasound parallel acquisition systems for flow imaging using spherical and plane waves emissions. The imaging methods are explained along with the advantages of using these very fast and sensitive velocity estimators. These experimental systems are capable of acquiring thousands of images per second for fast moving flow as well as yielding estimates of low velocity flow. These emerging techniques allow vector flow systems to assess highly complex flow with transitory vortices and moving tissue, and they can also be used in functional ultrasound imaging for studying brain function in animals. The paper explains the underlying acquisition and estimation methods for fast 2-D and 3-D velocity imaging and gives a number of examples. Future challenges and the potentials of parallel acquisition systems for flow imaging are also discussed.

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Ultrasound Vector Flow Imaging: Part I: Sequential Systems

The paper gives a review of the most important methods for blood velocity vector flow imaging (VFI) for conventional, sequential data acquisition. This includes multibeam methods, speckle tracking, transverse oscillation, color flow mapping derived vector flow imaging, directional beamforming, and variants of these. The review covers both 2-D and 3-D velocity estimation and gives a historical perspective on the development along with a summary of various vector flow visualization algorithms. The current state-of-the-art is explained along with an overview of clinical studies conducted and methods for presenting and using VFI. A number of examples of VFI images are presented, and the current limitations and potential solutions are discussed.

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Vector Velocity Estimation for Portable Ultrasound using Directional Transverse Oscillation and Synthetic Aperture Sequential Beamforming

In this paper, a vector flow imaging method is presented, which combines the directional transverse oscillation approach with synthetic aperture sequential beamforming to achieve an efficient estimation of the velocities. A double oscillating field is synthesized using two sets of focused emissions separated by a distance in the lateral direction. A low resolution line (LRL) is created for each emission in the first stage beamformer, and a second beamformer provides the high resolution data used for the velocity estimation. The method makes it possible to have continuously available data in the whole image. Therefore, high and low velocities can

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be estimated with a high frame rate and a low standard deviation. The first stage is a fixed-focus beamformer that can be integrated in the transducer handle, enabling the wireless transmission of the LRLs. The approach does not require any angle compensation or prior knowledge on the beam-to-flow angle. The feasibility of the method is demonstrated through simulations and flow rig measurements of a parabolic flow in a vessel at 90-degree beam-to-flow angle. The mean bias obtained from 50 independent measurements is equal to -0.67% for the lateral profile and -0.43% for the axial profile. The relative standard deviation is 3.19% and 0.47% for the lateral and axial profiles. It is, therefore, demonstrated that vector velocity estimation can be efficiently integrated in a portable ultrasound scanner with state-of-the-art performance.

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**Vector velocity volume flow estimation: Sources of error and corrections applied for arteriovenous fistulas**
A method for vector velocity volume flow estimation is presented, along with an investigation of its sources of error and correction of actual volume flow measurements. Volume flow errors are quantified theoretically by numerical modeling, through flow phantom measurements, and studied in vivo. This paper investigates errors from estimating volumetric flow using a commercial ultrasound scanner and the common assumptions made in the literature. The theoretical model shows, e.g. that volume flow is underestimated by 15%, when the scan plane is off-axis with the vessel center by 28% of the vessel radius. The error sources were also studied in vivo under realistic clinical conditions, and the theoretical results were applied for correcting the volume flow errors. Twenty dialysis patients with arteriovenous fistulas were scanned to obtain vector flow maps of fistulas. When fitting an ellipsis to cross-sectional scans of the fistulas, the major axis was on average 10.2 mm, which is 8.6% larger than the minor axis. The ultrasound beam was on average 1.5 mm from the vessel center, corresponding to 28% of the semi-major axis in an average fistula. Estimating volume flow with an elliptical, rather than circular, vessel area and correcting the ultrasound beam for being off-axis, gave a significant (p = 0.008) reduction in error from 31.2% to 24.3%. The error is relative to the Ultrasound Dilution Technique, which is considered the gold standard for volume flow estimation for dialysis patients. The study shows the importance of correcting for volume flow errors, which are often made in clinical practice.

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Volumetric Synthetic Aperture Imaging with a Piezoelectric 2-D Row-Column Probe.

The synthetic aperture (SA) technique can be used for achieving real-time volumetric ultrasound imaging using 2-D row-column addressed transducers. This paper investigates SA volumetric imaging performance of an in-house prototyped 3 MHz λ/2-pitch 62+62 element piezoelectric 2-D row-column addressed transducer array. Utilizing single element transmit events, a volume rate of 90 Hz down to 14 cm deep is achieved. Data are obtained using the experimental ultrasound scanner SARUS with a 70 MHz sampling frequency and beamformed using a delay-and-sum (DAS) approach. A signal-to-noise ratio of up to 32 dB is measured on the beamformed images of a tissue mimicking phantom with attenuation of 0.5 dB cm⁻¹ MHz⁻¹, from the surface of the probe to the penetration depth of 300λ. Measured lateral resolution as Full-Width-at-Half-Maximum (FWHM) is between 4λ and 10λ for 18 % to 65 % of the penetration depth from the surface of the probe. The averaged contrast is 13 dB for the same range. The imaging performance assessment results may represent a reference guide for possible applications of such an array in different medical fields.

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3-D Imaging Using Row-Column-Addressed Arrays With Integrated Apodization: Part II: Transducer Fabrication and Experimental Results

This paper demonstrates the fabrication, characterization, and experimental imaging results of a 62×62 element λ/2-pitch row-column-addressed capacitive micromachined ultrasonic transducer (CMUT) array with integrated apodization. A new fabrication process was used to manufacture a 26.3 mm by 26.3 mm array using five lithography steps. The array includes an integrated apodization, presented in detail in Part I of this paper, which is designed to reduce the amplitude of the ghost echoes that are otherwise prominent for row-column-addressed arrays. Custom front-end electronics were produced with the capability of transmitting and receiving on all elements, and the option of disabling the integrated apodization. The center frequency and -6-dB fractional bandwidth of the array elements were 2.77 ± 0.26 MHz and 102 ± 10%, respectively. The surface transmit pressure at 2.5 MHz was 590 ± 73 kPa, and the sensitivity was 0.299 ± 0.090 V/Pa. The nearest neighbor crosstalk level was -23.9 ± 3.7 dB, while the transmit-to-receive-elements crosstalk level was -40.2 ± 3.5 dB. Imaging of a 0.3-mm-diameter steel wire using synthetic transmit focusing with 62 single-element emissions demonstrated axial and lateral FWHMs of 0.71 mm and 1.79 mm (f-number: 1.4), respectively, compared with simulated axial and lateral FWHMs of 0.69 mm and 1.76 mm. The dominant ghost echo was reduced by 15.8 dB in measurements using the integrated apodization compared with the disabled configuration. The effect was reproduced in simulations, showing a ghost echo reduction of 18.9 dB.

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This paper investigates the effect of transducer-integrated apodization in row–column-addressed arrays and presents a beamforming approach specific for such arrays. Row–column addressing 2-D arrays greatly reduces the number of active channels needed to acquire a 3-D volume. A disadvantage of row–column-addressed arrays is an apparent ghost effect in the point spread function caused by edge waves. This paper investigates the origin of the edge waves and the effect of introducing an integrated apodization to reduce the ghost echoes. The performance of a λ/2-pitch 5-MHz 128 × 128 row–column-addressed array with different apodizations is simulated. A Hann apodization is shown to decrease imaging performance away from the center axis of the array because of a decrease in main lobe amplitude. Instead, a static roll-off apodization region located at the ends of the line elements is proposed. In simulations, the peak ghost echo intensity of a scatterer at (x, y, z) = (8, 3, 30) mm was decreased by 43 dB by integrating roll-off apodization into the array. The main lobe was unaffected by the apodization. Simulations of a 3-mm-diameter anechoic blood vessel at 30 mm depth showed that applying the transducer-integrated apodization increased the apparent diameter of the vessel from 2.0 mm to 2.4 mm, corresponding to an increase from 67% to 80% of the true vessel diameter. The line element beamforming approach is shown to be essential for achieving correct time-of-flight calculations, and hence avoid geometrical distortions. In Part II of this work, experimental results from a capacitive micromachined ultrasonic transducer with integrated roll-off apodization are given to validate the effect of integrating apodization into the line elements.
3-D Vector Velocity Estimation with Row-Column Addressed Arrays
The concept of 2-D row-column (RC) addressed arrays for 3-D imaging have shown to be an interesting alternative to 2-D matrix array, due to the reduced channel count. However, the properties for RC arrays to estimate blood velocities have never been reported, which is of great importance for a clinical implementation of this type of array. The aim of this study is, thus, to develop a technique for estimating 3-D vector flow with a RC array using the transverse oscillation (TO) method. The properties are explored both in a simulation study and with a prototype probe for experimental use. In both setups, a 124 channel 2-D RC array with integrated apodization, pitch = 270 µm and a center frequency of 3.0 MHz was used. The performance of the estimator was tested on a simulated vessel (Ø = 12 mm) with a parabolic flow profile and a peak velocity of 1 m/s. Measurements were made in a flowrig (Ø = 12 mm) containing a laminar parabolic flow and a peak velocity of 0.54 m/s. Data was sampled and stored on the experimental ultrasound scanner SARUS. Simulations yields relative mean biases at (-1.1%, -1.5%, -1.0%) with mean standard deviations of σ̃ were (8.5%, 9.0%, 1.4%) % for (vx, vy, vz) from a 3-D velocity vector in a 15° rotated vessel with a 75° beam-to-flow angle. In the experimental setup with a 90° beam-to-flow angle, the relative mean biases were (-2.6%, -1.3%, 1.4%) with a relative standard deviation of (5.0%, 5.2%, 1.0%) for the respective transverse, lateral and axial velocity component.

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Acoustical cross-talk in row–column addressed 2-D transducer arrays for ultrasound imaging
The acoustical cross-talk in row–column addressed 2-D transducer arrays for volumetric ultrasound imaging is investigated. Experimental results from a 2.7 MHz, λ/2-pitch capacitive micromachined ultrasonic transducer (CMUT) array with 62 rows and 62 columns are presented and analyzed in the frequency-wavenumber domain. The sources of cross-talk are identified and predicted theoretically. The nearest neighbor cross-talk is 23.9±3.7 dB when the array is used as a 1-D array with the rows functioning as both transmitters and receivers. In the row–column configuration, with the columns transmitting and the rows receiving, the cross-talk is reduced to 40.2±3.5 dB.

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Advanced automated gain adjustments for in-vivo ultrasound imaging

Automatic gain adjustments are necessary on the state-of-the-art ultrasound scanners to obtain optimal scan quality, while reducing the unnecessary user interactions with the scanner. However, when large anechoic regions exist in the scan plane, the sudden and drastic variation of attenuations in the scanned media complicates the gain compensation. This paper presents an advanced and automated gain adjustment method that precisely compensate for the gains on scans and dynamically adapts to the drastic attenuation variations between different media. The proposed algorithm makes use of several ultrasonic physical estimates such as scattering strength, focus gain, acoustic attenuation, and noise level to gain a more quantitative understanding of the scanned media and to provide an intuitive adjustment of gains on the scan. The proposed algorithm was applied to a set of 45 in-vivo movie sequences each containing 50 frames. The scans are acquired using a recently commercialized BK3000 ultrasound scanner (BK Ultrasound, Denmark). Matching pairs of in-vivo sequences, unprocessed and processed with the proposed method were visualized side by side and evaluated by 4 radiologists for image quality. Wilcoxon signed-rank test was then applied to the ratings provided by radiologists. The average VAS score was highly positive 12.16 (p-value: 2.09 x 10-23) favoring the gain-adjusted scans with the proposed algorithm.

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A hand-held row-column addressed CMUT probe with integrated electronics for volumetric imaging

A 3 MHz, λ / 2-pitch 62+62 channel row-column addressed 2-D CMUT array designed to be mounted in a probe handle and connected to a commercial BK Medical scanner for real-time volumetric imaging is presented. It is mounted and wire-bonded on a flexible PCB, which is connected to two rigid PCBs with pre-amplifiers for driving the cable to the scanner. The array and PCBs are encapsulated in a 3-D printed handle, and a grounded shielding layer and silicone coating is applied to the front-side of the array for physical and electrical isolation. The handle is assembled together with a 192-channel coaxial cable that connects it to the ultrasound scanner, which supplies the probe with a 190 V DC bias voltage and up to ±75V AC excitation voltage. The probe was successfully connected to a BK3000 scanner and used as two decoupled 1-D phased arrays. Volumetric imaging was demonstrated using the experimental SARUS scanner with 132 volumes/sec.

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Assessment of flatness of assumed planar surfaces for ultrasound investigation of elastic surfaces

Automated Hierarchical Time Gain Compensation for In Vivo Ultrasound Imaging

Time gain compensation (TGC) is essential to ensure the optimal image quality of the clinical ultrasound scans. When large fluid collections are present within the scan plane, the attenuation distribution is changed drastically and TGC compensation becomes challenging. This paper presents an automated hierarchical TGC (AHTGC) algorithm that accurately adapts to the large attenuation variation between different types of tissues and structures. The algorithm relies on estimates of tissue attenuation, scattering strength, and noise level to gain a more quantitative understanding of the underlying tissue and the ultrasound signal strength. The proposed algorithm was applied to a set of 44 in vivo abdominal movie sequences each containing 15 frames. Matching pairs of in vivo sequences, unprocessed and processed with the proposed AHTGC were visualized side by side and evaluated by two radiologists in terms of image quality. Wilcoxon signed-rank test was used to evaluate whether radiologists preferred the processed sequences or the unprocessed data. The results indicate that the average visual analogue scale (VAS) is positive (p-value: 2.34 \times 10^{-13}) and estimated to be 1.01 (95% CI: 0.85; 1.16) favoring the processed data with the proposed AHTGC algorithm.
Clinical evaluation of synthetic aperture harmonic imaging for scanning focal malignant liver lesions

The purpose of the study was to perform a clinical comparison of synthetic aperture sequential beamforming tissue harmonic imaging (SASB-THI) sequences with a conventional imaging technique, dynamic receive focusing with THI (DRF-THI). Both techniques used pulse inversion and were recorded interleaved using a commercial ultrasound system (UltraView 800, BK Medical, Herlev, Denmark). Thirty-one patients with malignant focal liver lesions (confirmed by biopsy or computed tomography/magnetic resonance) were scanned. Detection of malignant focal liver lesions and preference of image quality were evaluated blinded off-line by eight radiologists. In total, 2,032 evaluations of 127 image sequences were completed. The sensitivity (77% SASB-THI, 76% DRF-THI, p = 0.54) and specificity (71% SASB-THI, 72% DRF-THI, p = 0.67) of detection of liver lesions and the evaluation of image quality (p = 0.63) did not differ between SASB-THI and DRF-THI. This study indicates the ability of SASB-THI in a true clinical setting.
Convex Array Vector Velocity Imaging Using Transverse Oscillation and Its Optimization

A method for obtaining vector flow images using the transverse oscillation (TO) approach on a convex array is presented. The paper presents optimization schemes for TO fields and evaluates their performance using simulations and measurements with an experimental scanner. A 3-MHz 192-element convex array probe (pitch 0.33 mm) is used in both simulations and measurements. A parabolic velocity profile is simulated at a beam-to-flow angle of 90°. The optimization routine changes the lateral oscillation period λx as a function of depth to yield the best possible estimates based on the energy ratio between positive and negative spatial frequencies in the ultrasound field. The energy ratio is reduced from −17.1 dB to −22.1 dB. Parabolic profiles are estimated on simulated data using 16 emissions. The optimization gives a reduction in standard deviation from 8.81% to 7.4% for 16 emissions, with a reduction in lateral velocity bias from −15.93% to 0.78% at 90° (transverse flow) at a depth of 40 mm. Measurements have been performed using the experimental ultrasound scanner and a convex array transducer. A bias of −0.93% was obtained at 87° for a parabolic velocity profile along with a standard deviation of 6.37%. The livers of two healthy volunteers were scanned using the experimental setup. The in vivo images demonstrate that the method yields realistic estimates with a consistent angle and mean velocity across three heart cycles.

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Electrostatic and Small-Signal Analysis of CMUTs With Circular and Square Anisotropic Plates

Traditionally, Capacitive Micromachined Ultrasonic Transducers (CMUTs) are modeled using the isotropic plate equation and this leads to deviations between analytical calculations and Finite Element Modeling (FEM). In this paper, the deflection is calculated for both circular and square plates using the full anisotropic plate equation. It is shown that the anisotropic calculations match perfectly with FEM while an isotropic approach causes up to 10% deviations in deflection. For circular plates an exact solution can be found and for square plates using the Galerkin method and utilizing the symmetry of the silicon crystal, a compact and accurate expression for the deflection can be obtained. The deviation from FEM in center deflection is < 0.1%. The theory of multilayer plates is also applied to the CMUT. The deflection of a square plate was measured on fabricated CMUTs using a white light interferometer. Fitting the plate parameter for the anisotropic calculated deflection to the measurement, a deviation of 0.07% is seen. Furthermore, electrostatic analysis is performed using energy considerations and the calculated deflections to include the anisotropy. The stable position, effective spring constant, pull-in distance and pull-in voltage are found for both circular and square anisotropic plates and the pressure dependence is also included by comparing to the corresponding analysis for a parallel plate. Finally, it was also measured how fabricated devices with both circular and square plates behaved under increasing bias voltage and it is observed that the models including anisotropic effects are within the uncertainty interval of the measurements.

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First Clinical Investigations of New Ultrasound Techniques in Three Patient Groups: Patients with Liver Tumors, Arteriovenous Fistulas, and Arteriosclerotic Femoral Arteries

In this PhD project two newer ultrasound techniques are for the first time used for clinical scans of patients with malignant liver tumors (Study I), arteriovenous fistulas for hemodialysis (Study II) and arteriosclerotic femoral arteries (Study III). The same commercial ultrasound scanner was used in all three studies. Study I was a comparative study of B-mode ultrasound images obtained with conventional technique and the experimental technique Synthetic Aperture Sequential Beamforming (SASB). SASB is a data reducing version of the technique synthetic aperture, which has the potential to produce ultrasound images of very high quality with high frame rate. Synthetic aperture is unfortunately very demanding computationally, and is therefore used only in experimental scanners. SASB reduces the data volume by a factor of 64, thereby making it possible to implement the technology on a commercial ultrasound scanner, to perform wireless data transfer and in the future to develop e.g. a wireless ultrasonic transducer. Nineteen patients with either primary liver cancer or liver metastases from colon cancer were ultrasound scanned the day before planned liver resection. Patients were scanned simultaneously with the conventional technique and SASB, and the image quality was subsequently evaluated from a clinical perspective by five radiologists with ultrasound experience. The evaluations showed a slight (statistically insignificant) advantage to SASB, and the study thereby showed that SASB, in spite of the significant data reduction, is suitable for clinical use. In Study II, 20 patients with arteriovenous fistulas for hemodialysis were ultrasound scanned directly on the most superficial and accessible part of the fistula. The vector ultrasound technique Vector Flow Imaging (VFI) was used. VFI can quantitatively estimate the direction and velocity of the blood flow in a vessel, independently of the angle of insonation. Conventional Doppler technique is dependent on an angle of insonation < 60-70° when a quantitative estimation of flow is needed. It is therefore challenging to use on the very superficial arteriovenous fistulas. The fistulas were scanned perpendicular to the vessel, the cross-sectional area was calculated and blood flow velocity measured. The average flow velocity was calculated and multiplied by the cross sectional area, thereby calculating volume flow in the fistula. This was compared with the gold standard for volume flow measurements (ultrasound dilution technique), and was 31 – 35 % lower than the gold standard, but showed a 4 significantly improved standard deviation. The study thus demonstrated a new, direct and intuitive way to measure blood flow in arteriovenous fistulas. Study III was also a flow study using VFI. Eleven patients with arteriosclerotic disease in the superficial femoral artery had an ultrasound scan of the vessel performed just before a planned angiography of the arteries. If turbulent/disturbed flow was identified with VFI, and suspicion of a flow disturbing arteriosclerotic lesion was raised, recordings of the flow were made. The recordings were subsequently analyzed, and for each recording blood flow velocity at the lesion was compared with the flow velocity in a healthy adjacent arterial segment. If the velocity at the lesion was higher than in the healthy segment, it was considered a stenosis. By comparison with the subsequent angiography a strong correlation was found between the calculated velocity ratios and the measured angiographic stenosis degrees. Thus, it was possible to assess stenosis degree quantitatively from the VFI ultrasound scan. Furthermore, it was calculated that a doubling of the flow velocity indicates a stenosis degree of 50 %, and thus a clinically significant stenosis requiring treatment. The study is the first of its kind where a vector ultrasound technique is used to calculate velocity ratios related to arteriosclerotic stenoses, and the obtained results are consistent with previous studies performed with conventional Doppler technique. Use of VFI is more intuitive, and may be used to perform faster and more accurate screening of these patients before they are referred to angiography. The three studies demonstrate the first application of the new ultrasound techniques in selected groups of patients. For all three studies the results are promising, and hopefully the techniques will find their way into everyday clinical practice for the benefit of both patients and healthcare practitioners.
Fourier beamformation of multistatic synthetic aperture ultrasound imaging

A new Fourier beamformation (FB) algorithm is presented for multistatic synthetic aperture ultrasound imaging. It can reduce the number of computations by a factor of 20 compared to conventional Delay-and-Sum (DAS) beamformers. The concept is based on the wavenumber algorithm from radar and sonar in the frequency domain, which is extended to a multistatic configuration. Window functions are used to reduce the sidelobe levels. Field II simulated data have been used to evaluate the results in terms of point spread function, resolution, contrast, and processing time. Lateral resolutions of 0.75 mm and 0.82 mm are obtained for FB and DAS on simulated point target data. Corresponding axial resolutions are 0.33 mm for FB and 0.35 mm for DAS. The cystic resolution of point targets at different depths for −20 dB and −6 dB demonstrates a better resolution for FB at all depths. A cyst phantom was also used to calculate the contrast ratio, which is 94.04% and 94.72% for DAS and FB, respectively. The corresponding processing times are 118 sec and 2186 sec for FB and DAS. Results show that FB can reduce the processing time by the factor of 20.4 while retaining the image quality.

High Frame Rate Vector Velocity Estimation using Plane Waves and Transverse Oscillation

This paper presents a method for estimating 2-D vector velocities using plane waves and transverse oscillation. The approach uses emission of a low number of steered plane waves, which result in a high frame rate and continuous acquisition of data for the whole image. A transverse oscillating field is obtained by filtering the beamformed RF images in the Fourier domain using a Gaussian filter centered at a desired oscillation frequency. Performance of the method is quantified through measurements with the experimental scanner SARUS and the BK 2L8 linear array transducer. Constant parabolic flow in a flow rig phantom is scanned at beam-to-flow angles of 90, 75, and 60°. The relative bias is between -1.4 % and -5.8 % and the relative std. between 5 % and 8.2 % for the lateral velocity component at the measured beam-to-flow angles. The estimated flow angle is 73.4° ± 3.6° for the measurement at 75°. Measurement of pulsatile flow through a constricted vessel demonstrate the application of the method in a realistic flow environment with...
Large spatial and temporal flow gradients.

**High Resolution Depth-Resolved Imaging From Multi-Focal Images for Medical Ultrasound**

An ultrasound imaging technique providing subdiffraction limit axial resolution for point sources is proposed. It is based on simultaneously acquired multi-focal images of the same object, and on the image metric of sharpness. The sharpness is extracted by image data and presents higher values for in-focus images. The technique is derived from biological microscopy and is validated here with simulated ultrasound data. A linear array probe is used to scan a point scatterer phantom that moves in depth with a controlled step. From the beamformed responses of each scatterer position the image sharpness is assessed. Values from all positions plotted together form a curve that peaks at the receive focus, which is set during the beamforming. Selection of three different receive foci for each acquired dataset will result in the generation of three overlapping sharpness curves. A set of three calibration curves combined with the use of a maximum-likelihood algorithm is then able to estimate, with high precision, the depth location of any emitter from each single image. Estimated values are compared with the ground truth demonstrating that an accuracy of 28.6 µm (0.13λ) is achieved for a 4 mm depth range.

**Image Quality Degradation from Transmit Delay Profile Quantization**

The investigated hypothesis is that quantization of the transmit delay profiles degrades the image quality in plane wave ultrasound imaging. Simulated point spread functions show that transmit delay profile quantization gives rise to artefacts behind the point target. The axial and lateral 6 dB resolution is unaffected, but contrast is reduced. This is quantified by a 20 dB cystic resolution of 1.23 mm compared to 0.53 mm for the ideal (non-quantized) case at 10 mm depth. It is also shown that providing individually phase-shifted excitation waveforms to each element restores the image quality, as seen by the 20 dB cystic resolution being restored to 0.53 mm. The impact on high-quality imaging is discussed.
Implementation of real-time duplex synthetic aperture ultrasonography

This paper presents a real-time duplex synthetic aperture imaging system, implemented on a commercially available tablet. This includes real-time wireless reception of ultrasound signals and GPU processing for B-mode and Color Flow Imaging (CFM). The objective of the work is to investigate the implementation complexity and processing demands. The image processing is performed using the principle of Synthetic Aperture Sequential Beamforming (SASB) and the flow estimator is implemented using the cross-correlation estimator. Results are evaluated using a HTC Nexus 9 tablet and a BK Medical BK3000 ultrasound scanner emulating a wireless probe. The duplex imaging setup consists of interleaved B-mode and CFM frames. The required data throughput for real-time imaging is 36.1 MB/s. The measured data throughput peaked at 39.562 MB/s, covering the requirement for real-time data transfer and overhead in the TCP/IP protocol. Benchmarking of real-time imaging showed a total processing time of 25.7 ms (39 frames/s) which is less than the acquisition time (29.4 ms). In conclusion, the proposed implementation demonstrates that both B-mode and CFM can be executed in-time for real-time ultrasound imaging and that the required bandwidth between the probe and processing unit is within the current Wi-Fi standards.

Improved Vector Velocity Estimation using Directional Transverse Oscillation

A method for estimating vector velocities using transverse oscillation (TO) combined with directional beamforming is presented. Directional Transverse Oscillation (DTO) is self-calibrating, which increase the estimation accuracy and finds the lateral oscillation period automatically. A normal focused field is emitted and the received signals are beamformed in the lateral direction transverse to the ultrasound beam. A lateral oscillation is obtained by having a receive apodization waveform with two separate peaks. The IQ data are obtained by making a Hilbert transform of the directional signal, and a modified TO estimator can be used to find both the lateral and axial velocity. The approach is self-calibrating as the lateral oscillation period directly is estimated from the directional signal through a Fourier transform. The approach was implemented on the SARUS scanner using a BK Medical 8820e transducer with a focal point at 105.6 mm (F#=5) for Vector Flow Imaging (VFI). A 6 mm radius tube in a circulating flow rig was scanned and the parabolic volume flow of 112.7 l/h (peak velocity 0.55 m/s) measured by a Danfoss Magnetic flow meter for reference. Velocity estimates for DTO
are found for 32 emissions at a 90 degrees beam-to-flow angle at a vessel depth of 30 mm. The standard deviation (SD) drops from 9.14% for TO to 5.4%, when using DTO. The bias is -5.05% and the angle is found within +/- 3.93 degrees. At 70 mm a relative SD of 7% is obtained, the bias is -1.74%, and the angle is found within +/- 2.6 degrees showing a low bias across depths.

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Increased Frame Rate for Plane Wave Imaging Without Loss of Image Quality
Clinical applications of plane wave imaging necessitate the creation of high-quality images with the highest possible frame rate for improved blood flow tracking and anatomical imaging. However, linear array transducers create grating lobe artefacts, which degrade the image quality especially in the near field for $\lambda$-pitch transducers. Artefacts can only partly be suppressed by increasing the number of emissions, and this paper demonstrates how the frame rate can be increased without loss of image quality by using $\lambda/2$-pitch transducers. The number of emissions and steering angles are optimized in a simulation study to get the best images with as high a frame rate as possible. The optimal setup for a simulated 4.1 MHz $\lambda$-pitch transducer is 73 emissions and a maximum steering of 22°. The achieved FWHM is 1.3$\lambda$ and the cystic resolution is -25 dB for a scatter at 9 mm. Only 37 emissions are necessary within the same angle range when using a $\lambda/2$-pitch transducer, and the cystic resolution is reduced to -56 dB. Measurements are performed with the experimental SARUS scanner connected to a $\lambda$-pitch and $\lambda/2$-pitch transducer. A wire phantom and a tissue mimicking phantom containing anechoic cysts are scanned and show the performance using the optimized sequences for the transducers. Measurements confirm results from simulations, and the $\lambda$-pitch transducer show artefacts at undesirable strengths of -25 dB for a low number of emissions.

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In Vivo 3-D Vector Velocity Estimation with Continuous Data
In this study, a method for estimating 3-D vector velocities at very high frame rate using continuous data acquisition is presented. An emission sequence was designed to acquire real-time continuous data in one plane. The transverse oscillation (TO) method was used to estimate 3-D vector flow in a carotid flow phantom and in vivo in the common carotid artery of a healthy 27-year old female. Based on the out-of-plane velocity component during four periodic cycles,
estimated flow rates in an experimental setup was 2.96 ml/s ± 0.35 ml/s compared to the expected 3.06 ml/s ± 0.09 ml/s. In the in vivo measurements, three heart cycles acquired at 2.1 kHz showed peak out-of-plane velocities of 83 cm/s, 87 cm/s and 90 cm/s in agreement with the 92 cm/s found with spectral Doppler. Mean flow rate was estimated to 257 ml/min. The results demonstrate that accurate real-time 3-D vector velocities can be obtained using the TO method, which can be used to improve operator independece when examining blood flow in vivo, thereby increasing accuracy and consistency.

In Vivo Real Time Volumetric Synthetic Aperture Ultrasound Imaging

Synthetic aperture (SA) imaging can be used to achieve real-time volumetric ultrasound imaging using 2-D array transducers. The sensitivity of SA imaging is improved by maximizing the acoustic output, but one must consider the limitations of an ultrasound system, both technical and biological. This paper investigates the in vivo applicability and sensitivity of volumetric SA imaging. Utilizing the transmit events to generate a set of virtual point sources, a frame rate of 25 Hz for a 90° x 90° field-of-view was achieved. Data were obtained using a 3.5 MHz 32 x 32 elements 2-D phased array transducer connected to the experimental scanner (SARUS). Proper scaling is applied to the excitation signal such that...
intensity levels are in compliance with the U.S. Food and Drug Administration regulations for in vivo ultrasound imaging. The measured Mechanical Index and spatial-peak-time-average intensity for parallel beamforming (PB) are 0.83 and 377.5mW/cm², and for SA are 0.48 and 329.5mW/cm². A human kidney was volumetrically imaged with SA and PB techniques simultaneously. Two radiologists for evaluation of the volumetric SA were consulted by means of a questionnaire on the level of details perceivable in the beamformed images. The comparison was against PB based on the in vivo data. The feedback from the domain experts indicates that volumetric SA images internal body structures with a better contrast resolution compared to PB at all positions in the entire imaged volume. Furthermore, the autocovariance of a homogeneous area in the in vivo SA data, had 23.5% smaller width at the half of its maximum value compared to PB.

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Non-invasive Estimation of Pressure Changes along a Streamline using Vector Velocity Ultrasound
A non-invasive method for estimating pressure changes along a streamline using ultrasound is presented. The suggested method estimates pressure gradients from 2-D vector velocity fields. Changes in pressure are derived using a model based on the Navier-Stokes equations. Scans of a carotid bifurcation phantom with a 70% constriction are performed using a linear array transducer connected to the experimental scanner, SARUS. 2-D fields of angle-independent vector velocities are acquired to a depth of 3 cm using directional synthetic aperture vector flow imaging. The performance of the suggested estimator is evaluated by comparing its results to a 3-D numerical simulation model. The study showed pressure drops across the constricted phantom varying from -5 Pa to 7 Pa with a standard deviation of 4%. The proposed method had a normalised rootmean-square error of 10% in reference to the simulation model. Further, an in-vivo scan of the carotid bifurcation is made to show the feasibility of the technique in a less experimental environment.

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Output pressure and harmonic characteristics of a CMUT as function of bias and excitation voltage

The large bandwidth makes CMUT based transducers interesting for both conventional and harmonic imaging. The inherent nonlinear behavior of the CMUT, however, poses an issue for harmonic imaging as it is difficult to dissociate the harmonics generated in the tissue from the harmonic content of the transmitted signal. The generation of intrinsic harmonics by the CMUT can be minimized by decreasing the excitation signal. This, however, leads to lower fundamental pressure which limits the desired generation of harmonics in the medium. This work examines the output pressure and harmonic characteristics of a CMUT as function of bias and excitation voltage. The harmonic to fundamental ratio of the surface pressures declines for decreasing excitation voltage and increasing bias voltage. The ratio, however, becomes unchanged for bias levels close to the pull-in voltage. The harmonic limitations of the CMUT is emphasized by a maximum ratio of −12 dB between harmonics generated in the medium and total harmonics measured at 10 mm.

Surveillance of Hemodialysis Vascular Access with Ultrasound Vector Flow Imaging

The aim of this study was prospectively to monitor the volume flow in patients with arteriovenous fistula (AVF) with the angle independent ultrasound technique Vector Flow Imaging (VFI). Volume flow values were compared with Ultrasound dilution technique (UDT). Hemodialysis patients need a well-functioning vascular access with as few complications as possible and preferred vascular access is an AVF. Dysfunction due to stenosis is a common complication, and regular monitoring of volume flow is recommended to preserve AVF patency. UDT is considered the gold standard for volume flow surveillance, but VFI has proven to be more precise, when performing single repeated instantaneous measurements. Three patients with AVF were monitored with UDT and VFI monthly for five months. A commercial ultrasound scanner with a 9 MHz linear array transducer with integrated VFI was used to obtain data. UDT values were obtained with Transonic HD03 Flow-QC Hemodialysis Monitor. Three independent measurements at each scan session were obtained with UDT and VFI each month. Average deviation of volume flow between UDT and VFI was 25.7 % (CI: 16.7% to 34.7%) (p = 0.73). The standard deviation for all patients, calculated from the mean variance of each individual scan sessions, was 199.8 ml/min for UDT and 47.6 ml/min for VFI (p = 0.002). VFI volume flow values were not significantly different from the corresponding estimates obtained using UDT, and VFI measurements were more precise than UDT. The study indicates that VFI can be used for surveillance of volume flow.
Transverse oscillation vector flow imaging for transthoracic echocardiography

This work presents the development and first results of in vivo transthoracic cardiac imaging using an implementation of Vector Flow Imaging (VFI) via the Transverse Oscillation (TO) method on a phased-array transducer. Optimal selection of the lateral wavelength of the transversely-oscillating receive field is described, and results from Field II simulations are presented. Measurements are made using the SARUS experimental ultrasound scanner driving an intercostal phased-array probe. The acquisition sequence was composed of interleaved frames of 68-line B-mode and 17-direction, 32-shot vector velocity flow images. A flow pump was programmed for constant flow for in vitro acquisitions at varying depths in a tissue-mimicking fluid. Additionally, mitral, aortic, and tricuspid valves of two healthy volunteers were scanned from intercostal acoustic windows. The acquired RF data were beamformed via the TO method, and fourth-order estimators were employed for the velocity estimation. The resulting images were compared with those from conventional spectral Doppler and color flow mapping sequences. VFI is shown to be a clinically-feasible tool, which enables new exibility for choosing acoustic windows, visualizing turbulent ow patterns, and measuring velocities.
Vector flow imaging of the ascending aorta. Are systolic backflow and atherosclerosis related?

In the ascending aorta, atherosclerotic plaque formation, which is a risk factor for cerebrovascular events, most often occurs along the inner curvature. Atherosclerosis is a multifactorial disease, but the predilection site for the aortic vessel degradation is probably flow dependent. To better understand the aortic flow and especially the complex flow patterns, the ascending aorta was scanned intraoperatively in patients undergoing heart surgery using the angle-independent vector velocity ultrasound method Transverse Oscillation (TO). The primary aim of the study was to analyze systolic backflow in relation to atherosclerosis. Thirteen patients with normal aortic valves were included in the study. TO implemented on a conventional US scanner (ProFocus 2202 UltraView, BK Medical, Herlev, Denmark) with a linear array transducer (8670, BK Medical, Herlev, Denmark) was used intraoperatively on the ascending aorta in long axis view. The presence of systolic backflow, visualized with TO, was correlated to aortic atherosclerosis, to systolic velocities obtained with transesophageal echocardiography and cardiac output obtained with pulmonary artery catheter thermodilution, to gender, age, aortic diameter, left ventricular ejection fraction (LVEF) and previous myocardial infarctions (MI). Systolic backflow in the ascending aorta was present for 38% of the patients. The location of the backflow was strongly associated to the location of the plaques (p<0.005), and backflow was associated to high systolic velocities (p<0.05). The other obtained parameters were not associated to systolic backflow. It was shown that systolic backflow is a common flow feature in the ascending aorta, and that backflow is associated to atherosclerotic plaques and systolic velocities. The study indicates that vector flow imaging using TO can provide important blood flow information in the assessment of atherosclerosis.

Velocity Estimation of the Main Portal Vein with Transverse Oscillation.

This study evaluates if Transverse Oscillation (TO) can provide reliable and accurate peak velocity estimates of blood flow in the main portal vein. TO was evaluated against the recommended and most widely used technique for portal flow estimation, Spectral Doppler Ultrasound (SDU). The main portal vein delivers blood from the bowls to the liver, and patients with certain liver diseases have decreased flow in the portal vein. Errors in velocity estimation with SDU are well described, when the beam-to-flow angle is >70 degrees. TO estimates the flow angle independently and is not limited by the beam-to-flow angle. It is less operators depended, as no angle correction is necessary. TO measurements were performed with a 3 MHz convex probe (BK medical 8820e, Herlev, Denmark) connected to the experimental ultrasound scanner SARUS (Synthetic Aperture Real-time Ultrasound Scanner). SDU velocity measurements were performed with a commercial ultrasound scanner (BK 3000, BK Ultrasound, Herlev Denmark) and a convex probe (BK ultrasound 6C2,
Herlev, Denmark). Ten healthy volunteers were scanned, and recordings of the portal flow during 3-5 heartbeats were conducted with an intercostal and subcostal view. Intercostal TO peak velocities were not significantly different from SDU peak velocities (TO=0.203m/s, SDU=0.202m/s, p=0.94). Subcostal and Intercostal obtained TO values were not significantly different (intercostal mean TO=0.203m/s, subcostal mean TO=0.180m/s, p=0.26). SDU values obtained intercostal and subcostal were significantly different (intercostal mean SDU=0.202m/s, subcostal mean SDU=0.320m/s, p=0.001). Standard deviation for TO beam-to-flow angle was 10.3°- 91.5°, indicating a large beam-to-flow angle variability in the portal vein. This can affect the peak velocity estimation, and is not addressed in SDU. The TO convex array implementation provides the first vector velocity measurements below 60mm (mean 89mm), and is a useful alternative for flow estimation in abdominal ultrasound. It may provide new information of abdominal fluid dynamics and yield both velocity and angle estimates for a more realistic flow characterization.
Angle independent velocity spectrum determination.
An ultrasound imaging system (100) includes a transducer array (102) that emits an ultrasound beam and produces at least one transverse pulse-echo field that oscillates in a direction transverse to the emitted ultrasound beam and that receive echoes produced in response thereto and a spectral velocity estimator (110) that determines a velocity spectrum for flowing structure, which flows at an angle of 90 degrees and flows at angles less than 90 degrees with respect to the emitted ultrasound beam, based on the received echoes.

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Ultrasound imaging probe with sigma-delta beamformer and apodization therein
An ultrasound transducer probe (104) includes a transducer array (108) of elements (110) that emit an ultrasound signal and receive analog echo signals produced in response thereto and a beamformer (112), housed by the probe, that converts the analog echo signals to digital signals, applies delays to the digital signals, and sums the delayed digital signals, produces a value of a bit stream, wherein the beamformer apodizes the signals.

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2-D Tissue Motion Compensation of Synthetic Transmit Aperture Images
Synthetic transmit aperture (STA) imaging is susceptible to tissue motion because it uses summation of low-resolution images to create the displayed high-resolution image. A method for 2-D tissue motion correction in STA imaging is presented. It utilizes the correlation between high-resolution images recorded using the same emission sequence. The velocity and direction of the motion are found by crosscorrelating short high-resolution lines beamformed along selected angles. The motion acquisition is interleaved with the regular B-mode emissions in STA imaging, and the motion compensation is performed by tracking each pixel in the reconstructed image using the estimated velocity and direction. The method is evaluated using simulations, and phantom and in vivo experiments. In phantoms, a tissue velocity of 15 cm/s at a 45° angle was estimated with relative bias and standard deviation of −6.9% and 5.4%; the direction was estimated with relative bias and standard deviation of −8.4% and 6.6%. The contrast resolution in the corrected image was −0.65% lower than the reference image. Abdominal in vivo experiments with induced transducer motion demonstrate that...
severe tissue motion can be compensated for, and that doing so yields a significant increase in image quality.

3-D Velocity Estimation for Two Planes in vivo
3-D velocity vectors can provide additional flow information applicable for diagnosing cardiovascular diseases e.g. by estimating the out-of-plane velocity component. A 3-D version of the Transverse Oscillation (TO) method has previously been used to obtain this information in a carotid flow phantom with constant flow. This paper presents the first in vivo measurements of the 3-D velocity vector, which were obtained over 3 cardiac cycles in the common carotid artery of a 32-year-old healthy male volunteer. Data were acquired using a Vermon 3.5 MHz 32x32 element 2-D phased array transducer and stored on the experimental scanner SARUS. The full 3-D velocity profile can be created and examined at peak-systole and end-diastole without ECG gating in two planes. Maximum out-of-plane velocities for the three peak-systoles and end-diastoles were 68.5 ± 5.1 cm/s and 26.3 ± 3.3 cm/s, respectively. In the longitudinal plane, average maximum peak velocity in flow direction was 65.2 ± 14.0 cm/s at peak-systole and 33.6 ± 4.3 cm/s at end-diastole. A commercial BK Medical ProFocus UltraView scanner using a spectral estimator gave 79.3 cm/s and 14.6 cm/s for the same volunteer. This demonstrates that real-time 3-D vector velocity imaging without ECG gating yields quantitative in vivo estimations on flow direction and magnitude.
Accuracy and Sources of Error for an Angle Independent Volume Flow Estimator

This paper investigates sources of error for a vector velocity volume flow estimator. Quantification of the estimator’s accuracy is performed theoretically and investigated in vivo. Womersley’s model for pulsatile flow is used to simulate velocity profiles and calculate volume flow errors in cases of elliptical vessels and not placing the transducer at the vessel center. Simulations show, i.e., that volume flow is underestimated with 5%, when the transducer is placed 15% from the vessel center. Twenty patients with arteriovenous fistulas for hemodialysis are scanned in a clinical study. A BK Medical UltraView 800 ultrasound scanner with a 9 MHz linear array transducer is used to obtain Vector Flow Imaging sequences of a superficial part of the fistulas. Cross-sectional diameters of each fistula are measured on B-mode images by rotating the scan plane 90 degrees. The major axis of the fistulas was on average 8.6% larger than the minor axis, so elliptic dimensions should be taken into account in volume flow estimation. The ultrasound beam was on average 1.5 ± 0.8 mm off-axis, corresponding to 28.5 ± 11.3% of the major semi-axis of a fistula, and this could result in 15% underestimated volume flow according to the simulation. Volume flow estimates were corrected for the beam being off-axis, but was not able to significantly decrease the error relative to measurements with the reference method.

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A comparison between temporal and subband minimum variance adaptive beamforming

This paper compares the performance between temporal and subband Minimum Variance (MV) beamformers for medical ultrasound imaging. Both adaptive methods provide an optimized set of apodization weights but are implemented in the time and frequency domains respectively. Their performance is evaluated with simulated synthetic aperture data obtained from Field II and is quantified by the Full-Width-Half-Maximum (FWHM), the Peak-Side-Lobe level (PSL) and the contrast level. From a point phantom, a full sequence of 128 emissions with one transducer element transmitting and all 128 elements receiving each time, provides a FWHM of 0.03 mm (0.14λ) for both implementations at a depth of 40 mm. This value is more than 20 times lower than the one achieved by conventional beamforming. The corresponding values of PSL are -58 dB and -63 dB for time and frequency domain MV beamformers, while a value no lower than -50 dB can be obtained from either Boxcar or Hanning weights. Interestingly, a single emission with central element #64 as the transmitting aperture provides results comparable to the full sequence. The values of FWHM are 0.04 mm and 0.03 mm and those of PSL are -42 dB and -46 dB for temporal and subband approaches. From a cyst phantom and for 128 emissions, the contrast level is calculated at -54 dB and -63 dB respectively at the same depth, with the initial shape of the cyst being preserved in contrast to conventional beamforming. The difference between the two adaptive beamformers is less significant in the case of a single emission, with the contrast level being estimated at -42 dB for the time domain and -43 dB for the frequency domain implementation. For the estimation of a single MV weight of a low resolution image formed by a single emission, 0.44 109 calculations per second are required for the temporal approach. The same numbers for the subband approach are 0.62 109 for the point and 1.33 109 for the cystphantom. The comparison demonstrates similar resolution but slightly lower side-lobes and higher contrast for the subband approach at the expense of increased computation time.

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Adaptive Multi-Lag for Synthetic Aperture Vector Flow Imaging

The range of detectable velocities in ultrasound flow imaging is linked to the user selection of pulse repetition frequency. Whenever a region with large differences in velocity magnitude is visualized, a trade-off has to be made. This work suggests an adaptive spatio-temporally independent, multi-lag method, which is performed in synthetic aperture vector flow data. Measurements are made on laminar and pulsatile, transverse flow profiles. A 7 MHz linear array is connected to the SARUS research, and acquisitions are made on a vessel phantom with recirculating blood mimicking fluid driven by a software controlled pump. A multi-lag velocity estimation is performed, and a lag is adaptively selected for every estimation point. Results from the constant flow compared to a true parabolic profile show an improvement in relative bias from 76.99% to 0.91% and standard deviation from 13.60% to 1.83% for the low velocity flow of 0.04 m/s; and relative bias from -2.23% to -1.87% and standard deviation from 3.71% to 2.29% for the high velocity flow of 0.4 m/s

A Multi-threaded Version of Field II

A multi-threaded version of Field II has been developed, which automatically can use the multi-core capabilities of modern CPUs. The memory allocation routines were rewritten to minimize the number of dynamic allocations and to make pre-allocations possible for each thread. This ensures that the simulation job can be automatically partitioned and the interdependence between threads minimized. The new code has been compared to Field II version 3.22, October 27, 2013 (latest free-ware version). A 64 element 5 MHz focused array transducer was simulated. One million point scatterers randomly distributed in a plane of 20 x 50 mm (width x depth) with random Gaussian amplitudes were simulated using the command calc scat. Dual Intel Xeon CPU E5-2630 2.60 GHz CPUs were used under Ubuntu Linux 10.02 and Matlab version 2013b. Each CPU holds 6 cores with hyper-threading, corresponding to a total of 24 hyper-threading cores. The averaged simulation time for 10 realizations for the old version was 85.1 s. A single thread run for the new version took 27.7 s; a speed-up of 3.1. Employing all 24 cores gave a simulation time of 3.27 s for the one million scatterers corresponding to a speed-up factor of 26 times. The speed-up in general depends on the transducer, scatterers and simulation, and it varies across applications between 13 and 30. The program is fully compatible with older versions, and only a single command has been added for setting the number of threads to use. The division of labor is automatically handled by the program. For a phantom with 100,000 scatterers, it is now possible to simulate a full 128 line image in around 42 seconds with full precision.
A phantom study on temporal and subband Minimum Variance adaptive beamforming

This paper compares experimentally temporal and subband implementations of the Minimum Variance (MV) adaptive beamformer for medical ultrasound imaging. The performance of the two approaches is tested by comparing wire phantom measurements, obtained by the research ultrasound scanner SARUS. A 7 MHz BK8804 linear transducer was used to scan a wire phantom in which wires are separated by 10 mm. Performance is then evaluated by the lateral Full-Width-Half-Maximum (FWHM), the Peak Sidelobe Level (PSL), and the computational load. Beamformed single emission responses are also compared with those from conventional Delay-and-Sum (DAS) beamformer. FWHM measured at the depth of 46.6 mm, is 0.02 mm (0.09λ) for both adaptive methods while the corresponding values for Hanning and Boxcar weights are 0.64 and 0.44 mm respectively. Between the MV beamformers a -2 dB difference in PSL is noticed in favor of the subband approach (-31 and -33 dB), whereas values from conventional are not lower than -29 dB. This slight improvement in the case of the subband implementation comes at the expense of increased computational cost; 3.7 TFLOPs per image are required in contrast to 130 GFLOPs of the temporal one, when only 0.5 GFLOPs are needed in DAS beamforming.

A Transverse Oscillation Approach for Estimation of Three-Dimensional Velocity Vectors, Part I: Concept and Simulation Study

A method for 3-D velocity vector estimation using transverse oscillations is presented. The method employs a 2-D transducer and decouples the velocity estimation into three orthogonal components, which are estimated simultaneously.
and from the same data. The validity of the method is investigated by conducting simulations emulating a $32 \times 32$ matrix transducer. The results are evaluated using two performance metrics related to precision and accuracy. The study includes several parameters including 49 flow directions, the SNR, steering angle, and apodization types. The 49 flow directions cover the positive octant of the unit sphere. In terms of accuracy, the median bias is $-2\%$. The precision of $v_x$ and $v_y$ depends on the flow angle $\beta$ and ranges from 5\% to 31\% relative to the peak velocity magnitude of 1 m/s. For comparison, the range is 0.4 to 2\% for $v_z$. The parameter study also reveals, that the velocity estimation breaks down with an SNR between $-6$ and $-3$ dB. In terms of computational load, the estimation of the three velocity components requires 0.75 billion floating point operations per second (0.75 GFlops) for a realistic setup. This is well within the capability of modern scanners.

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A Transverse Oscillation Approach for Estimation of Three-Dimensional Velocity Vectors, Part II: Experimental Validation

The 3-D transverse oscillation method is investigated by estimating 3-D velocities in an experimental flowrig system. Measurements of the synthesized transverse oscillating fields are presented as well. The method employs a 2-D transducer; decouples the velocity estimation; and estimates the axial, transverse, and elevation velocity components simultaneously. Data are acquired using a research ultrasound scanner. The velocity measurements are conducted with steady flow in sixteen different directions. For a specific flow direction with $[\alpha, \beta] = [45, 15]^\circ$, the mean estimated velocity vector at the center of the vessel is $(v_x, v_y, v_z) = (33.8, 34.5, 15.2) \pm (4.6, 5.0, 0.6) \text{cm/s}$ where the expected velocity is $(34.2, 34.2, 13.0) \text{cm/s}$. The velocity magnitude is $50.6 \pm 5.2 \text{cm/s}$ with a bias of $0.7 \text{cm/s}$. The flow angles $\alpha$ and $\beta$ are estimated as $45.6 \pm 4.9^\circ$ and $17.6 \pm 1.0^\circ$. Subsequently, the precision and accuracy are calculated over the entire velocity profiles. On average for all directions, the relative mean bias of the velocity magnitude is $0.08\%$. For $\alpha$ and $\beta$, the mean bias is $-0.2^\circ$ and $-1.5^\circ$. The relative standard deviations of the velocity magnitude ranges from 8 to 16\%. For the flow angles, the ranges of the mean angular deviations are 5° to 16° and 0.7° and 8°.

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Clinical evaluation of Synthetic Aperture Sequential Beamforming and Tissue Harmonic Imaging
This study determines if the data reduction achieved by the combination Synthetic Aperture Sequential Beamforming (SASB) and Tissue Harmonic Imaging (THI) affects image quality. SASB-THI was evaluated against the combination of Dynamic Received Focusing and Tissue Harmonic Imaging (DRF-THI). A BK medical UltraView 800 ultrasound scanner equipped with a research interface and an abdominal 3.5 MHz 3.5CL192-3ML convex array transducer was used and connected to a stand alone PC. SASB-THI and DRF-THI scan sequences were recorded interleaved and processed offline. Nineteen patients diagnosed with focal liver pathology were scanned to set a clinical condition, where ultrasonography is often performed. A total of 114 sequences were recorded and evaluated by five radiologists. The evaluators were blinded to the imaging technique, and each sequence was shown twice with different left-right positioning, resulting in 1140 evaluations. The program Image Quality Assessment Program (IQap) and a Visual Analog Scale (VAS) were applied for the evaluation. The scale ranged from -50 to 50, where positive values favored SASB-THI. SASB-THI and DRF-THI were evaluated alike in 49% of the evaluations, 28% favored SASB-THI and 23% favored DRF-THI. The average rating was 0.70 (CI: -0.80 to 2.19). The statistical analysis, where the hypothesis of no differences between the techniques was tested, yielded a p-value of p=0.64, indicating no preference to any technique. This study demonstrates that SASB-THI and DRF-THI have equally good image quality although a data reduction of 64 times is achieved with SASB-THI.

Clinical evaluation of synthetic aperture sequential beamforming ultrasound in patients with liver tumors
Medical ultrasound imaging using synthetic aperture sequential beamforming (SASB) has for the first time been used for clinical patient scanning. Nineteen patients with cancer of the liver (hepatocellular carcinoma or colorectal liver metastases) were scanned simultaneously with conventional ultrasound and SASB using a commercial ultrasound scanner and abdominal transducer. SASB allows implementation of the synthetic aperture technique on systems with restricted data handling capabilities due to a reduction in the data rate in the scanner by a factor of 64. The image quality is potentially maintained despite the data reduction. A total of 117 sequences were recorded and evaluated blinded by five radiologists from a clinical perspective. Forty-eight percent of the evaluations were in favor of SASB, 33% in favor of conventional ultrasound and 19% were equal, that is, a clear, but non-significant trend favoring SASB over conventional ultrasound (p 0.18), despite the substantial data reduction. © 2014 World Federation for Ultrasound in Medicine & Biology.
Comparison of 3-D Synthetic Aperture Phased-Array Ultrasound Imaging and Parallel Beamforming

This paper demonstrates that synthetic aperture imaging (SAI) can be used to achieve real-time 3-D ultrasound phased-array imaging. It investigates whether SAI increases the image quality compared with the parallel beam-forming (PB) technique for real-time 3-D imaging. Data are obtained using both simulations and measurements with an ultrasound research scanner and a commercially available 3.5-MHz 1024-element 2-D transducer array. To limit the probeable thickness, 256 active elements are used in transmit and receive for both techniques. The two imaging techniques were designed for cardiac imaging, which requires sequences designed for imaging down to 15 cm of depth and a frame rate of at least 20 Hz. The imaging quality of the two techniques is investigated through simulations as a function of depth and angle. SAI improved the full-width at half-maximum (FWHM) at low steering angles by 35%, and the 20-dB cystic resolution by up to 62%. The FWHM of the measured line spread function (LSF) at 80 mm depth showed a difference of 20% in favor of SAI. SAI reduced the cyst radius at 60 mm depth by 39% in measurements. SAI improved the contrast-to-noise ratio measured on anechoic cysts embedded in a tissue-mimicking material by 29% at 70 mm depth. The estimated penetration depth on the same tissue-mimicking phantom shows that SAI increased the penetration by 24% compared with PB. Neither SAI nor PB achieved the design goal of 15 cm penetration depth. This is likely due to the limited transducer surface area and a low SNR of the experimental scanner used.
Comparison of Vector Velocity Imaging using Directional Beamforming and Transverse Oscillation for a Convex Array Transducer

Vector velocity imaging can reveal both the magnitude and direction of the blood velocity. Several techniques have been suggested for estimating the velocity, and this paper compares the performance for directional beamforming and transverse oscillation (TO) vector flow imaging (VFI). Data have been acquired using the SARUS experimental ultrasound scanner connected to a BK 8820e (BK Medical, Herlev, Denmark) convex array probe with 192 active elements. A duplex sequence with 129 B-mode emissions interleaved with 129 flow emissions has been made. The flow was generated in a recirculating flow rig with a stationary, laminar flow, and the volume flow was measured by a MAG 3000 (Danfos, Sønderborg, Denmark) magnetic flow meter for reference. Data were beamformed with an optimized transverse oscillation scheme for the TO VFI, and standard fourth-order estimators were employed for the velocity estimation. Directional RF lines were beamformed along the flow direction and cross-correlation employed to estimate the velocity magnitude. The velocities were determined for beam-to-flow angles of 60, 75 and 90 degrees. Using 32 emissions the standard deviation relative to the peak velocity for TO estimation was 7.0% at a beam-to-flow angle of 75. This was 3.8% for directional beamforming and at 60 it was 2.2%. The general improvement, however, comes at an increase by a factor of roughly 11 in the number of calculations for the directional beamformation compared to the TO method.

Data adaptive estimation of transversal blood flow velocities

The examination of blood flow inside the body may yield important information about vascular anomalies, such as possible indications of, for example, stenosis. Current Medical ultrasound systems suffer from only allowing for measuring the blood flow velocity along the direction of irradiation, posing natural difficulties due to the complex behaviour of blood flow, and due to the natural orientation of most blood vessels. Recently, a transversal modulation scheme was introduced to induce also an oscillation along the transversal direction, thereby allowing for the measurement of also the transversal blood flow. In this paper, we propose a novel data-adaptive blood flow estimator exploiting this modulation scheme. Using realistic Field II simulations, the proposed estimator is shown to achieve a notable performance improvement as compared to current state-of-the-art techniques.
Determining inter-fractional motion of the uterus using 3D ultrasound imaging during radiotherapy for cervical cancer

Uterine positional changes can reduce the accuracy of radiotherapy for cervical cancer patients. The purpose of this study was to: 1) Quantify the inter-fractional uterine displacement using a novel 3D ultrasound (US) imaging system, and 2) Compare the result with the bone match shift determined by Cone-Beam CT (CBCT) imaging. Five cervical cancer patients were enrolled in the study. Three of them underwent weekly CBCT imaging prior to treatment and bone match shift was applied. After treatment delivery they underwent a weekly US scan. The transabdominal scans were conducted using a Clarity US system (Clarity® Model 310C00). Uterine positional shifts based on soft-tissue match using US was performed and compared to bone match shifts for the three directions. Mean value (±1 SD) of the US shifts were (mm); anterior-posterior (A/P): (3.8±5.5), superior-inferior (S/I): (-3.5±5.2), and left-right (L/R): (0.4±4.9). The variations were larger than the CBCT shifts. The largest inter-fractional displacement was from -2 mm to +14 mm in the AP-direction for patient 3. Thus, CBCT bone matching underestimates the uterine positional displacement due to neglecting internal uterine positional change to the bone structures. Since the US images were significantly better than the CBCT images in terms of soft-tissue visualization, the US system can provide an optional image-guided radiation therapy (IGRT) system. US imaging might be a better IGRT system than CBCT, despite difficulty in capturing the entire uterus. Uterine shifts based on US imaging contains relative uterus-bone displacement, which is not taken into consideration using CBCT bone match.

Dimensional Scaling for Optimized CMUT Operations

This work presents a dimensional scaling study using numerical simulations, where gap height and plate thickness of a CMUT cell is varied, while the lateral plate dimension is adjusted to maintain a constant transmit immersion center frequency of 5 MHz. Two cell configurations have been simulated, one with a single square cell and one with an infinite array of square cells. It is shown how the radiation impedance from neighboring cells has a significant impact on the design process. For transmit optimization, both plate dimensions and gap height should be increased. For receive mode, the gap height should be increased while the effect of plate dimensions is ambiguous depending on if the array design is closest to a single cell or infinite array of cells. The findings of the simulations are verified by acoustical measurements on two CMUT arrays with different plate dimensions.
First report on intraoperative vector flow imaging of the heart among patients with healthy and diseased aortic valves

The vector velocity method Transverse Oscillation (TO) implemented on a conventional ultrasound (US) scanner (ProFocus, BK Medical, Herlev, Denmark) can provide real-time, angle-independent estimates of the cardiac blood flow. During cardiac surgery, epicardial US examination using TO was performed on (A) 3 patients with healthy aortic valve and (B) 3 patients with aortic valve stenosis. In group B, the systolic flow of the ascending aorta had higher velocities, was more aliased and chaotic. The jet narrowed to 44% of the lumen compared to 75% in group A and with a vector concentration, a measure of flow complexity, of 0.41 compared to 0.87 in group A. The two groups had similar secondary flow of the ascending aorta with an average rotation frequency of 4.8 Hz. Simultaneous measurements were obtained with spectral Doppler (SD) and a thermodilution technique (TD). The mean difference in peak systolic velocity compared to SD in group A was 22% and 45% in B, while the mean difference in volume flow compared to TD in group A was 30% and 32% in B. TO can potentially reveal new information of cardiac blood flow, and may become a valuable diagnostic tool in the evaluation of patients with cardiovascular diseases.

Implementation of synthetic aperture imaging on a hand-held device

This paper presents several implementations of Synthetic Aperture Sequential Beamforming (SASB) on commercially available hand-held devices. The implementations include real-time wireless reception of ultrasound radio frequency signals and GPU processing for B-mode imaging. The proposed implementation demonstrates that SASB can be executed in-time for real-time ultrasound imaging. The wireless communication between probe and processing device satisfies the required bandwidth for real-time data transfer with current 802.11ac technology. The implementation is evaluated using four different hand-held devices all with different chipsets and a BK Medical UltraView 800 ultrasound scanner emulating a wireless probe. The wireless transmission is benchmarked using an imaging setup consisting of 269 scan lines x 1472 complex samples (1.58 MB pr. frame, 16 frames per second). The measured data throughput reached an average of 28.8 MB/s using a LG G2 mobile device, which is more than the required data throughput of 25.3 MB/s. Benchmarking the processing performance for B-mode imaging showed a total processing time of 18.9 ms (53 frames/s), which is less than the acquisition time (62.5 ms).
Increasing the Dynamic Range of Synthetic Aperture Vector Flow Imaging

In current ultrasound systems the dynamic range of detectable velocities is susceptible to the selected pulse repetition frequency, thus limiting the dynamic range of flow mapping. To establish the feasibility of extending the range of detectable velocities towards low velocity vessels, results are presented using synthetic aperture which increases the frame-to-frame signal correlation of the scatterer displacement while providing continuous data. In this paper, recursive synthetic aperture acquisition, directional beamforming, and cross-correlation are used to produce B-mode and vector velocity images. The emissions for the two imaging modes are interleaved 1-to-1 ratio, providing a high frame rate equal to the effective pulse repetition frequency of each imaging mode. The direction of the flow is estimated, and the velocity is then determined in that direction. This method works for all angles, including fully axial and transverse flows. The method is investigated using Field II simulations and data from the experimental ultrasound scanner SARUS, acquired from a circulating flow rig with a parabolic flow. A 7 MHz linear array transducer is used, and several pulse repetition frequencies are synthesized in a simulated flow phantom with linearly increasing velocity and in a dual-vessel phantom with laminar flow with peak velocities of 0.05 m/s and 0.5 m/s. The experimental measurements are made with laminar flow as in the simulations. For the simulated and experimental vessel with peak velocity of 0.05 m/s and flow angle of 75°, the relative bias is -0.29% and -3.19%, and the relative standard deviations are 2.39% and 5.75% respectively. For the simulated and experimental vessel with peak velocity of 0.5 m/s and flow angle of -90°, the relative biases are -4.30% and -7.37%, and the relative standard deviations are 1.59% and 6.12%, respectively. The presented method can improve the estimates by synthesizing a lower pulse repetition frequency, thereby increasing the dynamic range of the vector velocity imaging.

Investigation of PDMS as coating on CMUTs for Imaging

A protective layer is necessary for Capacitive Micromachined Ultrasonic Transducers (CMUTs) to be used for imaging purposes. The layer should both protect the device itself and the patient while maintaining the performance of the device. In this work Sylgard 170 PDMS is tested as coating material for CMUTs through comparison of transmit pressure and receive sensitivity in immersion of coated and uncoated elements. It is seen that the transmitted pressure decreases with
27% and the receive sensitivity decreases 35 % when applying the coating using a dam and fill principle. This matches well with the estimated value of 31 %. With the coating, the center frequency was found to be decreased from 4.5 MHz to 4.1 MHz and the fractional bandwidth was increased from 77 % to 84 % in transmit. In receive the center frequency was found to decrease from 4.4 MHz to 3.9 MHz and the fractional bandwidth was decreased from 108 % to 92 %, when applying the PDMS coating.

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**In-vivo Convex Array Vector Flow Imaging**
In-vivo VFI scans obtained from the abdomen of a human volunteer using a convex array transducers and transverse oscillation vector flow imaging (VFI) are presented. A 3 MHz BK Medical 8820e (Herlev, Denmark) 192-element convex array probe is used with the SARUS experimental ultrasound scanner. A sequence with a 129-line B-mode image is followed by a VFI sequence in 17 directions with 32 emissions in each direction. The pulse repetition frequency was set to 5 kHz, and the intensity and MI were measured with the Acoustic Intensity Measurement System AIMS III (Onda, Sunnyvale, California, USA). The derated Ispta:3 was 79.7 mW/m2 and MI was 1.32, which are within FDA limits for abdominal scans. The right liver lobe of a 28-year healthy volunteer was scanned with a view of the main portal vein and vena cava inferior at a frame rate of 7.4 Hz. Thirty frames were acquired, giving 4 seconds of data. For this volunteer the duration corresponded to roughly 3 heartbeats. The velocities were found at a beam-to-flow angle of 72 ± 2°, where a conventional CFM scan would yield poor results. Three VF images from the same position in the cardiac cycle were investigated and the mean lateral velocities were -0.079, -0.081 and -0.080 m/s showing the consistence of the in-vivo results.

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In-Vivo Synthetic Aperture and Plane Wave High Frame Rate Cardiac Imaging
A comparison of synthetic aperture imaging using spherical and plane waves with low number of emission events is presented. For both wave types, a 90 degree sector is insonified using 15 emission events giving a frame rate of 200 frames per second. Field II simulations of point targets show similar resolution of approximately one wavelength radially and one degree angularly for both wave types. The use of spherical waves is found to have higher signal strength and better cystic resolution than plane waves. Measurements on wires in water yield similar results to simulations with similar resolution between the two wave types but better cystic resolution for spherical waves. Mea- surements on tissue mimicking phantoms show that both wave types penetrate down to 11 cm. Intensity measurements show an I spta: 3 of 18.4 mW/cm 2 for spherical waves and 22.7 mW/cm 2 for plane waves. The derated MI is 0.43 for spherical and 0.70 for plane waves. All measures are well within FDA limits for cardiac imaging. In-vivo images of the heart of a healthy 28-year old volunteer are shown.

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Modal radiation patterns of baffled circular plates and membranes
The far field velocity potential and radiation pattern of baffled circular plates and membranes are found analytically using the full set of modal velocity profiles derived from the corresponding equation of motion. The derivation is valid for a plate or membrane subjected to an external excitation force, which is used as a sound receiver in any medium or as a sound transmitter in a gaseous medium. A general, concise expression is given for the radiation pattern of any mode of the membrane and the plate with arbitrary boundary conditions. Specific solutions are given for the four special cases of a plate with clamped, simply supported, and free edge boundary conditions as well as for the membrane. For all non-axisymmetric modes, the velocity potential along the axis of the radiator is found to be strictly zero. In the long wavelength limit, the radiation pattern of all axisymmetric modes approaches that of a monopole, while the non-axisymmetric modes exhibit multipole behavior. Numerical results are also given, demonstrating the implications of having non-axisymmetric excitation using both a point excitation with varying eccentricity and a homogeneous excitation acting on half of the circular radiator.

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Noninvasive estimation of 2-D pressure gradients in steady flow using ultrasound

A noninvasive method for estimating 2-D pressure gradients from ultrasound vector velocity data is presented. It relies on vector velocity fields acquired using the transverse oscillation method during steady flow conditions. The pressure gradients are calculated from the velocity fields using the Navier-Stokes equations. Scans of a carotid bifurcation phantom with a 70% constriction are performed using a linear transducer connected to a scanner. The performance of the estimator is evaluated by comparing its results to those of a computational fluid dynamics model of the carotid bifurcation phantom. The geometry of the model is determined from magnetic resonance imaging. The presented study is conducted assuming steady flow using velocity data acquired at 18 frames per second. The proposed method shows pressure gradients at the constricted region from -8 kPa/m to 9 kPa/m, with a maximum bias of -7% for the axial component and -8% for the lateral component. The relative standard deviation of the estimator is 5% (axial component) and 30% (lateral component) when studying the pressure gradient across the constriction using 3 velocity frames per pressure estimate. The study shows that 2-D pressure gradients can be achieved noninvasively using ultrasound data in a constant flow environment.

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Non-invasive Estimation of Pressure Gradients in Pulsatile Flow using Ultrasound

This paper investigates how pressure gradients in a pulsatile flow environment can be measured non-invasively using ultrasound. The presented set-up is based on vector velocity fields measured on a blood mimicking fluid moving at a peak flow rate of 1 ml/s through a constricted vessel. Fields of pressure gradients are calculated using the Navier-Stokes equations. Flow data are acquired to a depth of 3 cm using directional synthetic aperture flow imaging on a linear array transducer producing 1500 image frames of velocity estimates per second. Scans of a carotid bifurcation phantom with a 70% constriction are performed using an experimental scanner. The performance of the presented estimator is evaluated by comparing its results to a numerical simulation model, which geometry is reconstructed from MRI data. The study showed pressure gradients varying from 0 kPa/m to 4.5 kPa/m with a maximum bias and standard deviation of 10% and 13%, respectively, relative to peak estimated gradient. The paper concludes that maps of pressure gradients can be measured non-invasively using ultrasound with a precision of more than 85%

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Novel flow quantification of the carotid bulb and the common carotid artery with vector flow ultrasound.

Abnormal blood flow is usually assessed using spectral Doppler estimation of the peak systolic velocity. The technique, however, only estimates the axial velocity component, and therefore the complexity of blood flow remains hidden in conventional ultrasound examinations. With the vector ultrasound technique transverse oscillation the blood velocities of both the axial and the transverse directions are obtained and the complexity of blood flow can be visualized. The aim of the study was to determine the technical performance and interpretation of vector concentration as a tool for estimation of flow complexity. A secondary aim was to establish accuracy parameters to detect flow changes/patterns in the common carotid artery (CCA) and the carotid bulb (CB). The right carotid bifurcation including the CCA and CB of eight healthy volunteers were scanned in a longitudinal plane with vector flow ultrasound (US) using a commercial vector flow ultrasound scanner (ProFocus, BK Medical, Denmark) with a linear 5 MHz transducer transverse oscillation vector flow software. CCA and CB areas were marked in one cardiac cycle from each volunteer. The complex flow was assessed by medical expert evaluation and by vector concentration calculation. A vortex with complex flow was found in all carotid bulbs, whereas the CCA had mainly laminar flow. The medical experts evaluated the flow to be mainly laminar in the CCA (0.82 +/- 0.14) and mainly complex (0.23 +/- 0.22) in the CB. Likewise, the estimated vector concentrations in CCA (0.96 +/- 0.16) indicated mainly laminar flow and in CB (0.83 +/- 0.07) indicated mainly turbulence. Both methods were thus able to clearly distinguish the flow patterns of CCA and CB in systole. Vector concentration from angle-independent vector velocity estimates is a quantitative index, which is simple to calculate and can differentiate between laminar and complex flow. (C) 2014 World Federation for Ultrasound in Medicine & Biology.
Performance evaluation of compounding and directional beamforming techniques for carotid strain imaging using plane wave transmissions

Carotid strain imaging in 3D is not possible with conventional focused imaging, because the frame rate is too low. Plane wave ultrasound provides sufficiently high frame rates, albeit at the cost of image quality, especially in the off-axis direction due to the lack of focusing. Multiple techniques have been developed to cope with the low off-axis image quality when performing 2D (and in future 3D) motion estimation: cross correlation with directional beamforming (with or without RF (coherent) compounding) and displacement compounding. This study compares the precision of these techniques using linear array ultrasound data of a pulsating concentric homogeneous artery simulated using Field II. The transducer (f_c = 9 MHz, pitch = 197.9 μm, 192 elements, f_s = 180 MHz) transmitted plane waves at 3 sequentially alternating angles (0°, +θ, -θ) at a PRF of 2 kHz. Simulations were repeated for θ ranging from 1° to 20° with increments of 1°. Displacements were estimated for frame intervals of 1/15th s, tracked, and cumulated from diastole to systole using either displacement compounding, or directional beamforming optionally enhanced by RF compounding. 1D directional beamforming with RF compounding and 2D displacement compounding with θ ≈ 20° performed equally and best with a relative root-mean-squared error of ~2% with respect to the analytical solution. The mean and standard deviation of the estimated motion direction for 2D displacement compounding with θ = 20° was 0.03° ± 1.43°. Since displacement compounding requires no assumptions regarding the motion direction, this technique seems the best option for plane wave carotid strain imaging.

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Rapid Measurements of Intensities for Safety Assessment of Advanced Imaging Sequences
FDA requires that intensity and safety parameters are measured for all imaging schemes for clinical imaging. This is often cumbersome, since the scan sequence has to be broken apart, measurements conducted for the individually emitted beams, and the nal intensity levels calculated by combining the intensities from the individual beams. This paper suggests a fast measurement scheme using the multi-line sampling capability of modern scanners and research systems. The hydrophone is connected to one sampling channel in the research system, and the intensity is measured for all imaging lines in one emission sequence. This makes it possible to map out the pressure eld and hence intensity level for all imaging lines in a single measurement. The approach has several advantages: the scanner does not have to be re-programmed and can use the scan sequence without modication. The measurements are orders of magnitude faster (minutes rather than hours) and the nal intensity level calculation can be made generic and reused for any kind of scan sequence by just knowing the number of imaging lines and the pulse repetition time. The scheme has been implemented on the Acoustic Intensity Measurement System AIMS III (Onda, Sunnyvale, California, USA). The research scanner SARUS is used for the experiments, where one of the channels is used for the hydrophone signal. A 3 MHz BK 8820e (BK Medical, Herlev, Denmark) convex array with 192 elements is used along with an Onda HFL-0400 hydrophone connected to a AH-2010 pre-amplier (Onda Corporation, Sunnyvale, USA). A single emission sequence is employed for testing and calibrating the approach. The measurements using the AIMS III and SARUS systems after calibration agree within a relative standard deviation of 0.24%. A duplex B-mode and ow sequence is also investigated. The complex intensity map is measured and the time averaged spatial peak intensity is found. A single point measurement takes 3.43 seconds and the whole sequence can be characterized on the acoustical axis in around 6 minutes.
Real-Time GPU Implementation of Transverse Oscillation Vector Velocity Flow Imaging

Rapid estimation of blood velocity and visualization of complex flow patterns are important for clinical use of diagnostic ultrasound. This paper presents real-time processing for two-dimensional (2-D) vector flow imaging which utilizes an off-the-shelf graphics processing unit (GPU). In this work, Open Computing Language (OpenCL) is used to estimate 2-D vector velocity flow in vivo in the carotid artery. Data are streamed live from a BK Medical 2202 Pro Focus UltraView Scanner to a workstation running a research interface software platform. Processing data from a 50 millisecond frame of a duplex vector flow acquisition takes 2.3 milliseconds seconds on an Advanced Micro Devices Radeon HD 7850 GPU card. The detected velocities are accurate to within the precision limit of the output format of the display routine. Because this tool was developed as a module external to the scanner’s built-in processing, it enables new opportunities for prototyping novel algorithms, optimizing processing parameters, and accelerating the path from development lab to clinic.

Row-Column Addressed 2-D CMUT Arrays with Integrated Apodization

Experimental results from row-column addressed capacitive micromachined ultrasonic transducers (CMUTs) with integrated apodization are presented. The apodization is supplied by varying the density of CMUT cells in the array with the objective of damping the edge waves originating from the element ends. Two row-column addressed 32×32 CMUT arrays are produced using a wafer-bonding technique, one with and one without integrated apodization. Hydrophone measurements of the emitted pressure field from the array with integrated apodization show a reduction in edge wave energy of 8.4 dB (85 %) compared to the array without integrated apodization. Field II simulations yield a corresponding reduction of 13.0 dB (95 %). The simulations are able to replicate the measured pressure field, proving the predictability of the technique.
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**Simulation and Efficient Measurements of Intensities for Complex Imaging Sequences**

It is investigated how linear simulation can be used to predict both the magnitude of the intensities as well as the placement of the peak values. An ultrasound sequence is defined through the normal setup routines for the experimental SARUS scanner, and Field II is then used automatically on the sequence to simulate both intensity and mechanical index (MI) according to FDA rules. A 3 MHz BK Medical 8820e convex array transducer is used with the SARUS scanner. An Onda HFL-0400 hydrophone and the Onda AIMS III system measures the pressure field for three imaging schemes: a fixed focus, single emission scheme, a duplex vector flow scheme, and finally a vector flow imaging scheme. The hydrophone is connected to a receive channel in SARUS, which automatically measures the emitted pressure for the complete imaging sequence. MI can be predicted with an accuracy of 16.4 to 38 %. The accuracy for the intensity is from -17.6 to 9.7 %, although the measured fields are highly non-linear (several MPa) and linear simulation is used. Linear simulation can, thus, be used to accurately predict intensity levels for any advanced imaging sequence and is an efficient tool in predicting the energy distribution.

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Simulation Study of Real Time 3-D Synthetic Aperture Sequential Beamforming for Ultrasound Imaging

This paper presents a new beamforming method for real-time three-dimensional (3-D) ultrasound imaging using a 2-D matrix transducer. To obtain images with sufficient resolution and contrast, several thousand elements are needed. The proposed method reduces the required channel count from the transducer to the main imaging system, by including electronics in the transducer handle. The reduction of element channel count is achieved using a sequential beamforming scheme. The beamforming scheme is a combination of a fixed focus beamformer in the transducer and a second dynamic focus beamformer in the main system. The real-time imaging capability is achieved using a synthetic aperture beamforming technique, utilizing the transmit events to generate a set of virtual elements that in combination can generate an image. The two core capabilities in combination is named Synthetic Aperture Sequential Beamforming (SASB). Simulations are performed to evaluate the image quality of the presented method in comparison to Parallel beamforming utilizing 16 receive beamformers. As indicators for image quality the detail resolution and Cystic resolution are determined for a set of scatterers at a depth of 90mm for elevation and azimuth angles from 0 to 25. Simulations show that the acoustic performance of the proposed method is less angle dependent than Parallel beamforming. The Cystic resolution is shown to be more than 50% improved, with a detail resolution on the same order as Parallel Beamforming.

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Synthetic Aperture Sequential Beamforming implemented on multi-core platforms

This paper compares several computational approaches to Synthetic Aperture Sequential Beamforming (SASB) targeting consumer level parallel processors such as multi-core CPUs and GPUs. The proposed implementations demonstrate that ultrasound imaging using SASB can be executed in real-time with a significant headroom for post-processing. The CPU implementations are optimized using Single Instruction Multiple Data (SIMD) instruction extensions and multithreading, and the GPU computations are performed using the APIs, OpenCL and OpenGL. The implementations include refocusing (dynamic focusing) of a set of fixed focused scan lines received from a BK Medical UltraView 800 scanner and subsequent image processing for B-mode imaging and rendering to screen. The benchmarking is performed using a clinically evaluated imaging setup consisting of 269 scan lines x 1472 complex samples (1.58 MB per frame, 16 frames per second) on an Intel Core i7 2600 CPU with an AMD HD7850 and a NVIDIA GTX680 GPU. The fastest CPU and GPU implementations use 14% and 1.3% of the real-time budget of 62 ms/frame, respectively. The maximum achieved processing rate is 1265 frames/s.

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Thermal Oxidation of Structured Silicon Dioxide

The topography of thermally oxidized, structured silicon dioxide is investigated through simulations, atomic force microscopy, and a proposed analytical model. A 357 nm thick oxide is structured by removing regions of the oxide in a masked etch with either reactive ion etching or hydrofluoric acid. Subsequent thermal oxidation is performed in both dry and wet ambients in the temperature range 950°C to 1100°C growing a 205 ± 12 nm thick oxide in the etched mask windows. Lifting of the original oxide near the edge of the mask in the range 6 nm to 37 nm is seen with increased lifting for increasing processing temperatures. Oxides structured by reactive ion etching are lifted on average a factor of four more than oxides etched in hydrofluoric acid. Both simulations and the analytical model successfully predict the oxide topography qualitatively, showing that the mask lifting phenomenon is governed mainly by diffusion and the geometry of the oxide. Simulations also predict the oxide topography quantitatively, with an average root mean square deviation of 1.2 nm and a maximum deviation of 13 nm (39%) from the mean of the measured values.

Tissue Harmonic Synthetic Aperture Ultrasound Imaging

Synthetic aperture sequential beamforming (SASB) and tissue harmonic imaging (THI) are combined to improve the image quality of medical ultrasound imaging. The technique is evaluated in a comparative study against dynamic receive focusing (DRF). The objective is to investigate if SASB combined with THI improves the image quality compared to DRF-THI. The major benefit of SASB is a reduced bandwidth between the probe and processing unit. A BK Medical 2202
Ultraview ultrasound scanner was used to acquire beamformed RF data for one evaluation. The acquisition was made interleaved between methods, and data were recorded with and without pulse inversion for tissue harmonic imaging. Data were acquired using a Sound Technology 192 element convex array transducer from both a wire phantom and a tissue mimicking phantom to investigate spatial resolution and penetration. In-vivo scans were also performed for a visual comparison. The spatial resolution for SASB-THI is on average 19% better than DRI-THI, and the investigation of penetration showed equally good signal-to-noise ratio. In-vivo B-mode scans were made and compared. The comparison showed that SASB-THI reduces the artefact and noise interference and improves image contrast and spatial resolution.

**General information**

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Research output: Contribution to journal › Journal article – Annual report year: 2014 › Research › peer-review

**Transverse Spectral Velocity Estimation**

A transverse oscillation (TO)-based method for calculating the velocity spectrum for fully transverse flow is described. Current methods yield the mean velocity at one position, whereas the new method reveals the transverse velocity spectrum as a function of time at one spatial location. A convex array probe is used along with two different estimators based on the correlation of the received signal. They can estimate the velocity spectrum as a function of time as for ordinary spectrograms, but they also work at a beam-to-flow angle of 90°. The approach is validated using simulations of pulsatile flow using the Womersley–Evans flow model. The relative bias of the mean estimated frequency is 13.6% and the mean relative standard deviation is 14.3% at 90°, where a traditional estimator yields zero velocity. Measurements have been conducted with an experimental scanner and a convex array transducer. A pump generated artificial femoral and carotid artery flow in the phantom. The estimated spectra degrade when the angle is different from 90°, but are usable down to 60° to 70°. Below this angle the traditional spectrum is best and should be used. The conventional approach can automatically be corrected for angles from 0° to 70° to give fully quantitative velocity spectra without operator intervention.

**General information**

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**Publication information**

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Volume: 61
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BFI (2014): BFI-level 2
Ultrasound Evaluation of an Abdominal Aortic Fluid-Structure Interaction Model

Ultrasound measurements are used for evaluating biomechanics of the abdominal aorta (AA) predicted by a fluid-structure interaction (FSI) simulation model. FSI simulation models describe the complete arterial physiology by quantifying the mechanical response in the vessel wall caused by the percolating pulsating blood. But the predictability of FSI models needs validation for these to be usable for diagnostic purposes. Ultrasound measurements are suitable for such an evaluation as the wall displacement can be measured in vivo and compared to the wall displacement simulated in the FSI model. Spectral Doppler velocity data from 3 healthy male volunteers were used to construct inlet profiles for the FSI model. Simultaneously, wall movement was tracked and used for comparison to FSI model results. Ultrasound data were acquired using a scanner equipped with a research interface. The wall displacement was estimated by time shift estimation obtained from cross-correlation of signals to a fixed reference. The FSI model was constructed as a 2D axisymmetric pipe with lumen diameter predicted by B-mode images from each volunteer. Visual comparison of wall displacement over 1 cardiac cycle show agreement except for 1 volunteer (Male, 23 yrs.). The magnitude of the displacement in simulation, \( u_{\text{fsi}} \), and in vivo, \( u_{\text{iv}} \), is within the same order of magnitude for the young (\( u_{\text{iv}} = 1:48 \) mm, \( u_{\text{fsi}} = 1:12 \) mm) and middle-aged volunteer (\( u_{\text{iv}} = 0:783 \) mm, \( u_{\text{fsi}} = 1:31 \) mm). For the elderly volunteer the simulated displacement (\( u_{\text{fsi}} = 0:975 \) 10

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Source-ID: 99358073
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2014 › Research › peer-review

Volume Flow in Arteriovenous Fistulas Using Vector Velocity Ultrasound

Volume flow in arteriovenous fistulas for hemodialysis was measured using the angle-independent ultrasound technique Vector Flow Imaging and compared with flow measurements using the ultrasound dilution technique during dialysis. Using an UltraView 800 ultrasound scanner (BK Medical, Herlev, Denmark) with a linear transducer, 20 arteriovenous fistulas were scanned directly on the most superficial part of the fistula just before dialysis. Vector Flow Imaging volume flow was estimated with two different approaches, using the maximum and the average flow velocities detected in the fistula. Flow was estimated to be 242 mL/min and 404 mL/min lower than the ultrasound dilution technique estimate, depending on the approach. The standard deviations of the two Vector Flow Imaging approaches were 175.9 mL/min and 164.8 mL/min compared with a standard deviation of 136.9 mL/min using the ultrasound dilution technique. The study supports that Vector Flow Imaging is applicable for volume flow measurements.

General information
Publication status: Published
Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging, Copenhagen University Hospital, University of Copenhagen
Three dimensional (3d) transverse oscillation vector velocity ultrasound imaging.

An ultrasound imaging system (300) includes a transducer array (302) with a two-dimensional array of transducer elements configured to transmit an ultrasound signal and receive echoes, transmit circuitry (304) configured to control the transducer array to transmit the ultrasound signal so as to traverse a field of view, and receive circuitry (306) configured to receive a two dimensional set of echoes produced in response to the ultrasound signal traversing structure in the field of view, wherein the structure includes flowing structures such as flowing blood cells, organ cells etc. A beamformer (312) configured to beamform the echoes, and a velocity processor (314) configured to separately determine a depth velocity component, a transverse velocity component and an elevation velocity component, wherein the velocity components are determined based on the same transmitted ultrasound signal and the same received set of two dimensional echoes form part of the imaging system.

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Contributors: Jensen, J. A., Pihl, M. J.
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2-D Row-Column CMUT Arrays with an Open-Grid Support Structure

Fabrication and characterization of 64 x 64 2-D row-column addressed CMUT arrays with 250 μm element pitch and 4.4 MHz center frequency in air incorporating a new design approach is presented. The arrays are comprised of two wafer bonded, structured silicon-on-insulator wafers featuring an opengrid support structure on top of the CMUT plates, omitting the need for through wafer vias. A 5 mask process is used to produce 2-D row-column addressed CMUT arrays with 74 nm vacuum gaps, single crystalline silicon plates with optional lithographically defined mass loads, 120 V pull-in voltage, and high voltage insulation up to 310 V.
3-D Ultrasound Imaging Performance of a Row-Column Addressed 2-D Array Transducer: A Measurement Study

A real-time 3-D ultrasound measurement using only 32 elements and 32 emissions is presented. The imaging quality is compared to a conventionally fully addressed array using 1024 elements and 256 emissions. The main-lobe of the measured line spread function is almost identical, but the side-lobe levels are higher for the row-column addressed array. The cystic resolution sampled at a relative intensity difference of 20 dB shows a cyst size of 5.00mm for the row-column addressed array and 2.39mm for the fully sampled array. A simulation study is carried out which compares how the imaging quality of the two addressing methods scales with the number of beamforming channels used. It is shown that for any fixed number of active elements, a row-column addressed array achieves a better image quality than fully addressing the array. When using 128 channels, the main-lobe when fully addressing the array is 510% larger than when row-column addressing the array. The cyst radius needed to achieve -20 dB intensity in the cyst is 396% larger for the fully addressed array compared to the row-column addressed array. The measurements were made using the experimental ultrasound scanner SARUS and a 32x32 element ultrasound probe made by Vermon S.A.

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10.1109/ULTSYM.2013.0370
Source: dtu
Source-ID: u::8251
Research output: Chapter in Book/Report/Conference proceeding > Article in proceedings – Annual report year: 2013 > Research > peer-review

3D ultrasound imaging performance of a row-column addressed 2D array transducer: a simulation study

This paper compares the imaging performance of a 128x128 element row-column addressed array with a fully addressed 1616 2D array. The comparison is made via simulations of the point spread function with Field II. Both arrays have lambda-pitch, a center frequency of 3.5MHz and use 256 active elements. The row-column addressed array uses 128 transmit channels and 128 receive channels, whereas the fully addressed array uses 256 channels in both transmit and receive. The large size of the emulated row and column elements in the row-column addressed array causes ghost echoes to appear. The ghost echoes are shown to be suppressed when the sub-elements within each of the emulated row
and column elements are apodized. The maximum ghost intensity is suppressed by 22.2 dB compared to using no apodization. With apodization applied, the full-width-at-half-maximum in the lateral direction for the fully addressed array is 2.81mm, and 1.01mm for the row-column addressed array. This shows that the detail resolution can be more than doubled using the row-column addressed array instead of the fully addressed array. The row column addressed array achieves a R20 dB cystic resolution of 0.76mm, compared to 3.16mm for the fully addressed array. The significantly smaller R20 dB-value for the row-column addressed array indicates that it can achieve a much higher contrast resolution than the fully addressed array.

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Contributors: Rasmussen, M. F., Jensen, J. A.
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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2013 › Research › peer-review

**A Delta-Sigma beamformer with integrated apodization**
This paper presents a new design of a discrete time Delta-Sigma (ΔΣ) oversampled ultrasound beamformer which integrates individual channel apodization by means of variable feedback voltage in the Delta-Sigma analog to digital (A/D) converters. The output bit-width of each oversampled A/D converter remains the same as in an unmodified one. The outputs of all receiving channels are delayed and summed, and the resulting multi-bit sample stream is filtered and decimated to become an image line. The simplicity of this beamformer allows the production of high-channel-count or very compact beamformers suitable for 2-D arrays or compact portable scanners. The new design is evaluated using measured data from the research scanner SARUS and a BK-8811 192 element linear array transducer (BK Medical, Herlev, Denmark), insonifying a water-filled wire phantom containing four wires orthogonal to the image plane. The data are acquired using 12-bit flash A/D converters at a sampling rate of 70 MHz, and are then upsampled off-line to 560 MHz for input to the simulated ΔΣ beamformer. The latter generates a B-mode image which is compared to that produced by a digital beamformer that uses 10-bit A/D converters. The performance is evaluated by comparing the width of the wire images at half amplitude and the noise level of the images. The ΔΣ beamformer resolution has been found to be identical to that of the multi-bit A/D beamforming architecture, while the noise floor is elevated by approximately 6 dB.

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Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging
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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2013 › Research › peer-review
Fast simulation of non-linear pulsed ultrasound fields using an angular spectrum approach

A fast non-linear pulsed ultrasound field simulation is presented. It is implemented based on an angular spectrum approach (ASA), which analytically solves the non-linear wave equation. The ASA solution to the Westervelt equation is derived in detail. The calculation speed is significantly increased compared to a numerical solution using an operator splitting method (OSM). The ASA has been modified and extended to pulsed non-linear ultrasound fields in combination with Field II, where any array transducer with arbitrary geometry, excitation, focusing and apodization can be simulated. The accuracy of the non-linear ASA is compared to the non-linear simulation program – Abersim, which is a numerical solution to the Burgers equation based on the OSM. Simulations are performed for a linear array transducer with 64 active elements, focus at 40 mm, and excitation by a 2-cycle sine wave with a center frequency of 5 MHz. The speed is increased approximately by a factor of 140 and the calculation time is 12 min with a standard PC, when simulating the second harmonic pulse at the focal point. For the second harmonic point spread function the full width error is 1.5% at 6 dB and 6.4% at 12 dB compared to Abersim.

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Web of Science (2013): Impact factor 1.805
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
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Research output: Contribution to journal › Journal article – Annual report year: 2013 › Research › peer-review

High frame rate synthetic aperture duplex imaging

Conventional color flow images are limited in velocity range and can either show the high velocities in systole or be optimized for the lower diastolic velocities. The full dynamics of the flow is, thus, hard to visualize. The dynamic range can be significantly increased by employing synthetic aperture flow imaging as demonstrated in this paper. Synthetic aperture, directional beamforming, and cross-correlation are used to produce B-mode and vector velocity images at high frame rates. The frame rate equals the effective pulse repetition frequency of each imaging mode. Emissions for making the B-mode images and velocity maps are interleaved in a 1-to-1 ratio. This provides continuous data allowing a wide range of velocities to be estimated. Two cases are considered in the flow estimation: In the first case, the angle of the flow is determined from the B-mode image. In the other case, the angle is determined by estimating the flow velocity in all directions and choosing the one with the strongest correlation. The method works for all angles, including fully axial and fully transverse flows. Field II simulations with a 192 element, 7 MHz linear array are made of laminar, transverse flow profiles. For a simulated peak velocity of 0.5 m/s, the relative bias is −6.8% and the relative standard deviation is 6.1%. The bias on the angle is 0.98 degrees with a standard deviation of 2.39 degrees when using the flow estimator to determine the angle. For a peak velocity of 0.05 m/s, the relative bias of the velocity estimation is −1.8% and the relative standard deviation 5.4%. The approach can thus estimate both high and low velocities with equal accuracy and thereby makes it possible to present vector flow images with a high dynamic range. Measurements are made using the SARUS research scanner, a linear array transducer similar to the simulated one, and a recirculating flow rig with a blood mimicking fluid and a parabolic flow profile with a peak velocity of approximately 0.3 m/s. The relative bias of the velocity estimation is 0.19% and the mean relative standard deviation 4.9%. For the direction estimation, the bias is 3.2 degrees with a standard deviation of 1.6 degrees.

General information
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Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging
Internal strain estimation for quantification of human heel pad elastic modulus: A phantom study

Shock absorption is the most important function of the human heel pad. However, changes in heel pad elasticity, as seen in e.g. long-distance runners, diabetes patients, and victims of Falanga torture are affecting this function, often in a painful manner. Assessment of heel pad elasticity is usually based on one or a few strain measurements obtained by an external load-deformation system. The aim of this study was to develop a technique for quantitative measurements of heel pad elastic modulus based on several internal strain measures from within the heel pad by use of ultrasound images. Nine heel phantoms were manufactured featuring a combination of three heel pad stiffnesses and three heel pad thicknesses to model the normal human variation. Each phantom was tested in an indentation system comprising a 7MHz linear array ultrasound transducer, working as the indentor, and a connected load cell. Load-compression data and ultrasound B-mode images were simultaneously acquired in 19 compression steps of 0.1mm each. The internal tissue displacement was for each step calculated by a phase-based cross-correlation technique and internal strain maps were derived from these displacement maps. Elastic moduli were found from the resulting stress–strain curves. The elastic moduli made it possible to distinguish eight of nine phantoms from each other according to the manufactured stiffness and showed very little dependence of the thickness. Mean elastic moduli for the three soft, the three medium, and the three hard phantoms were 89kPa, 153kPa, and 168kPa, respectively. The combination of ultrasound images and force measurements provided an effective way of assessing the elastic properties of the heel pad due to the internal strain estimation.

General information

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Research output: Contribution to journal › Journal article – Annual report year: 2013 › Research › peer-review
Inter-operator Variability in Defining Uterine Position Using Three-dimensional Ultrasound Imaging

In radiotherapy the treatment outcome of gynecological (GYN) cancer patients is crucially related to reproducibility of the actual uterine position. The purpose of this study is to evaluate the inter-operator variability in addressing uterine position using a novel 3-D ultrasound (US) system. The study is initiated by US-scanning of a uterine phantom (CIRS 404, Universal Medical, Norwood, USA) by seven experienced US operators. The phantom represents a female pelvic region, containing a uterus, bladder and rectal landmarks readily definable in the acquired US-scans. The organs are subjected to displacement by applied operator-pressure that mimics an actual GYN patient. The transabdominal scanning was performed using a 3D-US system (Clarity® Model 310C00, Elekta, Montreal, Canada). It consists of a US-acquisition-station, workstation, and a 128- element 1D array curved probe. The iterated US-scans were performed in four subsequent sessions (totally 21 US-scans) in a period of four weeks to investigate the randomness of the inter-operator variability. An additionally US-scan was performed as a reference target volume to the consecutive scans. At first, the phantom was marked with ball bearings for daily laser alignment. In each session the US-scans were acquired by the seven operators. The uterus was outlined in each of the US imagesets using Clarity autosegmentation in the workstation. Further, the shifts in the uterine centre of mass relative to the reference were measured for the three orthogonal directions; left (+)-right (LR), anterior (+)-posterior (AP), and inferior (+)-superior (IS), respectively. The same operator delineated the target volumes. The average inter-operator deviation ±1SD of the daily US scans was (in mm); LR: day 1 (-0.4±0.9), day 2 (-0.3±0.6), day 3 (-1.0±1.2), day 4 (1.3±0.5); AP: day 1 (0.0±1.7), day 2 (0.1±0.7), day 3 (-1.0±0.9), day 4 (0.2±1.2); IS: day 1 (-1.5±2.6), day 2 (0.1±1.8), day 3 (0.1±1.1), day 4 (0.5±3.1), respectively. The largest inter-operator discordance was observed to be 4.7 mm in the IS-direction in day 4. Published studies report significantly larger inter-fractional uterine positional displacement, in some cases up to 20 mm, which outweighs the magnitude of current inter-operator variations. Thus, the current US-phantom-study suggests that the inter-operator variability in addressing uterine position is clinically irrelevant.

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Contributors: Baker, M., Jensen, J. A., Behrens, C. F.
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Intraoperative Cardiac Ultrasound Examination Using Vector Flow Imaging

Conventional ultrasound (US) methods for blood velocity estimation only provide onedimensional and angle-dependent velocity estimates; thus, the complexity of cardiac flow has been difficult to measure. To circumvent these limitations, the Transverse Oscillation (TO) vector flow method has been proposed. The vector flow method implemented on a Commercial scanner provided real-time, angle-independent estimates of cardiac blood flow. Epicardiac and epiaortic, intraoperative US examinations were performed on three patients with stenosed coronary arteries scheduled for bypass surgery. Repeating cyclic beat-to-beat flow patterns were seen in the ascending aorta and pulmonary artery of each patient, but these patterns varied between patients. Early systolic retrograde flow filling the aortic sinuses was seen in the ascending aorta as well as early systolic retrograde flow in the pulmonary artery. In diastole, stable vortices in aortic sinuses of the ascending aorta created central antegrade flow. A stable vortex in the right atrium was seen during the entire heart cycle. The measurements were compared with estimates obtained intraoperatively with conventional spectral Doppler US using a transesophageal and an epiaortic approach. Mean differences in peak systole velocity of 11% and 26% were observed when TO was compared with transesophageal echocardiography and epiaortic US, respectively. In one patient, the cardiac output derived from vector velocities was compared with pulmonary artery catheter thermodilution technique and showed a difference of 16%. Vector flow provides real-time, angle-independent vector velocities of cardiac blood flow. The technique can potentially reveal new information of cardiovascular physiology and give insight into blood flow dynamics.

General information
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Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging, Copenhagen University Hospital
Intraoperative Vector Flow Imaging of the Heart

The cardiac flow is complex and multidirectional, and difficult to measure with conventional Doppler ultrasound (US) methods due to the one-dimensional and angle-dependent velocity estimation. The vector velocity method Transverse Oscillation (TO) has been proposed as a solution to this. TO is implemented on a conventional US scanner (Pro Focus 2202 UltraView, BK Medical) using a linear transducer (8670, BK Medical) and can provide real-time, angle-independent vector velocity estimates of the cardiac blood flow. During cardiac surgery, epicardiac US examinations using TO were performed on three patients. Antegrade central jet and retrograde flow near the vessel wall in the ascending aorta and the pulmonary artery were seen during systole, while stable vortices were seen in the aortic sinuses and complex flow patterns were seen around the valves during diastole. In the right atrium, a stable vortex was seen during the entire heart cycle. For comparison, simultaneous Measurements were obtained with conventional spectral Doppler (SD) and intravenous catheter thermodilution technique (TD). Peak systolic velocities were underestimated by 18% compared to SD and cardiac output was underestimated by 16% compared to TD. This is the first time TO measurements have been obtained of cardiac flow. TO can potentially reveal new information of cardiovascular physiology and blood flow dynamics, and become a valuable tool in cardiology.
Investigation of an angular spectrum approach for pulsed ultrasound fields
An Angular Spectrum Approach (ASA) is formulated and employed to simulate linear pulsed ultrasound fields for high bandwidth signals. Ageometrically focused piston transducer is used as the acoustic source. Signals are cross-correlated to find the true sound speed during the measurement to make the simulated and measured pulses in phase for comparisons. The calculated sound speed in the measurement is varied between 1487.45 m/s and 1487.75 m/s by using different initial values in the ASA simulation. Results from the pulsed ASA simulation using both Field II simulated and hydrophone measured acoustic sources are compared to the Field II simulated and hydrophone measured pulses, respectively. The total relative root mean square (RMS) errors of the pulsed ASA are investigated by using different time-point, zero-padding factors, spatial sampling interval and temporal sampling frequency in the simulation. Optimal parameters for the ASA are found in the simulation. The RMS error of the ASA simulation is reduced from 10.9% to 2.4% for the optimal parameters when comparing to Field II simulation. The comparison between the ASA calculated and measured pulses are illustrated and the corresponding RMS error is 25.4%.

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ISI indexed (2013): ISI indexed yes
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Source: dtu
Source-ID: u::7404
Research output: Contribution to journal & Journal article – Annual report year: 2013 & Research & peer-review

In Vivo Three-Dimensional Velocity Vector Imaging and Volumetric Flow Rate Measurements
The three-dimensional (3-D) Transverse Oscillation (TO) method is used to obtain 3-D velocity vector estimates in two orthogonal planes. The method is suitable for a real-time implementation. Data are acquired using a Vermon 3.0 MHz 32x32 element 2-D phased array and the experimental ultrasound scanner SARUS. Measurements are conducted on a carotid artery flow phantom from Danish Phantom Design, and 20 frames are acquired with a constant flow rate of 16.7±0.17 mL/s provided by a Shelley Medical Imaging Technologies CompuFlow 1000 system. The peak velocity magnitude in the vessel is found to be 52.3±8.1 m/s compared to an expected peak velocity of 53.6±0.54 cm/s. Based on the out-of-plane velocity component in the cross-sectional plane, the estimated volumetric flow rates are 17.1±1.4 mL/s. The coefficient of variation is 8.3%, and the bias is 2.2%. An in vivo measurement of 3-D M-mode velocities is conducted over five heartbeats. The peak systolic and end-diastolic velocities are 69±5.4 cm/s and 7.9±5.5 cm/s at the center of the vessel. For comparison, a commercial BK Medical ultrasound scanner using the spectral estimator yields 71.2 cm/s and 7.70 cm/s, respectively. The results demonstrate that the 3-D TO method can estimate 3-D velocities in two crossed planes, volumetric flow rates, and 3-D velocities in vivo.

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Contributors: Pihl, M. J., Stuart, M. B., Tomov, B. G., Hansen, P. M., Nielsen, M. B., Jensen, J. A.
Modeling and Measurements of CMUTs with Square Anisotropic Plates

The conventional method of modeling CMUTs uses the isotropic plate equation to calculate the deflection, leading to deviations from FEM simulations including anisotropic effects of around 10% in center deflection. In this paper, the deflection is found for square plates using the full anisotropic plate equation and the Galerkin method. Utilizing the symmetry of the silicon crystal, a compact and accurate expression for the deflection can be obtained. The deviation from FEM in center deflection is <0.1%. The deflection was measured on fabricated CMUTs using a white light interferometer. Fitting the anisotropic calculated deflection to the measurement a deviation of 0.5-1.5% is seen for the fitted values. Finally it was also measured how the device behaved under increasing bias voltage and it is observed that the model including anisotropic effects is within the uncertainty interval of the measurements.

New Developments in Vector Velocity Imaging using the Transverse Oscillation Approach

Vector velocity imaging using the Transverse Oscillation (TO) approach has recently been FDA approved for linear array transducers on a commercial platform. It can now be used clinically for studying the complex flow at e.g. bifurcations, valves, and the heart in real time. Several clinical examples from venous flow to rotational flow in the heart will be shown. The technique is also being further developed and adapted for convex and phased array probes, for spectral velocity estimation, pressure estimation, and for three dimensional velocity tensor imaging. It is shown how the methods are optimized using Field II simulations along with several examples of their performance.
Non-invasive Measurement of Pressure Gradients in Pulsatile Flow using Ultrasound

This paper demonstrates how pressure gradients in a pulsatile flow environment can be measured non-invasively using ultrasound. The proposed method relies on vector velocity fields acquired from ultrasound data. 2-D flow data are acquired at 18-23 frames/sec using the Transverse Oscillation approach. Pressure gradients are calculated from the measured velocity fields using the Navier-Stokes equation. Velocity fields are measured during constant and pulsating flow on a carotid bifurcation phantom and on a common carotid artery in-vivo. Scanning is performed with a 5 MHz BK8670 linear transducer using a BK Medical 2202 UltraView Pro Focus scanner. The calculated pressure gradients are validated through a finite element simulation of the constant flow model. The geometry of the flow simulation model is reproduced using MRI data, thereby providing identical flow domains in measurement and simulation. The proposed method managed to estimate pressure gradients that varied from 0 kPa/m–7 kPa/m during constant flow and from 0 kPa/m–200 kPa/m in the pulsatile flow environments. The estimator showed, in comparison to the simulation model, a bias of -9% and -8% given in reference to the peak gradient for the axial and lateral gradient component, respectively.

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Non-invasive measurement of pressure gradients using ultrasound

A non-invasive method for estimating 2-D pressure gradients from ultrasound vector velocity data is presented. The method relies on in-plane vector velocity fields acquired using the Transverse Oscillation method. The pressure gradients are estimated by applying the Navier-Stokes equations for isotropic fluids to the estimated velocity fields. The velocity fields were measured for a steady flow on a carotid bifurcation phantom (Shelley Medical, Canada) with a 70% constriction on the internal branch. Scanning was performed with a BK8670 linear transducer (BK Medical, Denmark) connected to a BK Medical 2202 UltraView Pro Focus scanner. The results are validated through finite element simulations of the carotid flow model where the geometry is determined from MR images. This proof of concept study was conducted at nine ultrasound frames per second. Estimated pressure gradients along the longitudinal direction of the constriction varied from 0 kPa/m to 10 kPa/m with a normalized bias of -9.1% for the axial component and -7.9% for the lateral component. The relative standard deviation of the estimator, given in reference to the peak gradient, was 28.4% in the axial direction and 64.5% in the lateral direction. A study made across the constriction was also conducted. This yielded magnitudes from 0 kPa/m to 7 kPa/m with a normalized bias of -5.7% and 13.9% for the axial and lateral component, respectively. The relative standard deviations of this study were 45.2% and 83.2% in the axial and lateral direction, respectively.

General information
Optimization of Transverse Oscillating Fields for Vector Velocity Estimation with Convex Arrays

A method for making Vector Flow Images using the transverse oscillation (TO) approach on a convex array is presented. The paper presents optimization schemes for TO fields for convex probes and evaluates their performance using Field II simulations and measurements using the SARUS experimental scanner. A 3 MHz 192 elements convex array probe (pitch 0.33 mm) is used in both simulations and measurements. An F-number of 5 is used in transmit and two 32 element wide peaks are used in receive separated by 96 elements between peaks. Parabolic velocity profiles are simulated at beam-to-flow angles from 90 to 45 degrees in steps of 15 degrees. The optimization routine changes the lateral oscillation period lx to yield the best possible estimates based on the energy ratio between positive and negative spatial frequencies in the ultrasound field. The basic equation for lx gives 1.14 mm at 40 mm, and 1.51 mm from the simulated point spread function. This results in a bias of 35% as lx directly scales the estimated velocities. Optimizing the focusing yields a lx of 1.61 mm. The energy ratio is reduced from -12.8 dB to -20.1 dB and the spectral bandwidth from 115.1 m⁻¹ to 96.5 m⁻¹. lx is maintained between 1.47 and 1.70 mm from 25 mm to 70 mm and is increased to 2.8 mm at a depth of 100 mm. Parabolic profiles are estimated using 16 missions. The optimization gives a reduction in std. from 8.5% to 5.9% with a reduction in bias from 35% to 1.02% at 90 degrees (transverse flow) at a depth of 40 mm. Measurements have been made using the SARUS experimental ultrasound scanner and a BK Medical 8820e convex array transducer. Sixty-four elements was used in transmit and 2 x 32 elements in receive for creating a color flow map image of a flow rig phantom with a laminar, parabolic flow. At 75 degrees a bias of less than 1% was obtained.

Preliminary examples of 3D vector flow imaging

This paper presents 3D vector flow images obtained using the 3D Transverse Oscillation (TO) method. The method employs a 2D transducer and estimates the three velocity components simultaneously, which is important for visualizing complex flow patterns. Data are acquired using the experimental ultrasound scanner SARUS on a flow rig system with steady flow. The vessel of the flow-rig is centered at a depth of 30 mm, and the flow has an expected 2D circular-
symmetric parabolic profile with a peak velocity of 1 m/s. Ten frames of 3D vector flow images are acquired in a cross-sectional plane orthogonal to the center axis of the vessel, which coincides with the y-axis and the flow direction. Hence, only out-of-plane motion is expected. This motion cannot be measured by typical commercial scanners employing 1D arrays. Each frame consists of 16 flow lines steered from -15 to 15 degrees in steps of 2 degrees in the ZX-plane. For the center line, 3200 M-mode lines are acquired yielding 100 velocity profiles. At the center of the vessel, the mean and standard deviation of the estimated velocity vectors are (vx, vy, vz) = (-0.026, 95, 1.0) (8.8, 6.2, 0.84) cm/s compared to the expected (0.0, 96, 0.0) cm/s. Relative to the velocity magnitude this yields standard deviations of (9.1, 6.4, 0.88) %, respectively. Volumetric flow rates were estimated for all ten frames yielding 57.92 ± 20 mL/s in comparison with 56.2 mL/s measured by a commercial magnetic flow meter. One frame of the obtained 3D vector flow data is presented and visualized using three alternative approaches. Practically no in-plane motion (vx and vz) is measured, whereas the out-of-plane motion (vy) and the velocity magnitude exhibit the expected 2D circular-symmetric parabolic shape. It is shown that the ultrasound method is suitable for real-time data acquisition as opposed to magnetic resonance imaging (MRI). The results demonstrate that the 3D TO method is capable of performing 3D vector flow imaging.

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Preliminary study of synthetic aperture tissue harmonic imaging on in-vivo data
A method for synthetic aperture tissue harmonic imaging is investigated. It combines synthetic aperture sequential beamforming (SASB) with tissue harmonic imaging (THI) to produce an increased and more uniform spatial resolution and improved side lobe reduction compared to conventional B-mode imaging. Synthetic aperture sequential beamforming tissue harmonic imaging (SASB-THI) was implemented on a commercially available BK 2202 Pro Focus UltraView ultrasound system and compared to dynamic receive focused tissue harmonic imaging (DRF-THI) in clinical scans. The scan sequence that was implemented on the UltraView system acquires both SASB-THI and DRF-THI simultaneously. Twenty-four simultaneously acquired video sequences of in-vivo abdominal SASB-THI and DRF-THI scans on 3 volunteers of 4 different sections of liver and kidney tissues were created. Videos of the in-vivo scans were presented in double blinded studies to two radiologists for image quality performance scoring. Limitations to the system's transmit stage prevented user defined transmit apodization to be applied. Field II simulations showed that side lobes in SASB could be improved by using Hanning transmit apodization. Results from the image quality study show that in the current configuration on the UltraView system, where no transmit apodization was applied, SASB-THI and DRF-THI produced equally good images. It is expected that given the use of transmit apodization, SASB-THI could be further improved.

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Real Time Deconvolution of In-Vivo Ultrasound Images
The axial resolution in medical ultrasound is directly linked to the emitted ultrasound frequency, which, due to tissue attenuation, is selected based on the depth of scanning. The resolution is determined by the transducers impulse response, which limits the attainable resolution to be between one and two wavelengths. This can be improved by deconvolution, which increases the bandwidth and equalizes the phase to increase resolution under the constraint of the electronic noise in the received signal. A fixed interval Kalman filter based deconvolution routine written in C is employed. It uses a state based model for the ultrasound pulse and can include a depth varying pulse and spatially varying signal-to-noise ratio. An autoregressive moving average (ARMA) model of orders 8 and 9 is used for the pulse, and the ARMA parameters are determined as a function of depth using a minimum variance algorithm using averaging over several RF lines. In vivo data from a 3 MHz mechanically rotating probe is used and the received signal is sampled at 20 MHz and 12 bits. In-vivo data acquired from a 16th week old fetus is used along with a scan from the liver and right kidney of a 27 years old male. The axial resolution has been determined from the in-vivo liver image using the auto-covariance function. From the envelope of the estimated pulse the axial resolution at Full-Width-Half-Max is 0.581 mm corresponding to 1.13 l at 3 MHz. The algorithm increases the resolution to 0.116 mm or 0.227 l corresponding to a factor of 5.1. The basic pulse can be estimated in roughly 0.176 seconds on a single CPU core on an Intel i5 CPU running at 1.8 GHz. An in-vivo image consisting of 100 lines of 1600 samples can be processed in roughly 0.1 seconds making it possible to perform real-time deconvolution on ultrasound data by using dual or quad core CPUs for frame-rates of 20-40 Hz.

SARUS: A Synthetic Aperture Real-Time Ultrasound System
The Synthetic Aperture Real-time Ultrasound System (SARUS) for acquiring and processing synthetic aperture (SA) data for research purposes is described. The specifications and design of the system are detailed, along with its performance for SA, nonlinear, and 3-D flow estimation imaging. SARUS acquires individual channel data simultaneously for up to 1024 transducer elements for a couple of heart beats, and is capable of transmitting any kind of excitation. The 64 boards in the system house 16 transmit and 16 receive channels each, where sampled channel data can be stored in 2 GB of RAM and processed using five field-programmable gate arrays (FPGAs). The fully parametric focusing unit calculates delays and apodization values in real time in 3-D space and can produce 350 million complex samples per channel per second for full non-recursive synthetic aperture B-mode imaging at roughly 30 high-resolution images/s. Both RF element data and beamformed data can be stored in the system for later storage and processing. The stored data can be transferred in parallel using the system's sixty-four 1-Gbit Ethernet interfaces at a theoretical rate of 3.2 GB/s to a 144-core Linux cluster.
Sequential Beamforming Synthetic Aperture Imaging

Synthetic aperture sequential beamforming (SASB) is a novel technique which allows to implement synthetic aperture beamforming on a system with a restricted complexity, and without storing RF-data. The objective is to improve lateral resolution and obtain a more depth independent resolution compared to conventional ultrasound imaging. SASB is a two-stage procedure using two separate beamformers. The initial step is to construct and store a set of B-mode image lines using a single focal point in both transmit and receive. The focal points are considered virtual sources and virtual receivers making up a virtual array. The second stage applies the focused image lines from the first stage as input data, and take advantage of the virtual array in the delay and sum beamforming. The size of the virtual array is dynamically expanded and the image is dynamically focused in both transmit and receive and a range independent lateral resolution is obtained. The SASB method has been investigated using simulations in Field II and by off-line processing of data acquired with a commercial scanner. The lateral resolution increases with a decreasing F#. Grating lobes appear if F# > 2 for a linear array with k-pitch. The performance of SASB with the virtual source at 20 mm and F# = 1.5 is compared with conventional dynamic receive focusing (DRF). The axial resolution is the same for the two methods. For the lateral resolution there is improvement in FWHM of at least a factor of 2 and the improvement at 40 dB is at least a factor of 3. With SASB the resolution is almost constant throughout the range. For DRF the FWHM increases almost linearly with range and the resolution at 40 dB is fluctuating with range. The theoretical potential improvement in SNR of SASB over DRF has been estimated. An improvement is attained at the entire range, and at a depth of 80 mm the improvement is 8 dB.
Spectral Velocity Estimation in the Transverse Direction

A method for estimating the velocity spectrum for a fully transverse flow at a beam-to-flow angle of 90° is described. The approach is based on the transverse oscillation (TO) method, where an oscillation across the ultrasound beam is made during receive processing. A fourth-order estimator based on the correlation of the received signal is derived. A Fourier transform of the correlation signal yields the velocity spectrum. Performing the estimation for short data segments gives the velocity spectrum as a function of time as for ordinary spectrograms, and it also works for a beam-to-flow angle of 90°. The approach is validated using Field II simulations. A 3 MHz convex array with lambda pitch is modeled. The transmit focus is at 200 mm and 2 times 32 elements are used in receive. A dual-peak Hamming apodization with a spacing of 96 elements between the peaks is used during receive beamforming for creating the lateral oscillation. Pulsatile flow in a femoral artery placed 40 mm from the transducer is simulated for one cardiac cycle using the Womersly-Evan's flow model. The bias of the mean estimated frequency is 13.6% compared to the true velocity and the mean relative std is 14.3%. This indicates that the new estimation scheme can reliably find the spectrum at 90°, where a traditional estimator yields zero velocity. Measurements have been conducted with the SARUS experimental scanner and a BK 8820e convex array transducer (BK Medical, Herlev, Denmark). A CompuFlow 1000 (Shelley Automation, Inc, Toronto, Canada) generated the artificial femoral artery flow in the phantom. It is demonstrated that the transverse spectrum can be found from the measured data. The estimated spectra degrade when the angle is different from 90°, but are usable down to 60-70°. Below this angle the traditional spectrum is best and should be used. The conventional approach can automatically be corrected for angles from 0-70° to give a fully quantitative velocity spectrum without operator intervention.

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Synthetic aperture flow imaging using dual stage beamforming: Simulations and experiments

A method for synthetic aperture flow imaging using dual stage beamforming has been developed. The main motivation is to increase the frame rate and still maintain a beamforming quality sufficient for flow estimation that is possible to implement in a commercial scanner. This method can generate continuous high frame rate flow images with lower calculation demands than the full synthetic aperture flow imaging. The performance of the approach was investigated using Field II simulations and the experimental scanner SARUS. A laminar flow with a parabolic profile was generated by a flow rig system. The flow data were acquired by a commercial 7 MHz linear array transducer. Four emissions were transmitted sequentially and repeated 12 times corresponding to 48 emissions. Flow with a peak velocity of 0.12 m/s was measured, the relative standard deviation was 6.4%, and the bias was 7.6% (2.1% and 3.2% for the
simulations). A parameter study revealed that emission spacing, number of cross-correlation functions used for averaging, and the length of the velocity searching range influence the performance. Compared to the full synthetic aperture flow imaging the total number of beamformed samples are reduced by a factor of 64 times, and the frame rate is much higher than the conventional method for the same velocity estimation accuracy.

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**Vector Volume Flow in Arteriovenous Fistulas**
The majority of patients with end stage renal disease are in hemodialysis, and therefore dependent on a well functioning vascular access. The arteriovenous fistula is the recommended access and in order to maintain and keep the fistula patent, regular monitoring of the function is necessary. The Ultrasound Dilution Technique is the reference method for volume flow measurement, but it only works in conjunction with the dialysis machine, and use is therefore restricted to dialysis sessions. Volume flow measurement with conventional Doppler ultrasound provides a non invasive, highly accessible solution, but is very challenging due to the angle dependency of the Doppler technique and the anatomy of the fistula. The angle independent vector ultrasound technique Transverse Oscillation provides a new and more intuitive way to measure volume flow in an arteriovenous fistula. In this paper the Transverse Oscillation has been used to measure volume flow directly on four patients’ arteriovenous fistulas, and the measurements were compared to subsequent measurements with the Ultrasound Dilution Technique. The results obtained with the Transverse Oscillation deviate -35.1 – 14.9 % from the reference method, and indicates potential for the method.

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Void-Free Direct Bonding of CMUT Arrays with Single Crystalline Plates and Pull-In Insulation

The implications on direct bonding quality, when using a double oxidation step to fabricate capacitive micromachined ultrasonic transducers (CMUTs), is analyzed. The protrusions along the CMUT cavity edges created during the second oxidation are investigated using simulations, AFM measurements, and a proposed analytical model, which is in good agreement with the simulated results. The results demonstrate protrusion heights in the order of 10 nm to 40 nm, with higher oxidation temperatures giving the highest protrusions. Isotropically wet etched cavities exhibit significantly smaller protrusions than anisotropically plasma etched cavities after the second oxidation. It is demonstrated that the protrusions will prevent good wafer bonding without subsequent polishing or etching steps. A new fabrication process is therefore proposed, allowing protrusion-free bonding surfaces with no alteration of the final structure and no additional fabrication steps compared to the double oxidation process. Two identical CMUT arrays with circular and square cavities having diameter/side lengths of 72 μm/65 μm and a 20 μm interdistance are fabricated with the two processes, demonstrating void-free bonding and 100 % yield from the proposed process compared to poor bonding and 7 % yield using the double oxidation process.

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Harmonic ultrasound imaging using synthetic aperture sequential beamforming

A method includes generating an ultrasound image based on the harmonic components in the received echoes using multi-stage beam forming and data generated therefrom. An ultrasound imaging system (100, 200) includes a transducer array (108) including a plurality of transducer elements configured to emit ultrasound signals and receive echoes generated in response to the emitted ultrasound signals. The ultrasound imaging system further includes transmit circuitry (110) that generates a set of pulses that actuate a set of the plurality of transducer elements to emit ultrasound signals. The ultrasound imaging system further includes receive circuitry (112), including a first beam former (122) configured to process the second harmonic signal components extracted from the received echo signals, generating intermediate scan lines. Memory (126) stores the generated intermediate scan lines. The ultrasound imaging system further includes a synthetic aperture processor (128), including a second beam former (130) configured to process the stored intermediate scan lines, based on a synthetic aperture algorithm, generating a focused image.

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In Vivo Evaluation of Synthetic Aperture Sequential Beamforming

Ultrasound in vivo imaging using synthetic aperture sequential beamformation (SASB) is compared with conventional imaging in a double blinded study using side-by-side comparisons. The objective is to evaluate if the image quality in terms of penetration depth, spatial resolution, contrast and unwanted artifacts is comparable to conventional imaging. In vivo data was acquired using a ProFocus ultrasound scanner (BK Medical, Herlev, Denmark) and a 192-element 3.5 MHz convex array transducer (Sound Technology Inc., PA, USA). Data were acquired interleaved, ensuring that the exact same anatomical locations were scanned. Eighteen volunteers were scanned abdominally resulting in 85 image sequence pairs. Evaluation of image quality was performed by five medical doctors. Results show that image quality using SASB was significantly better than conventional imaging (p value: <0.01). There was not a significant difference in penetration depth (p value: 0.55). The study supports that in vivo ultrasound imaging using SASB is feasible for abdominal imaging.

Age and gender related differences in aortic blood flow

The abdominal aorta (AA) is predisposed to development of abdominal aneurysms (AAA), a focal dilatation of the artery with fatal consequences if left untreated. The blood flow patterns in the AA is thought to play an important role in the development of AAA. The purpose of this work is to investigate the blood flow patterns within a group of healthy volunteers (4 females, 7 males) aged 23 to 76 years to identify changes and differences related to age and gender. The healthy volunteers were categorized by gender (male/female) and age (below/above 35 years). Subject-specific flow and geometry data were acquired using the research interface on a medical ultrasound scanner and segmentation of 3D magnetic resonance angiography respectively. The largest average diameter was among the elderly males (19.7 (± 1.33) mm) and smallest among the young females (12.4 (± 0.605) mm). The highest peak systolic velocity was in the young female group (1.02 (± 0.336) m/s) and lowest in the elderly male group (0.836 (± 0.127) m/s). A geometrical change with age was observed as the AA becomes more bended with age. This also affects the blood flow velocity patterns, which are markedly different from young to elderly. Thus, changes in blood flow patterns in the AA related to age and gender is
observed. Further investigations are needed to determine the relation between changes in blood flow patterns and AAA development.

**A Method for Direct Localized Sound Speed Estimates Using Registered Virtual Detectors**

Accurate sound speed estimates are desirable in a number of fields. In an effort to increase the spatial resolution of sound speed estimates, a new method is proposed for direct measurement of sound speed between arbitrary spatial locations. The method uses the sound speed estimator developed by Anderson and Trahey. Their least squares fit of the received waveform's curvature provides an estimate of the wave's point of origin. The point of origin and the delay profile calculated from the fit are used to arrive at a spatially registered virtual detector. Between a pair of registered virtual detectors, a spherical wave is propagated. By beamforming the data, the time-of-flight between the two virtual sources can be calculated. From this information, the local sound speed can be estimated. Validation of the estimator is made using phantom and simulation data. The set of test phantoms consisted of both homogeneous and inhomogeneous media. Several different inhomogeneous phantom configurations were used for the physical validation. The simulation validation focused on the limits of target depth and signal-to-noise ratio on virtual detector registration. The simulations also compare the impact of two- and three-layer inhomogeneous media. The phantom results varied based on signal-to-noise ratio and geometry. The results for all cases were generally less than 1% mean error and standard deviation. The simulation results varied somewhat with depth and F/#, but primarily, they varied with signal-to-noise ratio and geometry. With two-layer geometries, the algorithm has a worst-case spatial registration bias of 0.02%. With three-layer geometries, the axial registration error gets worse with a bias magnitude up to 2.1% but is otherwise relatively stable over depth. The stability over depth of the bias in a given medium still allows for accurate sound speed estimates with a mean relative error less than 0.2%.
Clinical evaluation of synthetic aperture sequential beamforming

In this study clinically relevant ultrasound images generated with synthetic aperture sequential beamforming (SASB) is compared to images generated with a conventional technique. The advantage of SASB is the ability to produce high resolution ultrasound images with a high frame rate and at the same time massively reduce the amount of generated data. SASB was implemented in a system consisting of a conventional ultrasound scanner connected to a PC via a research interface. This setup enables simultaneous recording with both SASB and conventional technique. Eighteen volunteers were ultrasound scanned abdominally, and 84 sequence pairs were recorded. Each sequence pair consists of two simultaneous recordings of the same anatomical location with SASB and conventional B-mode imaging. The images were evaluated in terms of spatial resolution, contrast, unwanted artifacts, and penetration depth of the ultrasound beam. Five ultrasound experts (radiologists) evaluated the sequence pairs in a side-by-side comparison, and the results show that image quality using SASB was better than conventional B-mode imaging. 73 % of the evaluations favored SASB, and a probability of 70 % was calculated for a new radiologist to prefer SASB over conventional imaging, if a new sequence was recorded. There was no significant difference in penetration depth.

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Comparison of 3D Synthetic Aperture Imaging and Explososcan using Phantom Measurements

In this paper, initial 3D ultrasound measurements from a 1024 channel system are presented. Measurements of 3D Synthetic aperture imaging (SAI) and Explososcan are presented and compared. Explososcan is the ‘gold standard’ for real-time 3D medical ultrasound imaging. SAI is compared to Explososcan by using tissue and wire phantom measurements. The measurements are carried out using a 1024 element 2D transducer and the 1024 channel experimental ultrasound scanner SARUS. To make a fair comparison, the two imaging techniques use the same number of active channels, the same number of emissions per frame, and they emit the same amount of energy per frame. The measurements were performed with parameters similar to standard cardiac imaging, with 256 emissions to image a volume spanning 90×90 and 150mm in depth. This results in a frame rate of 20 Hz. The number of active channels is set to 316 from the design of Explososcan. From wire phantom measurements the point spread functions of both techniques were measured. At 40mm depth Explososcan achieves a main lobe width (FWHM) of 2.5mm while SAI’s FWHM is 2.2 mm. At 80mm the FWHM is 5.2mm for Explososcan and 3.4mm for SAI, which is a difference of 35 %. Another metric used on the PSF is the cystic resolution, which expresses the ability to detect anechoic cysts in a uniform scattering media. SAI improved the cystic resolution, R20dB, at 40mm depth from 4.5mm to 1.7mm and at 80mm from 8.2mm to 2.8 mm, compared to Explososcan. The speckle pattern looked better for SAI compared to Explososcan’s spatial shift variant speckle pattern.
Comparison of Real-Time In Vivo Spectral and Vector Velocity Estimation
The purpose of this study is to show whether a newly introduced vector flow method is equal to conventional spectral estimation. Thirty-two common carotid arteries of 16 healthy volunteers were scanned using a BK Medical ProFocus scanner (DK-2730, Herlev, Denmark) and a linear transducer at 5 MHz. A triplex imaging sequence yields both the conventional velocity spectrum and a two-dimensional vector velocity image. Several clinical parameters were estimated and compared for the two methods: Flow angle, peak systole velocity (PS), end diastole velocity (ED) and resistive index (RI). With a paired t-test, the spectral and vector angles did not differ significantly (p = 0.658), whereas PS (p = 0.034), ED (p = 0.004) and RI (p <0.0001) differed significantly. Vector flow can measure the angle for spectral angle correction, thus eliminating the bias from the radiologist performing the angle setting with spectral estimation. The flow angle limitation in velocity estimation is also eliminated, so that flow at any angle can be measured.
measurements that the speckle is reduced and the contrast resolution improved when applying synthetic aperture compound imaging. At a depth of 4 cm, the size of the synthesized apertures is optimized for lesion detection based on the speckle information density. This is a performance measure for tissue contrast resolution which quantifies the tradeoff between resolution loss and speckle reduction. The speckle information density is improved by 25% when comparing synthetic aperture compounding to a similar setup for compounding using dynamic receive focusing. The cystic resolution and clutter levels are measured using a wire phantom setup and compared with conventional application of the array, as well as to synthetic aperture imaging without compounding. If the full aperture is used for synthetic aperture compounding, the cystic resolution is improved by 41% compared with conventional imaging, and is at least as good as what can be obtained using synthetic aperture imaging without compounding.

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**Computational fluid dynamics using in vivo ultrasound blood flow measurements**
This paper presents a model environment for construction of patient-specific computational fluid dynamic (CFD) models for the abdominal aorta (AA). Realistic pulsatile velocity waveforms are employed by using in vivo ultrasound blood flow measurements. Ultrasound is suitable for acquisition of blood velocity profiles, but these are influenced by noise, which will cause convergence problems in CFD simulations. Therefore, physiological smoothing of the velocity profiles is needed. This paper uses the Womersley-Evans model for physiological smoothing of measured blood velocity profiles in the AA. The geometry for the CFD simulation model was obtained by segmentation of MRI scans using a 3 Tesla scanner (Magnetom Trio, Siemens Healthcare, Erlangen, Germany). Spectral velocity data were obtained from a BK Medical ProFocus scanner using a research interface. All data were obtained from healthy volunteers. The estimated and smoothed velocity profiles were quantitatively compared. The energy contained in the velocity profile after smoothing is 65% larger relative to the noise contaminated estimated profiles. In conclusion, a model environment that produces realistic patient-specific CFD simulation models without convergence issues has been developed. The data processing for the model environment can be performed within six hours which is fast enough to be used in the clinical setting.

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Imaging blood's velocity using synthetic aperture ultrasound

The blood velocity vector can be estimated using synthetic aperture techniques in medical ultrasound by using short emission sequences. The whole image region is insonified and the flow can be tracked in all directions continuously. This is a major advantage compared to commercial systems, since the separation between blood and tissue is greatly eased by this, and the estimates can be averaged over long time than in traditional systems. Vector velocity imaging can, thus, be made and attain an order of magnitude higher precision than in current commercial systems and at higher frame rates. It is also possible to visualize very slow moving flow. The paper will present methods for making such imaging.

Implementation of a versatile research data acquisition system using a commercially available medical ultrasound scanner

This paper describes the design and implementation of a versatile, open-architecture research data acquisition system using a commercially available medical ultrasound scanner. The open architecture will allow researchers and clinicians to rapidly develop applications and move them relatively easy to the clinic. The system consists of a standard PC equipped with a camera link and an ultrasound scanner equipped with a research interface. The ultrasound scanner is an easy-to-use imaging device that is capable of generating high-quality images. In addition to supporting the acquisition of multiple data types, such as B-mode, M-mode, pulsed Doppler, and color flow imaging, the machine provides users with full control over imaging parameters such as transmit level, excitation waveform, beam angle, and focal depth. Beamformed RF data can be acquired from regions of interest throughout the image plane and stored to a file with a simple button press. For clinical trials and investigational purposes, when an identical image plane is desired for both an experimental and a reference data set, interleaved data can be captured. This form of data acquisition allows switching between multiple setups while maintaining identical transducer, scanner, region of interest, and recording time. Data acquisition is controlled through a graphical user interface running on the PC. This program implements an interface for third-party software to interact with the application. A software development toolkit is developed to give researchers and clinicians the ability to utilize third-party software for data analysis and flexible manipulation of control parameters. Because of the advantages of speed of acquisition and clinical benefit, research projects have successfully used the system to test and implement their customized solutions for different applications. Three examples of system use are presented in this paper: evaluation of synthetic aperture sequential beamformation, transverse oscillation for blood velocity estimation, and acquisition of spectral velocity data for evaluating aortic aneurysms.
Implementation of Tissue Harmonic Synthetic Aperture Imaging on a Commercial Ultrasound System

This paper presents an imaging technique for synthetic aperture (SAI) tissue harmonic imaging (THI) on a commercial ultrasound system. Synthetic aperture sequential beamforming (SASB) is combined with a pulse inversion (PI) technique on a commercial BK 2202 UltraView system. An interleaved scan sequence that performs dynamic receive focused (DRF) imaging and SASB, both using PI, is implemented. From each acquisition four images can be created: DRF image, SASB image, tissue harmonic DRF image (DRF-THI), and tissue harmonic SASB image (SASB-THI). For SASB imaging, a fixed transmit and receive focus at 80 mm and an F# of 3 is applied. For DRF imaging, default scanner settings are used, which are a focus at 85 mm and F# of 5.7 in transmit and a dynamic receive aperture with an F# of 0.8. In all cases a 2.14 MHz one-and-a-half cycle excitation transmit waveform is used. A BK 8820e 192 element convex array transducer is used to conduct scans of wire phantoms. The -6 dB and -20 dB lateral resolution is measured for each wire in the phantom. Results show that the -6 dB lateral resolution for SASB-THI is as good as for DRF-THI except at the point of the virtual source. SASB-THI even shows 7% reduction in -6 dB lateral resolution for the deepest wire at 100 mm. The -20 dB resolution for SASB-THI at [25, 50, 75, 100] mm was reduced by [5, 0, -34, 11] % compared to DRF-THI, which shows, that except for the point of the virtual source, the lateral resolution was improved by SASB-THI. A successful implementation of SASB-THI was achieved on a commercial system, which can be used for future pre-clinical trials.

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In vivo color flow mapping using synthetic aperture dual stage beamforming
An in vivo investigation of synthetic aperture flow imaging using a dual stage beamformer is presented in this paper. In the previous work, simulations and Doppler flow phantom experiments showed promising results, which indicated the methods capability of producing fast color flow mapping with a good quality. Due to the continuous data, both high velocity and low velocity can be estimated. Moreover, synthetic aperture flow imaging can be implemented on a commercial platform, because the number of calculations have been reduced. In this work, A commercial ultrasound scanner (Pro Focus equipped with a UA 2227 Research Interface, BK Medical, Herlev, Denmark) was used to transmit signals and record echoes. The data are processed off-line. The method is validated using a pulsatile flow phantom. Volume flow is calculated, and is compared with the volume flow set for the pump. The relative standard deviation is 14.3% and relative bias is 6.4% for the phantom measurements. The blood flow in a common carotid artery of a 35-year-old healthy male is scanned by a medical doctor (PMH). The in vivo data is processed off-line. Fast synthetic aperture color flow mapping with frame rate of 85 Hz is produced and the volume flow is calculated.
Measuring 3D Velocity Vectors using the Transverse Oscillation Method

Experimentally obtained estimates of threedimensional (3D) velocity vectors using the 3D Transverse Oscillation (TO) method are presented. The method employs a 2D transducer and synthesizes two double-oscillating fields in receive to obtain the axial, transverse, and elevation velocity components simultaneously. Experimental data are acquired using the ultrasound research scanner SARUS. The double-oscillating TO fields are investigated in an experimental scanning tank setup. The results demonstrate that the created fields only oscillate in the axial plus either the transverse or the elevation direction. Velocity measurements are conducted in an experimental flow-rig with steady flow in two different directions (mainly in x or y direction). Velocity estimates are obtained along the z axis. All three velocity components (vx, vy, vz) are measured with relative biases and standard deviations (normalized to expected value) below 5% and 12%, respectively. For an expected velocity magnitude of 25.2 cm/s, the method estimates 24.4±3.1 cm/s and 25.1±1.9 cm/s for the two directions. Under similar conditions, Field II simulations yield 25.1±1.5 cm/s and 25.4±1.6 cm/s. The experimental results validate the results obtained through simulations and verify that the 3D TO method estimates the full 3D velocity vectors simultaneously as well as the correct velocity magnitudes.
Modelling of CMUTs with Anisotropic Plates

Traditionally, CMUTs are modelled using the isotropic plate equation and this leads to deviations between analytical calculations and FEM simulations. In this paper, the deflection profile and material parameters are calculated using the anisotropic plate equation. It is shown that the anisotropic calculations match perfectly with FEM while an isotropic approach causes up to 10% deviations in deflection profile. Furthermore, we show how commonly used analytic modelling methods such as static calculations of the pull-in voltage and dynamic modelling through an equivalent circuit representation can be adjusted to include the correct anisotropic behaviour by using an effective flexural rigidity. The anisotropic calculations are also compared to experimental data from actual CMUTs showing an error of maximum 3%.

Multilayer piezoelectric transducer models combined with Field II

One-dimensional and three-dimensional axisymmetric transducer model have been compared to determine their feasibility to predict the volt-to-surface impulse response of a circular Pz27 piezoceramic disc. The ceramic is assumed mounted with silver electrodes, bounded at the outer circular boundary with a polymer ring, and submerged into water. The transducer models are developed to account for any external electrical loading impedance in the driving circuit. The models are adapted to calculate the surface acceleration needed by the Field II software in predicting pressure pulses at any location in front of the transducer. Results show that both models predict the longitudinal resonances with consistency. The one-dimensional model is found to exhibit approximately 2.9 dB peak overshoot at the lowest longitudinal resonance frequencies prediction. These values are decreasing for higher longitudinal modes. If the three-dimensional model is restricted in its radial movement at the circular boundary both models exhibit identical results. The Field II predicted pressure pulses are found to have oscillating consistency with a 2.0 dB overshoot on the maximum...
amplitude using the one-dimensional compared to the three-dimensional model. This is with no electronic loading. With a 50 Ω loading an amplitude overshoot is found to be 1.5 dB.

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**Optimizing Synthetic Aperture Compound Imaging**
Spatial compound images are constructed from synthetic aperture data acquired using a linear phased-array transducer. Compound images of wires, tissue, and cysts are created using a method, which allows both transmit and receive compounding without any loss in temporal resolution. Similarly to conventional imaging, the speckle reduction achieved by spatial compounding comes at the cost of a reduced detail resolution and a compromise must be made. Using a performance indicator, which can be measured from an image of a phantom without cysts, it is demonstrated how a compromise can be made, which is optimal for lesion detection. Synthetic aperture data are acquired from unfocused emissions and 154 compound images are constructed by synthesizing different aperture configurations with more or less compounding, all maintaining a constant resolution across depth corresponding to an f-number of 2.0 for transmit and receive. The same configurations are used for scanning a phantom with cysts, and it is demonstrated how an improved cysts contrast follows from an aperture configuration, which gives a higher value for the performance measure extracted from the phantom without cysts. A correlation value $R = 0.81$ is observed with a p-value less than 0.0001. For the optimal compound image, the contrast is improved by 3 dB for a cyst at a depth of 50 mm compared to an image without compounding.

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**Phased-array vector velocity estimation using transverse oscillations**
A method for estimating the 2-D vector velocity of blood using a phased-array transducer is presented. The approach is based on the transverse oscillation (TO) method. The purposes of this work are to expand the TO method to a phased-array geometry and to broaden the potential clinical applicability of the method. A phased-array transducer has a smaller...
footprint and a larger field of view than a linear array, and is therefore more suited for, e.g., cardiac imaging. The method relies on suitable TO fields, and a beamforming strategy employing diverging TO beams is proposed. The implementation of the TO method using a phased-array transducer for vector velocity estimation is evaluated through simulation and flow-rig measurements are acquired using an experimental scanner. The vast number of calculations needed to perform flow simulations makes the optimization of the TO fields a cumbersome process. Therefore, three performance metrics are proposed. They are calculated based on the complex TO spectrum of the combined TO fields. It is hypothesized that the performance metrics are related to the performance of the velocity estimates. The simulations show that the squared correlation values range from 0.79 to 0.92, indicating a correlation between the performance metrics of the TO spectrum and the velocity estimates. Because these performance metrics are much more readily computed, the TO fields can be optimized faster for improved velocity estimation of both simulations and measurements. For simulations of a parabolic flow at a depth of 10 cm, a relative (to the peak velocity) bias and standard deviation of 4% and 8%, respectively, are obtained. Overall, the simulations show that the TO method implemented on a phased-array transducer is robust with relative standard deviations around 10% in most cases. The flow-rig measurements show similar results. At a depth of 9.5 cm using 32 emissions per estimate, the relative standard deviation is 9% and the relative bias is ????- ????9%. At the center of the vessel, the velocity magnitude is estimated to be 0.25 ± 0.023 m/s, compared with an expected peak velocity magnitude of 0.25 m/s, and the beam-to-flow angle is calculated to be 89.3° ± 0.77°, compared with an expected angle value between 89° and 90°. For steering angles up to ±20° degrees, the relative standard deviation is less than 20%. The results also show that a 64-element transducer implementation is feasible, but with a poorer performance compared with a 128-element transducer. The simulation and experimental results demonstrate that the TO method is suitable for use in conjunction with a phased-array transducer, and that 2-D vector velocity estimation is possible down to a depth of 15 cm.

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Preliminary comparison of 3D synthetic aperture imaging with Explososcan
Explososcan is the ‘gold standard’ for real-time 3D medical ultrasound imaging. In this paper, 3D synthetic aperture imaging is compared to Explososcan by simulation of 3D point spread functions. The simulations mimic a 32x32 element prototype transducer. The transducer mimicked is a dense matrix phased array with a pitch of 300 μm, made by Vermon. For both imaging techniques, 289 emissions are used to image a volume spanning 60 in both the azimuth and elevation direction and 150mm in depth. This results for both techniques in a frame rate of 18 Hz. The implemented synthetic aperture technique reduces the number of transmit channels from 1024 to 256, compared to Explososcan. In terms of FWHM performance, was Explososcan and synthetic aperture found to perform similar. At 90mm depth is Explososcan’s FWHM performance 7% better than that of synthetic aperture. Synthetic aperture improved the cystic resolution, which expresses the ability to detect anechoic cysts in a uniform scattering media, at all depths except at Explososcan’s focus point. Synthetic aperture reduced the cyst radius, R20dB, at 90mm depth by 48%. Synthetic aperture imaging was shown to reduce the number of transmit channels by four and still, generally, improve the imaging quality.

General information
Quantification of In Vivo 2D Vector Flow Ultrasound
This PhD thesis has investigated the use of a new ultrasound technique that to measure the movement of blood. The technique was developed at the Center for Fast Ultrasound Imaging at the Technical University of Denmark and has previously only been available with experimental ultrasound scanners. Now, the method has been implemented into a commercial ultrasound scanner made for hospital use. In real-time, the technique measures movements in all directions as 2D vector fields, including movements perpendicular to the ultrasound beam. This is not available with conventional ultrasound scanners today. The thesis consists of three studies that uses vector flow ultrasound measurements on healthy volunteers. In study I the common carotid artery of 16 healthy volunteers were scanned simultaneously with the vector technique and the conventional, spectral estimation method. The study compared the clinical parameters: peak systole velocity, end diastole velocity, resistive index, and the flow direction. The results showed significant difference on the velocities and the resistive index. However, no significant difference on the manually defined flow angle and the calculated mean flow angle by the vector technique. With the conventional technique, the manual setting of the angle is operator dependent. With the calculated vector angle, this operator is relieved from the angle setting and the measurement is angle corrected by the identical method every time. With study II the carotid bifurcation including the carotid bulb and the common carotid artery were scanned on 8 healthy volunteers. The flow patterns of the two structures were outlined and presented to each of 5 experienced radiologists. The complexity of the identical areas were calculated by the vector concentration and compared to the visual evaluations. No significant difference was found between the two methods which were equally good at discriminating the laminar flow of the common carotid artery from the complex flow in the carotid bulb. Thus, a new method was presented to quantify complex flow patterns with vector flow. The final study III presented the rotational flow patterns in the cross-sectional plane of three arteries: The common carotid artery, the abdominal aorta, and the common iliac artery. Five healthy volunteers were included in the study and nine datasets visualized the flow patterns during the diastole. The rotational frequency was calculated and the results indicate a constant direction of the rotation for each artery. Extended measurements on the abdominal aorta showed a two-directional rotation during the cardiac cycle. An observation that corresponds to previous MR and Doppler studies. With the three studies, this thesis presents new methods that quantifies in vivo vector flow obtained in real-time with a new implementation.

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Shadow effects in simulated ultrasound images derived from computed tomography images using a focused beam tracing model
Simulation of ultrasound images based on computed tomography (CT) data has previously been performed with different approaches. Shadow effects are normally pronounced in ultrasound images, so they should be included in the simulation.
In this study, a method to capture the shadow effects has been developed, which makes the simulated ultrasound images appear more realistic. The method using a focused beam tracing model gives diffuse shadows that are similar to the ones observed in measurements on real objects. Ultrasound images of a cod (Gadus morhua) were obtained with a BK Medical 2202 ProFocus ultrasound scanner (BK Medical, Herlev, Denmark) equipped with a dedicated research interface giving access to beamformed radio frequency data. CT images were obtained with an Aquillion ONE Toshiba CT scanner (Toshiba Medical Systems Corp., Tochigi, Japan). CT data were mapped from Hounsfield units to backscatter strength, attenuation coefficients, and characteristic acoustic impedance. The focused beam tracing model was used to create maps of the transmission coefficient and scattering strength maps. FIELD II was then used to simulate an ultrasound image of 38.955.34.5 mm, using 106 point scatterers. As there is no quantitative method to assess quality of a simulated ultrasound image compared to a measured one, visual inspection was used for evaluation.

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**Spatial impulse response of a rectangular double curved transducer**
Calculation of the pressure field from transducers having both a convex and a concave surface geometry is a complicated assignment that often is accomplished by subdividing the transducer surface into smaller flat elements of which the spatial impulse response is known. This method is often seen applied to curved transducers because an analytical solution is unknown. In this work a semi-analytical algorithm for the exact solution to a first order in diffraction effect of the spatial impulse response of rectangular shaped double curved transducers is presented. The algorithm and an approximation of it are investigated. The approximation reformulates the algorithm to an analytically integrable expression which is computationally efficient to solve. Simulation results are compared with the simulation software Field II. Calculating the response from 200 different points yields a mean error for the different approximations ranging from 0.03 % to 0.8 % relative to a numerical solution for the spatial impulse response. It is shown that the presented algorithm gives consistent results with Field II for a linear flat, a linear focused, and a convex non-focused element. Best solution was found to be 0.01 % with a three-point Taylor expansion.

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Synthetic Aperture Sequential Beamformation applied to medical imaging.

Synthetic Aperture Sequential Beamforming (SASB) is applied to medical ultrasound imaging using a multi element convex array transducer. The main motivation for SASB is to apply synthetic aperture techniques without the need for storing RF-data for a number of elements and hereby devise a system with a reduced system complexity. Using a 192 element, 3.5 MHz, λ-pitch transducer, it is demonstrated using tissue-phantom and wire-phantom measurements, how the speckle size and the detail resolution is improved compared to conventional imaging.

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Transverse Oscillation Vector Velocity Estimation using a Phased Array Transducer

The Transverse Oscillation method has shown its commercial feasibility, providing the user with 2D velocity information. Today's implementation on commercial ultrasound platforms only support linear array transducers and are limited in depth. Extending the implementation to a phased array transducer, vector velocity echocardiography will become possible. This paper describes the general modification made on the BK Medical 2202 Pro Focus UltraView using a 64 element phased array transducer and the simulations and measurements performed. The results show that velocities can be obtained at depths even greater than 100 mm. Tests at depths of 72 mm and 82 mm with a peak velocity of 0.5 m/s, showed a relative mean bias ~Bvx that varied from 0 % and to 21 % and a relative mean standard deviation ~vx that varied from 18 % and to 51 %. The investigation showed an increasing bias with respect to depth, which leaves room for optimization. Despite the bias, the method has shown to work and produce reliable results, and 2D velocity estimates are provided within the entire color-box down to a depth of more than 100 mm making vector velocity imaging possible in the entire heart.

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Ultrasound backscatter from free-swimming fish at 1 MHz for fish identification

In the frequency range well below 1 MHz, the swimbladder is often considered the most important part for acoustic fish detection. In this work a portable system was developed to not only detect but also try to identify free-swimming fish. It has been used to measure the ultrasound backscatter at 1 MHz from fish.

The system consists of a Reson TC3210 1 MHz single-element transducer, a dual-frequency, multi-beam Blueview P900-2250 sonar, and three Oregon ATC9K cameras. The Reson transducer is connected to an Olympus pulser-receiver monitored by a portable computer through a Picoscope 4226 PC oscilloscope. Exsitu experiments were performed at the NorthSea Oceanarium in Hirtshals, Denmark. The positions, orientations, and lengths of fish were estimated by three dimensional image analysis, taking the measured acoustic distance into account, while species were identified manually. These experiments indicate that at 1 MHz the surface areas (also fins and tail) of the fish can give echoes that are much stronger (up to 3 times) than the swimbladder can, therefore important for identification of fish
increases, the angle-dependence decreases, as the echo process gradually changes from pure reflection to being predominantly governed by backscattering. The power of the echoes from the two roughest surfaces (Rq = 115 μm and 155 μm) are largely independent of angle at both 6 MHz and 12 MHz with a variation of 2 dB in the angular range from -10° to 10°. The least rough surfaces (Rq = 32 μm and 89 μm) have responses in between with a higher degree of angle-dependence at 6 MHz than at 12 MHz.

3D Vector Velocity Estimation using a 2D Phased Array

A method to estimate the three dimensional (3D) velocity vector is presented in this paper. 3D velocity vector techniques are needed to measure the full velocity and characterize the complicated flow patterns in the human body. The Transverse Oscillation (TO) method introduces oscillations transverse to the ultrasound beam, which enables the estimation of the transverse velocity. To expand the method from 2D to 3D, it is proposed to decouple the velocity estimation into separate estimates of vx, vy, and vz in combination with a 2D phased matrix array. Through simulations the feasibility of using the TO method for estimation 3D velocity vectors, and the proposed decoupling is demonstrated. A 64x64 and a 32x32 elements transducer are emulated using Field II. Plug flow with a speed of 1 m/s in a small region is rotated in the XY-plane. A binary flow example with [vx,vy]=[1,0] and [0,1] m/s shows, that the velocity estimation can be decoupled into the transverse and elevation velocity components. This is substantiated by the results for seven different angles, where the mean and the standard deviation of the estimated speed are 0.97 0.05 m/s and of the angle bias are -0.73 0.3 for the 64x64 matrix transducer. For the 32x32 transducer, the mean and standard deviation for the speed are 0.94 0.11 m/s and for the angle bias -0.48 0.7. The simulation study clearly demonstrates, that the new method can be used to estimate the 3D velocity vector using a 2D phased matrix array, and that the velocity vector estimation can be decoupled into separate estimates of vx, vy, and vz.
An Architecture and Implementation of Real-time Synthetic Aperture Compounding with SARUS

Synthetic aperture and compounding are imaging techniques for increasing the resolution and contrast of ultrasound images. Both techniques are computationally intensive, and combined they require approximately two orders of magnitude more lines to be beamformed per second compared to conventional B-mode imaging with similar frame rates. In this paper, an implementation of a system capable of synthetic aperture compound imaging in real-time producing more than 325 million complex beamformed samples per second is presented. This corresponds to synthetic aperture compound imaging at 13 frames per second with 64 emissions and 3 compound angles with 128 lines each. The beamformer is implemented in the SARUS research scanner which consists of 320 Virtex4 FPGAs and has 1024 independent transmit and receive channels. The beamformer is partitioned across 64 FPGAs and runs at 87.5 MHz while consuming 76% of the available logic resources in each FPGA. The beamformed images have resolution similar to offline processed images.

Angular spectrum approach for fast simulation of pulsed non-linear ultrasound fields

The paper presents an Angular Spectrum Approach (ASA) for simulating pulsed non-linear ultrasound fields. The source of the ASA is generated by Field II, which can simulate array transducers of any arbitrary geometry and focusing. The non-linear ultrasound simulation program - Abersim, is used as the reference. A linear array transducer with 64 active elements is simulated by both Field II and Abersim. The excitation is a 2-cycle sine wave with a frequency of 5 MHz. The second harmonic field in the time domain is simulated using ASA. Pulse inversion is used in the Abersim simulation to remove the fundamental and keep the second harmonic field, since Abersim simulates non-linear fields with all harmonic components. ASA and Abersim are compared for the pulsed fundamental and second harmonic fields in the time domain at depths of 30 mm, 40 mm (focal depth) and 60 mm. Full widths at -6 dB (FWHM) are f0.97, 0.95 mm at the focal depth for the fundamental fields for ASA and Abersim, and f0.56, 0.55 mm for the second harmonic fields. Full widths at -12 dB are f1.27, 1.26 mm for the fundamental fields for ASA and Abersim, and f0.77, 0.73 mm for the second harmonic fields. The calculation time, for the second harmonic fields, using ASA is 12 minutes and for all harmonic fields using Abersim is 14 hours. Compared to Abersim, the error of ASA for calculating the second harmonic fields is 1.5% at -6 dB and 6.4% at -12 dB, and the calculation time is reduced by a factor of 70.
An object-oriented multi-threaded software beamformation toolbox

Focusing and apodization are an essential part of signal processing in ultrasound imaging. Although the fundamental principles are simple, the dramatic increase in computational power of CPUs, GPUs, and FPGAs motivates the development of software based beamformers, which further improves image quality (and the accuracy of velocity estimation). For developing new imaging methods, it is important to establish proof-of-concept before using resources on real-time implementations. With this in mind, an effective and versatile Matlab toolbox written in C++ has been developed to assist in developing new beam formation strategies. It is a general 3D implementation capable of handling a multitude of focusing methods, interpolation schemes, and parametric and dynamic apodization. Despite being exible, it is capable of exploiting parallelization on a single computer, on a cluster, or on both. On a single computer, it mimics the parallelization in a scanner containing multiple beam formers. The focusing is determined using the positions of the transducer elements, presence of virtual sources, and the focus points. For interpolation, a number of interpolation schemes can be chosen, e.g. linear, polynomial, or cubic splines. Apodization can be specified by a number of window functions of fixed size applied on the individual elements as a function of distance to a reference point, or it can be dynamic with an expanding or contracting aperture to obtain a constant F-number, or both. On a standard PC with an Intel Quad-Core Xeon E5520 processor running at 2.26 GHz, the toolbox can beamform 300,000 points using 700,000 data samples in 3 seconds using a transducer with 192 elements, dynamic apodization in transmit and receive, and cubic splines for interpolation. This is 19 times faster than our previous toolbox.

Arterial secondary blood flow patterns visualized with vector flow ultrasound

This study presents the first quantification and visualisation of secondary flow patterns with vector flow ultrasound. The first commercial implementation of the vector flow method Transverse Oscillation was used to obtain in-vivo, 2D vector fields in real-time. The hypothesis of this study was that the rotational direction is constant within each artery. Three data sets of 10 seconds were obtained from three main arteries in healthy volunteers. For each data set the rotational flow patterns were identified during the diastole. Each data set contains a 2D vector field over time and with the vector angles and velocity magnitudes the blood flow patterns were visualised with streamlines in Matlab (Mathworks, Natick, MA, USA). The rotational flow was quantified by the angular frequency for each cardiac cycle, and the mean rotational frequencies and standard deviations were calculated for the abdominal aorta f=1.30±0.4; 1.00±0.3; 0.90±0.2, the common iliac artery f=0.40±0.1; 1.00±0.2; 0.40±0.1, and the common carotid artery f=0.80±0.3; 1.40±0.3; 0.40±0.1. A positive sign indicates an anticlockwise rotation, and a negative sign indicates clockwise rotation. The sign of the rotational directions within each artery were constant.
A Spiral And Discipline-Oriented Curriculum In Medical Imaging
This contribution describes and evaluates an experimental combination of a spiral and discipline-oriented curriculum implemented in the bachelor’s and master’s program in Medicine and Technology. The implementation in the master’s program is in the form of a study line in Medical Imaging and Radiation Physics containing three disciplines: Imaging modalities, Radiation therapy and Image processing. The two imaging courses in the bachelor’s program and the first imaging course in the master’s program follow a spiral curriculum in which most disciplines are encountered in all courses, but in a gradually more advanced manner. The remaining courses in the master’s program follow a discipline-oriented curriculum. From a practical point of view, the spiral course portfolio works well in an undergraduate environment, where the courses involved are to be taken by all students and in the order planned. However, in the master’s program, such a tight schedule is impractical since students are likely to seek specialization. From a pedagogical point of view, the spiral curriculum is advantageous to use in the initial semesters where the teaching can be conducted so that the students can build on their intuitive understanding of the subject. The program was evaluated in terms of the progression in scientific demands in exam from course to course and in terms of the pattern of course selection by the students. The analysis was based on 96 students. The pattern of course selection was found to follow the intentions of the program, thus demonstrating high fulfillment of the learning outcomes.

Blood velocity estimation using ultrasound and spectral iterave adaptive approaches
This paper proposes two novel iterative data-adaptive spectral estimation techniques for blood velocity estimation using medical ultrasound scanners. The techniques make no assumption on the sampling pattern of the emissions or the depth samples, allowing for duplex mode transmissions where B-mode images are interleaved with the Doppler emissions. Furthermore, the techniques are shown, using both simplified and more realistic Field II simulations as well as in vivo data, to outperform current state-of-the-art techniques, allowing for accurate estimation of the blood velocity spectrum using only 30% of the transmissions, thereby allowing for the examination of two separate vessel regions while retaining an adequate
upgrading rate of the B-mode images. In addition, the proposed methods also allow for more flexible transmission patterns, as well as exhibit fewer spectral artifacts as compared to earlier techniques.

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**Comparison of Simulated and Measured Non-linear Ultrasound Fields**
In this paper results from a non-linear AS (angular spectrum) based simulation program are compared to water-tank measurements. A circular concave transducer with a diameter of 1 inch (25.4 mm) is used as the emitting source. The measured pulses are rst compared with the linear simulation program Field II, which will be used to generate the source for the AS simulation. The generated non-linear ultrasound eld is measured by a hydrophone in the focal plane. The second harmonic component from the measurement is compared with the AS simulation, which is used to calculate both fundamental and second harmonic elds. The focused piston transducer with a center frequency of 5 MHz is excited by a waveform generator emitting a 6-cycle sine wave. The hydrophone is mounted in the focal plane 118 mm from the transducer. The point spread functions at the focal depth from Field II and measurements are illustrated. The FWHM (full width at half maximum) values are 1.96 mm for the measurement and 1.84 mm for the Field II simulation. The fundamental and second harmonic components of the experimental results are plotted compared with the AS simulations. The RMS (root mean square) errors of the AS simulations are 7.19% and 10.3% compared with the fundamental and second harmonic components of the measurements.

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Compound imaging using Synthetic Aperture Sequential Beamformation

Synthetic Aperture Sequential Beamforming (SASB) is a technique with low complexity and the ability to yield a more uniform lateral resolution with range. However, the presence of speckle artifacts in ultrasound images degrades the contrast. In conventional imaging speckle is reduced by using spatial compounding at the cost of a reduced frame rate. The objective is to apply spatial compounding to SASB and evaluate if the images have a reduced speckle appearance and thereby an improved image quality in terms of contrast compared to ordinary SASB. Using the simulation software Field II, RF data are acquired for a phantom with cysts at different sizes and scattering levels. 192 scanlines are recorded for five steering angles (0, 2, 4 degrees) using a 192 element linear array transducer. SASB is performed for each angle using a rectangular grid in the second stage beamformation. After envelope detection the five second stage images are added to form the compounded image. Using a ProFocus scanner and the 8804 linear array transducer (BK Medical, Herlev, Denmark) measurements of a phantom containing water filled cysts are obtained to validate the simulation results. The setup is the same as in the simulations and SASB second stage beamformation data are processed offline for each of the five angles. Contrast-to-noise ratio (CNR) and speckle-to-noise ratio (SNR) are extracted for the compounded image and the reference image (ordinary SASB). CNR was calculated for the simulated cysts at depths of 40, 50, 60, 70 and 80 mm. On average the CNR was improved by 33.2% compared to the values obtained from the reference image. For regions of increasing depth SNR was on average increased by 9.3%. Results from the simulation were confirmed by calculations on the measured data. CNR of cysts at depths from 18 to 78 mm with a separation of 10 mm was on average improved by 45.9%. On average an improvement of 16.6% in SNR was obtained. The calculations along with visual inspection revealed larger improvements in deeper regions, and the compounded image for the measured phantom showed a 3 mm diameter cyst not detectable in the reference image. Compounding applied to SASB improves CNR and SNR results in images with a reduced speckle appearance. This was shown for simulations and confirmed on measured data.

Demonstration of a Vector Velocity Technique

With conventional Doppler ultrasound it is not possible to estimate direction and velocity of blood flow, when the angle of insonation exceeds 60–70°. Transverse oscillation is an angle independent vector velocity technique which is now implemented on a conventional ultrasound scanner. In this paper a few of the possibilities with transverse oscillation are demonstrated.
Directional synthetic aperture flow imaging using a dual stage beamformer approach

A new method for directional synthetic aperture flow imaging using a dual stage beamformer approach is presented. The velocity estimation is angle independent and the amount of calculations is reduced compared to full synthetic aperture, but still maintains all the advantages at the same time. The new method has been studied using the Field II simulations and experimental flow rig measurements. A linear array transducer with 7 MHz center frequency is used, and 64 elements are active to transmit and receive signals. The data is processed in two stages. The first stage has a fixed focus point. In the second stage, focal points are considered as virtual sources and data is beamformed along the flow direction. Then the velocities are estimated by finding the spatial shift between two signals. In the experimental measurements the angle between the transmit beam and flow vessel was 70° and a laminar flow with a parabolic profile was generated by a flow rig. The flow with a peak velocity of 0.1 m/s was sampled at a pulse repetition frequency of 4 kHz. The signals were transmitted and received by the experimental scanner SARUS (Synthetic Aperture Realtime Ultrasound System). A relative standard deviation of 2.3% and bias of 6.4% at 65 were achieved in the simulations, and 4.3% and 4.2% for the experimental measurements. A color flow map image was made in 48 emissions corresponding to a frame rate of 83 frames/s.
Examples of Vector Velocity Imaging
To measure blood flow velocity in vessels with conventional ultrasound, the velocity is estimated along the direction of the emitted ultrasound wave. It is therefore impossible to obtain accurate information on blood flow velocity and direction, when the angle between blood flow and ultrasound wave approaches 90°. The majority of the vessels in the human body is parallel to the surface and therefore positioned in a way that prevents proper placement and angulation of the transducer, when the velocity and direction of blood flow is to be estimated. Different techniques to circumvent this problem have been tried including Transverse Oscillation. This method has been tested in computer simulations, on flow phantoms and in-vivo, and subsequently validated against MRI angiography. Transverse Oscillation is now implemented in a commercial ultrasound scanner from BK Medical (UltraView). In this article UltraView is demonstrated on the carotid artery, jugular vein and femoral vein that all runs almost parallel to the skin and thus is angled near 90° to the ultrasound waves. Arterial and venous simple and complex flow with formation of vortices is demonstrated by scanning on the longitudinal axis with a 90° angle on the vessel. Moreover secondary flow in the abdominal aorta is illustrated by scanning on the transversal axis.

Finite Element Implementation of a Structurally-Motivated Constitutive Relation for the Human Abdominal Aortic Wall with and without Aneurysms
The structural integrity of the abdominal aorta is maintained by elastin, collagen, and vascular smooth muscle cells. Changes with age in the structure can lead to development of aneurysms. This paper presents initial work to capture these changes in a finite element model (FEM) of a structurally-motivated anisotropic constitutive relation for the “four fiber family” arterial model. First a 2D implementation is used for benchmarking the FEM implementation to fitted biaxial stress-strain data obtained experimentally from four different groups of persons; 19-29 years, 30-60 years, 61-79 years
and abdominal aortic aneurysm (AAA) patients. Next the constitu-tive model is implemented in an anisotropic 3D FEM formula-tion for future simulation of intact aortic geometries. The 2D simulations of the biaxial test experiment show good agree-ment with experimental data with a standard deviation below 0.5% in all cases. The maximum axial and hoop stress in the group of AAA patients was 94.9 kPa (±0.283 kPa) and 94.3 kPa (±0.224 kPa) at maximum stretch ratios of 1.043 and 1.037, respectively. In the 3D simulations, the maximum stress is also found to occur in the AAA patient group, with the highest stress in the circumferential direction (275 kPa). Comparison with an already published isotropic model indicates that the latter underestimates the peak stress significantly. Based on these results it is concluded that the four fiber family model has been successfully implemented into a 3D anisotropic finite element model and that this model can provide more accurate insight into the stress conditions in aortic aneurysms.

In-vivo studies of new vector velocity and adaptive spectral estimators in medical ultrasound

In this PhD project new ultrasound techniques for blood flow measurements have been investigated in-vivo. The focus has mainly been on vector velocity techniques and four different approaches have been examined: Transverse Oscillation, Synthetic Transmit Aperture, Directional Beamforming and Plane Wave Excitation. Furthermore two different adaptive spectral estimators have been investigated: Blood spectral Power Capon method (BPC) and Blood Amplitude and Phase Estimation method (BAPES). The novel techniques investigated in this thesis are developed to circumvent some of the main limitations in conventional Doppler ultrasound. That is angle dependency, reduced temporal resolution and low frame rate. Transverse Oscillation, Synthetic Transmit Aperture and Directional Beamforming can estimate the blood velocity angle independently. The three methods were validated in-vivo against magnetic resonance phase contrast angiography when measuring stroke volumes in simple vessel geometry on 11 volunteers. Using linear regression and Bland-Altman analyses good agreements were found, indicating that vector velocity methods can be used for quantitative blood flow measurements. Plane Wave Excitation can estimate blood velocities angle independently with a high frame rate. Complex vessel geometries in the cardiovascular system were explored in-vivo on four volunteers using the technique. Flow patterns previously visualized with magnetic resonance angiography and predicted by models of computational fluid dynamics, were shown for the first time with ultrasound. Additionally, new information on complex flow patterns in bifurcations and around venous valves was discovered. BPC and BAPES are adaptive spectral estimators which can produce spectrograms with a high temporal resolution. Spectrograms obtained in-vivo with the two techniques on ten volunteers were evaluated quantitatively and qualitatively and compared to the conventional spectral Doppler method. Descriptive statistics, kappa statistics and multiple t-tests were performed and it was shown that BAPES and BPC can produce useful spectrograms with a narrower observation window compared to the conventional spectral Doppler method. The thesis shows, that novel information can be obtained with vector velocity methods providing quantitative estimates of blood flow and insight in to the complexity of fluid dynamics. This could give the clinician a new tool in assessment and treatment of cardiovascular diseases. Also solutions to produce spectrograms with fewer emissions per estimate were given. This could potentially bring improvements to spectral blood estimation as an increase of the temporal resolution of the spectrogram or as an increase of the frame rate for the interleaved B-mode images.
New interpretation of arterial stiffening due to cigarette smoking using a structurally motivated constitutive model

Cigarette smoking is the leading self-inflicted risk factor for cardiovascular diseases; it causes arterial stiffening with serious sequela including atherosclerosis and abdominal aortic aneurysms. This work presents a new interpretation of arterial stiffening caused by smoking based on data published for rat pulmonary arteries. A structurally motivated “four fiber family” constitutive relation was used to fit the available biaxial data and associated best-fit values of material parameters were estimated using multivariate nonlinear regression. Results suggested that arterial stiffening caused by smoking was reflected by consistent increase in an elastin-associated parameter and moreover by marked increase in the collagen-associated parameters. That is, we suggest that arterial stiffening due to cigarette smoking appears to be isotropic, which may allow simpler phenomenological models to capture these effects using a single stiffening parameter similar to the approach in isotropic continuum damage mechanics. There is a pressing need, however, for more detailed histological information coupled with more complete biaxial mechanical data for a broader range of systemic arteries.

Non-linear Imaging using an Experimental Synthetic Aperture Real Time Ultrasound Scanner

This paper presents the first non-linear B-mode image of a wire phantom using pulse inversion attained via an experimental synthetic aperture real-time ultrasound scanner (SARUS). The purpose of this study is to implement and validate non-linear imaging on SARUS for the further development of new non-linear techniques. This study presents non-linear and linear B-mode images attained via SARUS and an existing ultrasound system as well as a Field II simulation. The non-linear image shows an improved spatial resolution and lower full width half max and -20 dB resolution values.
compared to linear B-mode imaging on the other systems. For the second scatterer at 47 mm depth the -20 dB resolution value for the non-linear SARUS image is 0.9907 mm and 1.1970 mm for the linear image from SARUS.

Performance Evaluation of a Synthetic Aperture Real-Time Ultrasound System

This paper evaluates the signal-to-noise ratio, the time stability, and the phase difference of the sampling in the experimental ultrasound scanner SARUS: A synthetic aperture, real-time ultrasound system. SARUS has 1024 independent transmit and receive channels and is capable of handling 2D probes for 3D ultrasound imaging. It samples at 12 bits per sample and has a sampling rate of 70 MHz with the possibility of decimating the sampling frequency at the input. SARUS is capable of advanced real-time computations such as synthetic aperture imaging. The system is built using fieldprogrammable gate arrays (FPGAs) making it very flexible and allowing implementation of other real-time ultrasound processing methods in the future. For conventional B-mode imaging, a penetration depth around 7 cm for a 7 MHz transducer is obtained (signal-to-noise ratio of 0 dB), which is comparable to commercial ultrasound scanners. Furthermore, the jitter between successive acquisitions for flow estimation is around 1.41 ps with a standard deviation of 48.3 ps. This has a negligible impact (0.03%) on the flow measurement. Additionally, for the phase of the sampling, it is shown that the small differences between different channels (on average 111 ps for a 70 MHz sampling clock) are deterministic and can therefore be compensated for.

Performance of Synthetic Aperture Compounding for in-vivo imaging

A method for synthetic aperture compounding (SAC) is applied to data from water tank measurements, data from a tissue-mimicking phantom, and clinical data from the abdomen of a healthy 27 year old male. Further, using this method compounding can be obtained without any loss in temporal resolution. The water tank measurements reveal an improved detail resolution of 45% when comparing SAC to conventional compounding and an improvement of 22%, when comparing to synthetic aperture (SA) imaging. The cystic resolution at 12 dB is improved by 50% and 12% when
comparing SAC to conventional compounding and SA imaging respectively. The tissue phantom measurements show a 3.2 dB improvement of the normalized information density (NID) when comparing images formed using SAC to conventional compound images and an improvement of 2 dB for a comparison between SAC imaging and SA imaging. For the clinical images, contrast ratios (CR) are computed between regions in the portal and hepatic veins and the surrounding tissue. An average improvement of 15% is obtained when comparing SAC images to SA images without compounding.

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Preliminary comparison between real-time in-vivo spectral and transverse oscillation velocity estimates
Spectral velocity estimation is considered the gold standard in medical ultrasound. Peak systole (PS), end diastole (ED), and resistive index (RI) are used clinically. Angle correction is performed using a flow angle set manually. With Transverse Oscillation (TO) velocity estimates the flow angle, peak systole (PSTO), end diastole (EDTO), and resistive index (RITO) are estimated. This study investigates if these clinical parameters are estimated equally good using spectral and TO data. The right common carotid arteries of three healthy volunteers were scanned longitudinally. Average TO flow angles and std were calculated { 52±18 ; 55±23 ; 60±16 }°. Spectral angles { 52 ; 56 ; 52 }° were obtained from the B-mode images. Obtained values are: PSTO { 76±15 ; 89±28 ; 77±7 } cm/s, spectral PS { 77 ; 110 ; 76 } cm/s, EDTO { 10±3 ; 14±8 ; 15±3 } cm/s, spectral ED { 18 ; 13 ; 20 } cm/s, RITO { 0.87±0.05 ; 0.79±0.21 ; 0.79±0.06 }, and spectral RI { 0.77 ; 0.88 ; 0.73 }. Vector angles are within ±two std of the spectral angle. TO velocity estimates are within ±three std of the spectral estimates. RITO are within ±two std of the spectral estimates. Preliminary data indicates that the TO and spectral velocity estimates are equally good. With TO there is no manual angle setting and no flow angle limitation. TO velocity estimation can also automatically handle situations where the angle varies over the cardiac cycle. More detailed temporal and spatial vector estimates with diagnostic potential are available with the TO velocity estimation.

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Preliminary Experimental Verification of Synthetic Aperture Flow Imaging Using a Dual Stage Beamformer Approach

A dual stage beamformer method for synthetic aperture flow imaging has been developed. The motivation is to increase the frame rate and still maintain a beamforming quality sufficient for flow estimation that is possible to implement in a commercial scanner. With the new method high resolution images can be obtained continuously, which will highly increase the frame rate. The flow velocity is estimated by using a time-domain cross-correlation technique. The approach is investigated through experiments with the SARUS scanner (Synthetic Aperture Real-time Ultrasound System). A flow rig generates a parabolic laminar flow, and the SARUS scanner is used for acquiring the data from individual channels of the transducer. The experimental results showed that increasing the number of imaging lines used for the estimation from 4 to 24 reduces the standard deviation from 21% to 7.6%. The parameter study showed that the number of crosscorrelation functions for averaging and length of the search range influence the performance.

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Preliminary In-Vivo evaluation of Synthetic Aperture Sequential Beamformation using a multielement convex array

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Recent advances in blood flow vector velocity imaging

A number of methods for ultrasound vector velocity imaging are presented in the paper. The transverse oscillation (TO) method can estimate the velocity transverse to the ultrasound beam by introducing a lateral oscillation in the received ultrasound field. The approach has been thoroughly investigated using both simulations, flow rig measurements, and in-
vivo validation against MR scans. The TO method obtains a relative accuracy of 10% for a fully transverse flow in both simulations and flow rig experiments. In-vivo studies performed on 11 healthy volunteers comparing the TO method with magnetic resonance phase contrast angiography (MRA) revealed a correlation between the stroke volume estimated by TO and MRA of 0.91 (p<;0.01) with an equation for the line of regression given as: MRA = 1.1 · TO-0.4 ml. Several clinical examples of complex flow in e.g. bifurcations and around valves have been acquired using a commercial implementation of the method (BK Medical ProFocus Ultraview scanner). A range of other methods are also presented. This includes synthetic aperture imaging using either spherical or plane waves with velocity estimation performed with directional beamforming or speckle tracking. The key advantages of these techniques are very fast imaging that can attain an order of magnitude higher precision than conventional methods. SA flow imaging was implemented on the experimental scanner RASMUS using an 8-emission spherical emission sequence and reception of 64 channels on a BK Medical 8804 transducer. This resulted in a relative standard deviation of 1.2% for a fully transverse flow. Plane wave imaging was also implemented on the RASMUS scanner and a 100 Hz frame rate was attained. Several vector velocity image sequences of complex flow were acquired, which demonstrates the benefits of fast vector flow imaging. A method for extending the 2D TO method to 3D vector velocity estimation is presented and the implications for future vector velocity imaging is indicated.

Scalable Intersample Interpolation Architecture for High-channel-count Beamformers
Modern ultrasound scanners utilize digital beamformers that operate on sampled and quantized echo signals. Timing precision is of essence for achieving good focusing. The direct way to achieve it is through the use of high sampling rates, but that is not economical, so interpolation between echo samples is used. This paper presents a beamformer architecture that combines a band-pass filter-based interpolation algorithm with the dynamic delay-and-sum focusing of a digital beamformer. The reduction in the number of multiplications relative to a linear perchannel interpolation and band-pass per-channel interpolation architecture is respectively 58 % and 75 % beamformer for a 256-channel beamformer using 4-tap filters. The approach allows building high channel count beamformers while maintaining high image quality due to the use of sophisticated intersample interpolation.
Second harmonic imaging using synthetic aperture sequential beamforming

The paper investigates Second Harmonic Imaging (SHI) using Synthetic Aperture Sequential Beamforming (SASB). The investigation is made by an experimental Synthetic Aperture Real-time Ultrasound System (SARUS). A linear array transducer is used to scan 4 wires at the image depths of f2.5, 47.5, 72.5, 97.5 mm, respectively. Three different experiments are made using three different transmit foci at 10 mm, 25 mm and 50 mm. A 2-cycle sine wave with a center frequency of 5 MHz is used as the excitation. The SHI is achieved by using Pulse Inversion (PI) technique. The data received with and without PI from SARUS are beamformed using Dynamic Receive Focusing (DRF) and SASB by a Beamformation Toolbox. The Full Widths at Half Maximum (FWHM) in both the lateral and axial directions for these four wire targets using different imaging algorithms (DRF, DRF+SHI, SASB and SASB+SHI) are calculated and shown in the paper. The Full Width at One Tenth Maximum (FWOTM) is also investigated. By combining SASB and SHI, the lateral resolution is improved by 66%, 35% and 46% for FWHM, and 52%, 20% and 29% for FWOTM, compared to DRF, DRF+SHI and SASB, respectively. The axial resolution is improved 24% on average by SHI.

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Simulation of shadowing effects in ultrasound imaging from computed tomography images

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Contributors: Pham, A. H., Stage, B., Hemmsen, M. C., Lundgren, B., Pedersen, M. M., Jensen, J. A.
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Simulation of ultrasound backscatter images from fish

The objective of this work is to investigate ultrasound (US) backscatter in the MHz range from fish to develop a realistic and reliable simulation model. The long term objective of the work is to develop the needed signal processing for fish species differentiation using US. In in-vitro experiments, a cod (Gadus morhua) was scanned with both a BK Medical ProFocus 2202 ultrasound scanner and a Toshiba Aquilion ONE computed tomography (CT) scanner. The US images of the fish were compared with US images created using the ultrasound simulation program Field II. The center frequency of the transducer is 10 MHz and the Full Width at Half Maximum (FWHM) at the focus point is 0.54 mm in the lateral direction. The transducer model in Field II was calibrated using a wire phantom to validate the simulated point spread function. The inputs to the simulation were the CT image data of the fish converted to simulated scatter maps. The positions of the point scatterers were assumed to be uniformly distributed. The scatter amplitudes were generated with a new method based on the segmented CT data in Hounsfield Units and backscatter data for the different types of tissues from the literature. The simulated US images reproduce most of the important characteristics of the measured US image.

Synthetic Aperture Beamformation using the GPU

A synthetic aperture ultrasound beamformer is implemented for a GPU using the OpenCL framework. The implementation supports beamformation of either RF signals or complex baseband signals. Transmit and receive apodization can be either parametric or dynamic using a fixed F-number, a reference, and a direction. Images can be formed using an arbitrary number of emissions and receive channels. Data can be read from Matlab or directly from memory and the setup can be configured using Matlab. A large number of different setups has been investigated and the frame rate measured. A frame rate of 40 frames per second is obtained for full synthetic aperture imaging using 16 emissions and 64 receive channels for an image size of 512x512 pixels and 4000 complex 32-bit samples recorded at 40 MHz. This amount to a speed up of more than a factor of 6 compared to a highly optimized beamformer running on a powerful workstation with 2 quad-core Xeon-processors.
Synthetic Aperture Focusing for a Single Element Transducer undergoing Helix Motion

This paper describes the application of 3D synthetic aperture focusing (SAF) to a single element trans-rectal ultrasound transducer. The transducer samples a 3D volume by simultaneous rotation and translation giving a helix motion. Two different 3D SAF methods are investigated, a direct and a two-step approach. Both methods perform almost identical for simulated scatterers and give a significant improvement in azimuth resolution and a constant resolution in elevation. Side lobes below -60 dB is achievable for both methods. Validation of the method is achieved by scanning a simple wire phantom and a complex phantom containing wires in azimuth and elevation. The simple wire phantom shows the same results as that found through simulation. The complex phantom shows simultaneous focusing in azimuth and elevation for the wire scatterers. Considerations on processing requirements for both 3D SAF methods show that the two-step approach can give equivalent performance using an order of magnitude lower calculations. This reduction requires a temporary storage of 9.1 GB of data for the investigated setup.

General information

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Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging, BK Medical ApS
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Third Harmonic Imaging using a Pulse Inversion

The pulse inversion (PI) technique can be utilized to separate and enhance harmonic components of a waveform for tissue harmonic imaging. While most ultrasound systems can perform pulse inversion, only few image the 3rd harmonic component. PI pulse subtraction can isolate and enhance the 3rd harmonic component for imaging on any ultrasound system capable of PI. PI was used to perform 3rd harmonic Bmode scans of a water-filled wire phantom on an experimental ultrasound system. The 3rd harmonic scans were compared to fundamental and 2nd harmonic scans on the
same system. The 3rd harmonic image showed a 46% improvement in the lateral FWHM resolution compared to fundamental B-mode imaging at 75 mm depth and a 28% improvement compared to 2nd harmonic B-mode imaging. The axial FWHM resolution was improved by 35% and 30% for 3rd harmonic imaging compared to fundamental and 2nd harmonic imaging respectively. The improvements in spatial resolution and the fact that PI can isolate the 3rd harmonic suggest that it is advantageous to implement 3rd harmonic imaging on ultrasound systems capable of PI.

Ultrasonic colour Doppler imaging
Ultrasonic colour Doppler is an imaging technique that combines anatomical information derived using ultrasonic pulse-echo techniques with velocity information derived using ultrasonic Doppler techniques to generate colour-coded maps of tissue velocity superimposed on grey-scale images of tissue anatomy. The most common use of the technique is to image the movement of blood through the heart, arteries and veins, but it may also be used to image the motion of solid tissues such as the heart walls. Colour Doppler imaging is now provided on almost all commercial ultrasound machines, and has been found to be of great value in assessing blood flow in many clinical conditions. Although the method for obtaining the velocity information is in many ways similar to the method for obtaining the anatomical information, it is technically more demanding for a number of reasons. It also has a number of weaknesses, perhaps the greatest being that in conventional systems, the velocities measured and thus displayed are the components of the flow velocity directly towards or away from the transducer, while ideally the method would give information about the magnitude and direction of the three-dimensional flow vectors. This review briefly introduces the principles behind colour Doppler imaging and describes some clinical applications. It then describes the basic components of conventional colour Doppler systems and the methods used to derive velocity information from the ultrasound signal. Next, a number of new techniques that seek to overcome the vector problem mentioned above are described. Finally, some examples of vector velocity images are presented.
Ultrasonography Fused with PET-CT Hybrid Imaging

We present a method with fusion of images of three modalities 18F-FDG PET, CT, and 3-D ultrasound (US) applied to imaging of the anal canal and the rectum. To obtain comparable geometries in the three imaging modalities, a plexiglas rod, with the same dimensions as the US transducer, is placed in the anal canal prior to the PET-CT examination. The method is based on manual co-registration of PET-CT images and 3-D US images. The three-modality imaging of the rectum-anal canal may become useful as a supplement to conventional imaging in the external radiation therapy in the treatment of anal cancer, where the precise delineation of a tumor is crucial to avoid damage from radiation therapy to the healthy tissue surrounding it. The technique is still in a phase of development, and the demands for integration different company software systems are significant before commercial application. Three-modality imaging may also be used in certain other diagnostic or therapeutic fields.

A Method for Synthetic Aperture Compounding

An approach to perform ultrasound spatial compounding using synthetic aperture data is proposed. The approach allows compounding to be performed for any number of directions without reducing the frame rate or temporal resolution. It is demonstrated how the contrast is improved by compounding and the effect is quantized by speckle statistics and by computing contrast-to-noise ratios (CNR) from the resulting images. The method is validated using Field II simulations for a 7 MHz, 2-pitch transducer with 192 elements with 64 elements active for each scan line. Circular regions (cysts) with a diameter of 5 mm and scattering levels ranging from -3 to -12 dB relative to the background are imaged at 2 depths. Compound images composed of 1-5 images with an angular separation of 2 degrees are constructed and for the cysts at -3, -6, -9, and -12 dB, a CNR of -0.43, -1.11, -1.44, and -1.91 dB are obtained when using 5 images. Using the same RF data, a synthetic aperture image without compounding reveals a CNR of -0.36, -0.93, -1.23, and -1.61 dB for the four cysts, respectively.
A Movable Phantom Design for Quantitative Evaluation of Motion Correction Studies on High Resolution PET Scanners

Head movements during brain imaging using high resolution positron emission tomography (PET) impair the image quality which, along with the improvement of the spatial resolution of PET scanners, in general, raises the importance of motion correction. Here, we present a new design for an automatic, movable, mechanical PET phantom to simulate patients' head movements while being scanned. This can be used for evaluating motion correction methods. A low-cost phantom controlled by a rotary stage motor was built and tested for axial rotations of 1 degrees - 10 degrees with the multiple acquisition frame method. The phantom is able to perform stepwise and continuous axial rotations with submillimeter accuracy, and the movements are repeatable. The scans were acquired on the high resolution research tomograph dedicated brain scanner. The scans were reconstructed with the new 3-D ordered subset expectation maximization algorithm with modeling of the point spread function (3DOSEM-PSF), and they were corrected for motions based on external tracking information using the Polaris Vicra real-time stereo motion-tracking system. The new automatic, movable phantom has a robust design and is a potential quality assessment tool for the development and evaluation of future motion correction methods.
An Iterative Adaptive Approach for Blood Velocity Estimation Using Ultrasound
This paper proposes a novel iterative data-adaptive spectral estimation technique for blood velocity estimation using medical ultrasound scanners. The technique makes no assumption on the sampling pattern of the slow-time or the fast-time samples, allowing for duplex mode transmissions where B-mode images are interleaved with the Doppler emissions. Furthermore, the technique is shown, using both simplified and more realistic Field II simulations, to outperform current state-of-the-art techniques, allowing for accurate estimation of the blood velocity spectrum using only 30% of the transmissions, thereby allowing for the examination of two separate vessel regions while retaining an adequate updating rate of the B-mode images. In addition, the proposed method also allows for more flexible transmission patterns, as well as exhibits fewer spectral artifacts as compared to earlier techniques.

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Calibration of Field II using a Convex Ultrasound Transducer
Field II is an ultrasound simulation program capable of simulating the pressure scattering from inhomogeneous tissue. The simulations are based on a convolution between spatial impulse responses from the field in front of the transducer and the volt-to-surface acceleration impulse response of the transducer. For such simulations to reflect actual measured intensities and pressure levels, the transducer impulse response is to be known. This work presents the results of combining a modified form of a 1D linear transducer model originally suggested by Willatzen with the Field II program to calibrate the pressure simulations of a 128 element convex medical transducer with elevation focus at 70mm. The simulations are compared to pressure measurements from an automatic water bath needle hydrophone setup. The transducer was driven at 4.0 MHz using a research scanner with a commercial transducer amplifier from BK-Medical (Herlev, Denmark). As input waveform for the Field model we measured the output voltage of the research amplifier, which peak voltage was limited to 31 V to avoid too high non linear effects. We measured the hydrophone output from three transducer front elements by averaging 40 shoot sequences on each element using a remotely controlled Agilent MSO6014A oscilloscope. The pressure along the elevation line in 32 mm, 70 mm (elevation focus) and 112 mm for each element are measured.

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Organisations: Department of Electrical Engineering, Biomedical Engineering, Center for Fast Ultrasound Imaging
Contributors: Bæk, D., Jensen, J. A., Willatzen, M.
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Complex blood flow quantification using real-time in vivo vector flow ultrasound
A new method to define and quantify complex blood flow is presented. The standard deviations of real-time in vivo vector flow angle estimates are used. Using vector flow ultrasound imaging both carotid bifurcations of two healthy volunteers were scanned. Scanning was performed with a 7.6 MHz linear transducer (8670, B-K Medical, Denmark) and a commercial vector flow ultrasound scanner (ProFocus 2202, B-K Medical). Eight video sequences of one cardiac cycle
were obtained. In every frame boxes were placed to define the common carotid artery(box1) and the carotid bulb(box2). The standard deviation for the vector angle estimates was calculated for each box in every frame. For comparison three ultrasound experts evaluated the presence of complex flow in every box. The trial was blinded. For every sequence the mean standard deviation of the vector angle estimates were calculated for box1 [39;32;35;41;38;39;32;27] and box2 [22;12;11;13;15;22;17;21]. Mean values and standard deviations of the visual evaluations were calculated for the two boxes in every sequence. From regression analysis a standard deviation above 30 corresponds to complex flow according to the evaluation given by three experts. Complex flow patterns can be visualised and quantified with real-time in vivo vector flow. Good agreement between visual evaluation and the quantitative method has been shown. A standard deviation of vector angle estimates above 30 is proposed to define complex blood flow.

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**Effect of cigarette smoking on arterial stiffness re-interpreted using a structurally-based model**
Cigarette smoking constitutes a major risk factor for diverse cardiovascular diseases (CVD). Many physiological and pathophysiological parameters affect arterial stiffness. While underlying mechanisms remain unclear, smoking increases arterial stiffness, which contributes to many disease processes. The goal of this work was to use a structurally motivated nonlinear constitutive relation to quantify increased arterial stiffness based on available data. Specifically, we used a “four-fiber family model” that includes dominant effects of axial, circumferential, and symmetric-diagonal families of collagen fibers embedded within an isotropic, elastin-dominated matrix. Published data, i.e. biaxial responses during pressure-diameter and axial force-length tests on pulmonary arteries from rats subjected to 2 or 3 months of smoking, were used to determine the associated best-fit values of the material parameters. The primary finding was that cigarette smoking induces significant increases in the material parameters describing the micromechanical properties of all four families of collagen fibers with increased duration of smoking. Additionally, there was a moderate increase in the material parameter describing the behaviour of the elastic fibers. These findings suggest that arterial stiffening in response to smoking is isotropic due to the changes in the material parameters seen in all fiber directions. Although changes are manifested in both elastic and collagen fibers, the predominant stiffening appeared to be due mainly to changes in collagen fiber structure (e.g., cross-linking).

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**Evaluation of automatic time gain compensated in-vivo ultrasound sequences**
Ultrasound imaging is increasingly being used in applications such as surgery, anesthesia and urology, where the users are not trained radiologists. User studies indicate that these users rarely adjust the controls of the ultrasound scanner. This project presents a preliminary evaluation of a new algorithm for automatic time gain compensation (TGC) on in-vivo ultrasound sequences. Forty ultrasound sequences were recorded from the abdomen of two healthy volunteers. Each sequence of 5 sec was recorded with 40 frames/sec. Post processing each frame, a mask is created wherein anechoic and hyper echoic regions are mapped. Near field hyper intensity and deep areas with low signal strength are also included in the mask. The algorithm uses this mask to create a parallel image where anechoic and hyper echoic regions are eliminated. From this, the mean power is calculated as a function of depth. The power is then used as an estimate of the attenuation, and from this, the needed compensation is found. The measurements were performed by an experienced sonographer using an ultrasound scanner (2202 ProFocus, BK Medical, Denmark) with a 192 elements concave transducer (8820e BK Medical). A research interface was used to retrieve unprocessed data from the scanner with no preset TGC, using a standard abdominal setup. Five experts in medical ultrasound evaluated the unprocessed and processed video sequences in a double-blinded randomized trial on image quality and penetration depth. In the evaluation
of image quality, the unprocessed and processed sequences were displayed in pairs side-by-side in random order and with random left right placement. Each pair was displayed and scored twice, with different permutations. The sequences were evaluated on their relative clinical value. P-values on the order of 10^{-8} - 10^{-14} indicate that the image quality of the processed sequences are clinically better than the unprocessed. In the evaluation of penetration depth, all the processed and unprocessed sequences were displayed in random order. Each sequence was evaluated on the basis of; at what depth the image quality had decreased so much that it was of no clinical value. The pooled results show a mean increase in penetration depth of 1.91 cm with a p-value of 1.19 \times 10^{-18}. In conclusion a new algorithm has been developed and evaluated. It is capable of compensating for the depth attenuation on abdominal in-vivo ultrasound images.

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Impact of acoustic pressure on ambient pressure estimation using ultrasound contrast agent
Local blood pressure measurements provide important information on the state of health of organs in the body and can be used to diagnose diseases in the heart, lungs, and kidneys. This paper presents an approach for investigating the ambient pressure sensitivity of a contrast agent using diagnostic ultrasound. The experimental setup resembles a realistic clinical setup utilizing a single array transducer for transmit and receive. The ambient pressure sensitivity of SonoVue (Bracco, Milano, Italy) was measured twice using two different acoustic driving pressures, which were selected based on a preliminary experiment. To compensate for variations in bubble response and to make the estimates more robust, the relation between the energy of the subharmonic and the fundamental component was chosen as a measure over the subharmonic peak amplitude. The preliminary study revealed the growth stage of the subharmonic component to occur at acoustic driving pressures between 300 and 500 kPa. Based on this, the pressure sensitivity was investigated using a driving pressure of 485 and 500 kPa. At 485 kPa, a linear pressure sensitivity of 0.42 dB/kPa was found having a linear correlation coefficient of 0.94. The second measurement series at 485 kPa showed a sensitivity of 0.41 dB/kPa with a correlation coefficient of 0.89. Based on the measurements at 500 kPa, this acoustic driving pressure was concluded to be too high causing the bubbles to be destroyed. The pressure sensitivity for these two measurement series were 0.42 and 0.25 dB/kPa with linear correlation coefficients of 0.98 and 0.93, respectively.

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The main advantage of medical ultrasound imaging is its real-time capability, which makes it possible to visualize dynamic structures in the human body. Real-time synthetic aperture imaging puts very high demands on the hardware, which currently cannot be met. A method for reducing the number of calculations and still retain the many advantages of SA imaging is described. It consists of a dual stage beamformer, where the first can be a simple fixed focus analog beamformer and the second an ordinary digital ultrasound beamformer. The performance and constrictions of the approach are described.

**Introduction to vector velocity imaging**

Current ultrasound scanners can only estimate the velocity along the ultrasound beam and this gives rise to the cos() factor on all velocity estimates. This is a major limitation as most vessels are close to perpendicular to the beam. Also the angle varies as a function of space and time making it virtually impossible to compensate for the factor and obtain correct velocity estimates for either CFM or spectral velocity estimation. This talk will describe methods for finding the correct velocity by estimating both the axial and lateral component of the velocity vector. The transverse oscillation method introduces an ultrasound field that oscillates not only along the ultrasound beam but also transverse to it to estimate both the lateral and axial velocity for the full velocity vector. The correct velocity magnitude can be obtained over the full region of interest and a real-time image at a frame rate of 20 Hz can be displayed. Real-time videos have been obtained from both our research systems and from commercial BK Medical scanners. The vector velocity images reveal the full complexity of the human blood flow. It is easy to see direction and the correct velocity magnitude for any orientation of the vessels. At complex geometries like bifurcations, branching and for valves the approach reveals how the velocity changes magnitude and direction over the cardiac cycle. Vector velocity reveals a wealth of new information that now is accessible to the ultrasound community. The displaying and studying of this information is challenging as complex flow changes rapidly over the cardiac cycle.
In-vivo Validation of Fast Spectral Velocity Estimation Techniques

Spectrograms in medical ultrasound are usually estimated with Welch’s method (WM). WM is dependent on an observation window (OW) of up to 256 emissions per estimate to achieve sufficient spectral resolution and contrast. Two adaptive filterbank methods have been suggested to reduce the OW: Blood spectral Power Capon (BPC) and the Blood Amplitude and Phase ESTimation method (BAPES). Ten volunteers were scanned over the carotid artery. From each data set, 28 spectrograms were produced by combining four approaches (WM with a Hanning window (W.HAN), WM with a boxcar window (W.BOX), BPC and BAPES) and seven OWs (128, 64, 32, 16, 8, 4, 2). The full-width-at-half-maximum (FWHM) and the ratio between main and side-lobe levels were calculated at end-diastole for each spectrogram. Furthermore, all 280 spectrograms were randomized and presented to nine radiologists for visual evaluation: useful/not useful. BAPES and BPC compared to WM had better resolution (lower FWHM) for all OW <128 while only BAPES compared to WM had improved contrast (higher ratio). According to the scores given by the radiologists, BAPES, BPC and W.HAN performed equally well (p > 0.05) at OW 128 and 64, while W.BOX scored less (p <0.05). At OW 32, BAPES and BPC performed better than WM (p <0.0001) and BAPES was significantly superior to BPC at OW 16 (p = 0.0002) and 8 (p <0.0001). BPC at OW 32 performed as well as BPC at OW 128 (p = 0.29) and BAPES at OW 16 as BAPES at OW 128 (p = 0.55). WM at OW 16 and 8 failed as all four methods at OW 4 and 2. The intra-observer variability tested for three radiologist showed on average good agreement (90%, κ = 0.79) and inter-observer variability showed moderate agreement (78%, κ = 0.56). The results indicated that BPC and BAPES had better resolution and BAPES better contrast than WM, and that OW can be reduced to 32 using BPC and 16 using BAPES without reducing the usefulness of the spectrogram. This could potentially increase the temporal resolution of the spectrogram or the frame-rate of the interleaved B-mode images.

General information

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Modeling transducer impulse responses for predicting calibrated pressure pulses with the ultrasound simulation program FIELD II

FIELD II is a simulation software capable of predicting the field pressure in front of transducers having any complicated geometry. A calibrated prediction with this program is, however, dependent on an exact voltage-to-surface acceleration impulse response of the transducer. Such impulse response is not calculated by FIELD II. This work investigates the usability of combining a one-dimensional multilayer transducer modeling principle with the FIELD II software. Multilayer here refers to a transducer composed of several material layers. Measurements of pressure and current from Pz27 piezoceramic disks as well as pressure and intensity measurements in front of a 128 element commercial convex medical transducer are compared to the simulations. Results show that the models can predict the pressure from the piezoceramic
Disks with a root mean square (rms) error of 11.2% to 36.2% with a 2 dB amplitude decrease. The current through the external driving circuits are predicted within 8.6% to 36% rms error. Prediction errors of 30% and in the range of 5.8%-19.9% for the pressure and the intensity, respectively, are found when simulating the commercial transducer. It is concluded that the multilayer transducer model and the FIELD II software in combination give good agreement with measurements.

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**Performance of SARUS: A Synthetic Aperture Real-time Ultrasound System**
The SARUS scanner (Synthetic Aperture Real-time Ultrasound System) for research purposes is described. It can acquire individual channel data for multi-element transducers for a couple of heart beats, and is capable of transmitting any kind of excitement. It houses generous and flexible processing resources that can be reprogrammed and tailored to many kinds of algorithms. The 64 boards in the system house 16 transmit and 16 receive channels each, where data can be stored in 2 GB of RAM and processed using four Virtex 4FX100 and one FX60 FPGAs. The VHDL code can acquire data for 16 channels and perform real-time processing for four channels per board. The receive processing chain consists of three FPGAs. The beamformer FPGA houses 24 focusing units (6 x 4-way) each working in parallel at 220 MHz for parallel four-channel beamforming. The fully parametric focusing unit calculates delays and apodization values in real time in 3D space and can produce 630 million complex samples per second. The processing can, thus, beamform 192 image lines consisting of 1024 complex samples for each emission at a rate of 3200 frames a second yielding full nonrecursive synthetic aperture B-mode imaging at more than 30 high resolution images a second.

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Practical Applications of Synthetic Aperture Imaging

Synthetic aperture imaging has been a focus of research for almost 3 decades. The research carried out at the Center for Fast Ultrasound Imaging has demonstrated that synthetic aperture focusing not only can be used in-vivo, but that it also yields superior B-mode and blood flow images. In the last years synthetic aperture focusing has moved from the lab to commercial products. The implementations vary in their scope and purpose. Some scanners use synthetic aperture imaging to improve the detail and contrast resolution of the system. Others to increase the image uniformity. Yet others use synthetic aperture acquisition to achieve high frame rates and superior flow estimations. On the other end of the scale are the systems that utilize synthetic aperture techniques to reduce the data rate and take advantage of modern computer hardware. Retrospective transmit beamformation, zone sonography, and multiple angle flash imaging are just a few of the names used to describe the commercial implementations of synthetic aperture focusing. Although they sound like different algorithms, they are the same in their core, as revealed in this paper.

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Preliminary evaluation of vector flow and spectral velocity estimation.
Spectral estimation is considered as the golden standard in ultrasound velocity estimation. For spectral velocity estimation the blood flow angle is set by the ultrasound operator. Vector flow provides temporal and spatial estimates of the blood flow angle and velocity. A comparison of vector flow estimation and spectral estimates is presented. The variation of the blood flow angle and the effect on the velocity estimate is investigated. The right common carotid arteries of three healthy volunteers were scanned. Real-time spectral and vector flow data were obtained simultaneously from one range gate line covering the vessel diameter. A commercial ultrasound scanner (ProFocus 2202, BK Medical, Denmark) and a 7.6 MHz linear transducer was used (8670, BK Medical). The mean vector blood flow angle estimations were calculated \(52(18);55(23);60(16)\)°. For comparison the fixed angles for spectral estimation were obtained \(52;56;52\)°. The mean vector velocity estimates at PS \(76(15);95(17);77(16)\)cm/s and at end diastole (ED) \(17(6);18(6);24(6)\)cm/s were calculated. For comparison spectral velocity estimates at PS \(77;110;76\)cm/s and ED \(18;18;20\)cm/s were obtained. The mean vector angle estimates agrees with the spectral flow angle. The vector velocity estimates agrees with the spectral estimates at PS and ED. From preliminary data it is concluded that vector flow angle estimation can replace the operator-dependent angle correction used for spectral velocity estimation.
**Principle and performance of the transverse oscillation vector velocity technique in medical ultrasound**

Medical ultrasound systems measure the blood velocity by tracking the blood cells motion along the ultrasound field. This is done by pulsing in the same direction a number of times and then finding, e.g., the shift in phase between consecutive pulses. Properly normalized this is directly proportional to the axial blood velocity. A major drawback is that only the axial velocity component is found. Often the lateral component is more important as blood vessels run parallel to the skin surface. The talk presents the transverse oscillation approach, which also can find the lateral velocity component by using a double oscillating field. A special estimator is then used for finding both the axial and lateral velocity components, so that both magnitude and phase can be calculated. The method for generating double oscillating ultrasound fields and the special estimator are described, and its performance revealed for a flow rig setup. Several examples from clinical use of the approach are shown. From these it is seen that both velocity magnitude and angle vary temporally and spatially across the cardiac cycle, and it is, thus, important to estimate both continuously over the image region and time.

**Quantification of complex blood flow using real-time in vivo vector flow ultrasound**

A quantitative method for distinguishing complex from non-complex flow patterns in ultrasound is presented. A new commercial BK Medical ultrasound scanner uses the Transverse Oscillation vector flow technique for visualising flow patterns in real-time. In vivo vector flow data of the blood flow patterns of the common carotid artery and the carotid bulb were obtained simultaneously as the basis for quantifying complex flow. The carotid bifurcation of two healthy volunteers were scanned. The presence of complex flow patterns from eight cardiac cycles were evaluated by three experts in medical ultrasound. From the same data the mean standard deviation of the flow angles (MSTDA) were calculated and compared to the expert evaluations. Comparison between the combined experts evaluations and the MSTDA was performed. Using linear regression analysis, a correlation coefficient of 0.925 was found. The upper and lower bounds for a 95% confidence interval of 0.974 and 0.792 respectively, were calculated. The MSTDA was below 25 for the common carotid artery and above 25 for the carotid bulb. Thus, the MSTDA value can distinguishing complex flow from non-complex flow and can be used as the basis for automatic detection of complex flow patterns.
Simulating Capacitive Micromachined Ultrasonic Transducers (CMUTs) using Field II

Field II has been a recognized simulation tool for piezoceramic medical transducer arrays for more than a decade. The program has its strength in doing fast computations of the spatial impulse response (SIR) from array elements by dividing the elements into smaller mathematical elements (MEs) from which it calculates the SIR responses. The program features predefined models for classical transducer geometries, but currently none for the fast advancing CMUTs. This work addresses the assumptions required for modeling CMUTs with Field II. It is shown that rectangular array elements, populated with cells, can be well approximated by neglecting the cells. Further, it is demonstrated that scaling of the SIR translates into better computational efficiency.

Simulation of high quality ultrasound imaging

In this paper the influence using an idealized transducer model (ITM) and a realistic transducer model (RTM) is investigated in a comparative study between Synthetic Aperture Sequential Beamformation (SASB) and Dynamic Receive Focus (DRF).

Simulation of high quality ultrasound imaging

In this paper the influence using an idealized transducer model (ITM) and a realistic transducer model (RTM) is investigated in a comparative study between Synthetic Aperture Sequential Beamformation (SASB) and Dynamic Receive Focus (DRF).
**Simulation of High Quality Ultrasound Imaging**

This paper investigates if the influence on image quality using physical transducers can be simulated with sufficient accuracy to reveal system performance. The influence is investigated in a comparative study between Synthetic Aperture Sequential Beamformation (SASB) and Dynamic Receive Focus (DRF). The study is performed as a series of simulations and validated by measurements. The influence from individual element impulse response, phase, and amplitude deviations are quantized by the lateral resolution (LR) at Full Width at Half Maximum (FWHM), Full Width at One-Tenth Maximum (FWOTM), and at Full Width at One-Hundredth Maximum (FWOHM) of 9 points spread functions resulting from evenly distributed point targets at depths ranging from 10 mm to 90 mm. The results are documented for a 64 channel system, using a 192 element linear array transducer model. A physical BK Medical 8804 transducer is modeled by incorporating measured element pulse echo responses into the simulation software. Validation is performed through measurements on a water phantom with three metal wires, each with a diameter of 0.07 mm. Results show that when comparing measurement and simulation, the lateral beam profile using SASB can be estimated with a correlation coefficient of 0.97. Further, it is shown that SASB successfully maintains a constant LR though depth at FWHM, and is a factor of 2.3 better than DRF at 80 mm. However, when using SASB the LR at FWOHM is affected by non-ideal element responses. Introducing amplitude and phase compensation, the LR at FWOHM improves from 6.3 mm to 4.7 mm and is a factor of 2.2 better than DRF. This study has shown that individual element impulse response, phase, and amplitude deviations are important to include in simulated system performance evaluations. Furthermore, it is shown that SASB provides a constant LR through depth and has improved resolution and contrast compared to DRF.

**Simulation of Second Harmonic Ultrasound Fields**

A non-linear ultrasound imaging simulation software should be capable of simulating the non-linear fields for any kind of transducer, focusing, apodization, and attenuation. At present, a major issue is the overlong simulation time of the non-linear software. An Angular Spectrum Approach (ASA) using a quasi-linear approximation for solving the Westervelt equation can simulate the second harmonic pressure at any distance. Therefore, it shortens the execution time compared with the operator splitting method. The purpose of this paper is to implement the monochromatic solution for the second harmonic component based on ASA and Field II, and to compare with results from the simulation program Abersim. A linear array transducer with a center frequency of 4 MHz and 64 active elements is used as the transmitting source. The initial plane is 5 mm away from the transducer surface, and the fundamental pressure is calculated by Field II. The second harmonic pressure in k-space along the propagating direction is calculated as an auto-convolution of the fundamental pressure multiplied by an exponential propagating coefficient. In this case, the second harmonic pressure can be calculated using ASA for any plane parallel to the initial plane. In the focal plane (elevation-lateral) at 60 mm from the transducer surface, calculated by ASA, the RMS errors for the fundamental component are 2.66% referred to Field II and 4.28% referred to Abersim. For the second harmonic component, the RMS error is 0.91% referred to Abersim.
Synthetic aperture flow imaging using a dual beamformer approach

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Synthetic aperture flow estimation has several advantages compared to the conventional flow estimation however this requires a high number of calculations. A dual beamformer approach is proposed to lower the number of calculations and maintain a beamforming quality sufficient for flow estimation. This approach contains a two-stage procedure using two different beamformers. The first stage beamformer has a single focal point in both transmit and receive. The fully dynamic second beamformer uses the data from the first stage to beamform the image. Focal points in the first beamformer are considered as virtual sources in the second beamformation algorithm. High resolution image lines are generated by the second stage beamformation. Four emissions in each emission sequence repeat over time. The velocity is estimated by cross correlating high resolution lines which is a function of depth. The cross correlation functions are averaged over 16 high resolution image pairs to improve the better estimates. Varying interspaces [2, 6, 10, 14] resulted in the standard deviation and the bias B of the axial velocity were [1.92, 2.0, 2.07, 2.21] % and [0.61, 1.07, 1.29, 1.5] % compared to the peak velocity respectively. The parameter study showed that larger interspaces gave an increased standard deviation and the bias. Furthermore more emissions in averaging gave better performance. The performance of the simulation indicates that this dual beamformer approach is able to estimate the flow velocity. Interspaces between emissions and number of emission sets in averaging have an influence on the estimation.

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Testing of a spatial impulse response algorithm for double curved transducers
The spatial impulse response (SIR) method for solving the Rayleigh integral is a well known method for fast time response simulation of acoustic waves. Several analytical expressions have been found for simple transducer geometries such as rectangles and discs. However, no analytical solution is known for double curved transducers (DCT), i.e., transducers with both concave and convex radius. To calculate the SIR from such transducers Field II uses a far-field approximation by dividing the surface into smaller flat elements and then performing a summation of the response from all the elements using Huygen's principle. This calculation method involves several summations, and it relies on exact phase calculation to avoid numerical noise in the response. A stable analytical expression for the SIR would thus be beneficial to the Field II software as an alternative solver. A semi-analytic algorithm (SAA) has been developed, and it is the objective of this work to validate an analytical approximation of the algorithm as an alternative solver for Field II. Two approximations of a SAA that efficiently find the SIR for DCT have been implemented into a MATLAB and a C-code environment. The root mean square (RMS) error of calculating the SIR using Field II and the C-implemented approximations are calculated relative to a high resolution solution obtained with MATLAB on a DCT, a linear concave, and a flat transducer. The computation time for solving an aperture 400 times is also found. Calculations are performed at sampling frequencies ranging from 100 MHz to 15 GHz in steps of 100 MHz. The transducer width is 250 μm and the height is 10 mm. The C-implementation exhibits errors ranging from 4.910^-4 % to 0.91 % and Field II 0.0117 % to 0.94 %. A slight trade-off between accuracy and computation time is found. Field II outperforms the SAA in computation time if high accuracy is not needed. However, if a higher accuracy is required, the SAA is the best model choice. © 2010 IEEE.

Three-Dimensional Synthetic Aperture Focusing Using a Rocking Convex Array Transducer
Volumetric imaging can be performed using 1-D arrays in combination with mechanical motion. Outside the elevation focus of the array, the resolution and contrast quickly degrade compared with the lateral plane, because of the fixed transducer focus. This paper shows the feasibility of using synthetic aperture focusing for enhancing the elevation focus for a convex rocking array. The method uses a virtual source (VS) for defocused multi-element transmit, and another VS in
the elevation focus point. This allows a direct time-of-flight to be calculated for a given 3-D point. To avoid artifacts and increase SNR at the elevation VS, a plane-wave VS approach has been implemented. Simulations and measurements using an experimental scanner with a convex rocking array show an average improvement in resolution of 26% and 33%, respectively. This improvement is also seen in in vivo measurements. An evaluation of how a change in transducer design will affect the resolution improvement shows a potential for using a modified transducer for 3-D imaging with improved elevation focusing and contrast.

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Transducer models in the ultrasound simulation program FIELD II and their accuracy
The FIELD II simulation program can be used for simulating any kind of linear ultrasound fields. The program is capable of describing multi-element transducers used with any kind of excitation, apodization, and focusing. The program has been widely used in both academia and by commercial ultrasound companies for investigating novel transducer geometries and advanced linear imaging schemes. The program models transducer geometries using a division of the transducer elements into either rectangles, triangles, or bounding lines. The precision of the simulation and the simulation time is intimately linked through the choice of the fundamental elements. The rectangular elements use a far-field approximation, whereas the two other methods use the full analytic solution, leading to a higher precision at the price of a slower simulation time. The talk will describe the different compromises and solutions to obtain a fast simulation and still attain a high precision including a newly developed semi-analytic solution for a convex surface elements.

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Transverse Oscillations for Phased Array Vector Velocity Imaging

Medical ultrasound imaging is widely used to visualize blood flow in the human circulatory system. However, conventional methods are angle dependent. The Transverse Oscillation (TO) method is able to measure the lateral velocity component, and it has been demonstrated in in vivo measurements of superficial blood vessels. To broaden the usability of the method, it should be expanded to a phased array geometry enabling vector velocity imaging of the heart. Therefore, the scan depth has to be increased to 10-15 cm. This paper presents suitable pulse echo fields (PEF). Two lines are beamformed in receive to obtain lateral spatial in-phase and quadrature components. The relative mean bias and standard deviation of the lateral velocity component are computed as performance measures. For the PEF, the coefficient of variance, CV, of the spectral frequencies, and the energy ratio, ER, of leakage into negative frequencies are used as metrics to assess estimator performance. At 10 cm's depth for an initial setup, the relative mean bias and standard deviation are 9.1% and 9.5%, respectively. At a depth of 15 cm, the values are 20% and 13%, respectively. The PEF metric ER can be used to assess the bias (correlation coefficient, R: -0.76), and therefore predict estimator performance. CV is correlated with the standard deviation (R=0.74). The results demonstrate the potential for using a phased array for vector velocity imaging at larger depths, and potentially for imaging the heart.

Ultrasound Image Quality Assessment: A framework for evaluation of clinical image quality

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Ultrasound Image Quality Assessment: A framework for evaluation of clinical image quality

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Ultrasound Image Quality Assessment: A framework for evaluation of clinical image quality

Improvement of ultrasound images should be guided by their diagnostic value. Evaluation of clinical image quality is generally performed subjectively, because objective criteria have not yet been fully developed and accepted for the evaluation of clinical image quality. Based on recommendation 500 from the International Telecommunication Union - Radiocommunication (ITU-R) for such subjective quality assessment, this work presents equipment and a methodology for clinical image quality evaluation for guiding the development of new and improved imaging. The system is based on a BK-Medical 2202 ProFocus scanner equipped with a UA2227 research interface, connected to a PC through X64-CL Express camera link. Data acquisition features subject data recording, loading/saving of exact scanner settings (for later experiment reproducibility), free access to all system parameters for beamformation and is applicable for clinical use. The free access to all system parameters enables the ability to capture standardized images as found in the clinic and experimental data from new processing or beamformation methods. The length of the data sequences is only restricted by the memory of the external PC. Data may be captured interleaved, switching between multiple setups, to maintain identical transducer, scanner, region of interest and recording time on both the experimental- and standardized images. Data storage is approximately 15.1 seconds pr. 3 sec sequence including complete scanner settings and patient information, which is fast enough to get sufficient number of scans under realistic operating conditions, so that statistical evaluation is valid and reliable.

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Using Phased Array for Transverse Oscillation Vector Velocity Imaging

Objective Previous in vivo measurements of superficial blood vessels using linear arrays have demonstrated that the Transverse Oscillation (TO) method is able to measure the lateral velocity component contrary to conventional velocity estimators. To broaden its usability, the method should be expanded to phased arrays enabling vector velocity imaging of the heart. Therefore, the performance of the TO estimator has to be evaluated for depths up to 10-15 cm. Methods The TO method is based on creating a double oscillating field. Flow phantoms were simulated with a transverse (90°) parabolic flow profile (peak = 1 m/s) and a vessel radius of 5 mm, and 'scanned' orthogonal to the flow with a 3.5 MHz phased array transducer. The performance of the lateral velocity estimates were evaluated by calculating the relative mean bias, Br, and relative mean standard deviation, σr. Results With a F-number of 10 in transmit and receive peaks (spaced 96 elements apart) shaped as Hanning functions, parabolic velocity profiles were be observed for all cases. At depths of 10, 12, and 15 cm, the following results were obtained in pairs of σr & Br: 6.5% & 2.6%, 7.5% & 3.8%, and 8.5% & 4.2%, respectively. Conclusions The results show that the TO estimator performs comparably with a standard axial estimator at depths of 10-15 cm. This demonstrates the potential of the TO method for scanning the heart using a phased array.
Method and apparatus for processing ultrasonic signals.

Adaptive Receive and Transmit Apodization for Synthetic Aperture Ultrasound Imaging

This paper suggests a framework for utilizing adaptive, data-dependent apodization weights on both the receiving and transmitting aperture for Synthetic Aperture (SA) ultrasound imaging. The suggested approach is based on the Minimum Variance (MV) beamformer and consists of two steps. A set of uniquely designed receive apodization weights are applied to pre-summed element data forming a set of adaptively weighted images; these are in SA literature conventionally referred to as low-resolution images. The adaptive transmit apodization is obtained by applying MV across the full set of single emission images before summation. The method is investigated using simulated SA ultrasound data obtained using Field II. Data of 13 point targets distributed at depths from 40 mm to 70 mm, and a 5.5 MHz, 64-element linear array transducer have been used. The investigation has shown that the introduction of adaptive apodization weights on the transmitting aperture provides a main-lobe reduction (estimated at -30 dB) by a factor of 1.8 compared to the method using adaptive apodization weights on the receiving aperture only.
Adaptive Spectral Doppler Estimation

In this paper, 2 adaptive spectral estimation techniques are analyzed for spectral Doppler ultrasound. The purpose is to minimize the observation window needed to estimate the spectrogram to provide a better temporal resolution and gain more flexibility when designing the data acquisition sequence. The methods can also provide better quality of the estimated power spectral density (PSD) of the blood signal. Adaptive spectral estimation techniques are known to provide good spectral resolution and contrast even when the observation window is very short. The 2 adaptive techniques are tested and compared with the averaged periodogram (Welch’s method). The blood power spectral capon (BPC) method is based on a standard minimum variance technique adapted to account for both averaging over slow-time and depth. The blood amplitude and phase estimation technique (BAPES) is based on finding a set of matched filters (one for each velocity component of interest) and filtering the blood process over slow-time and averaging over depth to find the PSD. The methods are tested using various experiments and simulations. First, controlled flow-rig experiments with steady laminar flow are carried out. Simulations in Field II for pulsating flow resembling the femoral artery are also analyzed. The simulations are followed by in vivo measurement on the common carotid artery. In all simulations and experiments it was concluded that the adaptive methods display superior performance for short observation windows compared with the averaged periodogram. Computational costs and implementation details are also discussed.

Ambient pressure sensitivity of microbubbles investigated through a parameter study

Measurements on microbubbles clearly indicate a relation between the ambient pressure and the acoustic behavior of the bubble. The purpose of this study was to optimize the sensitivity of ambient pressure measurements, using the subharmonic component, through microbubble response simulations. The behavior of two microbubbles corresponding to two different contrast agents was investigated as a function of driving pulse and ambient overpressure, pov. Simulations of Levovist using a rectangular driving pulse show an almost linear reduction in the subharmonic component as pov is increased. For a 20 cycles driving pulse, a reduction of 4.6 dB is observed when changing pov from 0 to 25 kPa. Increasing the pulse duration makes the reduction even more clear. For a pulse with 64 cycles, the reduction is 9.9 dB. This simulation is in good correspondence with measurement results presented by Shi et al. 1999, who found a linear reduction of 9.6 dB. Further simulations of Levovist show that also the shape and the acoustic pressure of the driving pulse are very important factors. The best pressure sensitivity of Levovist was found to be 0.68 dB/kPa. For Sonazoid, a sensitivity of 1.14 dB/kPa has been found, although the reduction is not completely linear as a function of the ambient pressure.
A new tool fixation for external 3D head tracking using the Polaris Vicra system with the HRRT PET scanner

Objectives: The Polaris Vicra system (Northern Digital Inc.) is used for external 3D head registration with the Siemens HRRT brain PET. Our new tool fixation using a standard bandaid with a velcro-strap implies an improved frame repositioning.

Methods: Head movements during serial PET 15O-water studies for up to 75 min (3-8 injections) were registered by the Polaris system in 4 volunteers. The tracking tool was fixed. Scans were divided into subframes based on the registered movements and reconstructed using the 3D-OSEM PSF method. The reconstructed subframes were repositioned to a reference position and pairwise similarity of subframes was evaluated before and after the repositioning.

Results: Registered movements during scans were less than 4.3mm with. Images were compared before/after motion correction. Conclusions: Our new velcro band-aid fixation is suitable for clinical use: easy to use, disposable, comfortable, independent of head size, and has low cost. It is reliable with only a limited contact area with the movable structures of the head. Registered movements corresponded to those seen on the PET images and correlations between scans were improved after repositioning based on the tracked head position.

Angular Spectrum Simulation of Pulsed Ultrasound Fields

The optimization of non-linear ultrasound imaging should in a first step be based on simulation, as this makes parameter studies considerably easier than making transducer prototypes. Such a simulation program should be capable of simulating non-linear pulsed fields for arbitrary transducer geometries for any kind of focusing and apodization. The Angular Spectrum Approach (ASA) is capable of simulating monochromatic non-linear acoustic wave propagation. However, for ultrasound imaging the time response of each specific point in space is required, and a pulsed ASA simulation with multi temporal frequencies must be performed. Combining it with Field II, the generation of non-linear simulation for any geometry with any excitation array transducer becomes feasible. The purpose of this paper is to make a general pulsed simulation software using the modified ASA. Linear and phased array transducers are used to create the source plane, which is 2 mm from the transducer surface. Field II generates pulses for all the points in the source plane,
and the 3D matrix data (1D time, 2D space) are obtained. The pulses in the simulated plane are calculated by the modified ASA, which is the 3D inverse Fourier transform of the values in a series of planes corresponding to each temporal frequency. The values in the planes are the multiplications between the 2D spatial Fourier transform of the pressure in the source plane and the ASA propagator for every temporal frequency component. The beam focusing is produced by Field II in the source plane. A rectangular plane matched to the shape of the transducer surface is chosen as the source. The plane covering 12.7×156.3 mm² has 33,407 points with a spatial sampling interval of 1/2 wavelength. A comparison of ASA to Field II at the focal point (0, 0, 64) mm for a 64-element, 2 MHz linear array transducer has been made in the paper, and the root mean square (RMS) error is 2.7%. For further validation, 3 randomly selected points in the simulated plane have RMS errors of 12.5%, 13.3%, 23.4% at the positions (3.9, -1.5, 64), (-1.9, 1.9, 64), (6.2, -4.2, 64) mm. The RMS error of the pulses for all points in the simulated plane is 10.9%. The good agreement between ASA and Field II simulation for the pulsed ultrasound fields obtained in this paper makes it possible to expand Field II to non-linear pulsed fields.

APES Beamforming Applied to Medical Ultrasound Imaging

Recently, adaptive beamformers have been introduced to medical ultrasound imaging. The primary focus has been on the minimum variance (MV) (or Capon) beamformer. This work investigates an alternative but closely related beamformer, the Amplitude and Phase Estimation (APES) beamformer. APES offers added robustness at the expense of a slightly lower resolution. The purpose of this study was to evaluate the performance of the APES beamformer on medical imaging data, since correct amplitude estimation often is just as important as spatial resolution. In our simulations we have used a 3.5 MHz, 96 element linear transducer array. When imaging two closely spaced point targets, APES displays nearly the same resolution as the MV, and at the same time improved amplitude control. When imaging cysts in speckle, APES offers speckle statistics similar to that of the DAS, without the need for temporal averaging.
Broadband Minimum Variance Beamforming for Ultrasound Imaging
A minimum variance (MV) approach for near-field beamforming of broadband data is proposed. The approach is implemented in the frequency domain, and it provides a set of adapted, complex apodization weights for each frequency subband. The performance of the proposed MV beamformer is tested on simulated data obtained using Field II. The method is validated using synthetic aperture data and data obtained from a plane wave emission. Data for 13 point targets and a circular cyst with a radius of 5 mm are simulated. The performance of the MV beamformer is compared with delay-and-sum (DS) using boxcar weights and Harming weights and is quantified by the full width at half maximum (FWHM) and the peak-side-lobe level (PSL). Single emission (DS boxcar, DS Harming, MV) provide a PSL of {-16, -36, -49} dB and a FWHM of {0.79, 1.33, 0.08} mm. Using all 128 emissions, (DS boxcar, DS Harming, MV) provides a PSL of {-32, -49, -65} dB, and a FWHM of {0.63, 0.97, 0.08} mm. The simulations have shown that the frequency subband MV beamformer provides a significant increase in lateral resolution compared with DS, even when using considerably fewer emissions. An increase in resolution is seen when using only one single emission. Furthermore, the effect of steering vector errors is investigated. The steering vector errors are investigated by applying an error of the sound speed estimate to the ultrasound data. As the error increases, it is seen that the MV beamformer is not as robust compared with the DS beamformer with boxcar and Harming weights. Nevertheless, it is noted that the DS does not outperform the MV beamformer. For errors of 2% and 4% of the correct value, the FWHM are {0.81, 1.25, 0.34} mm and {0.89, 1.44, 0.46} mm, respectively.

Evaluation Study of Fast Spectral Estimators Using In-vivo Data
Spectrograms in medical ultrasound are usually estimated with Welch's method (WM). To achieve sufficient spectral resolution and contrast, WM uses an observation window (OW) of up to 256 emissions per estimate. Two adaptive filterbank methods have been suggested to reduce the OW: Blood spectral Power Capon (BPC) and the Blood Amplitude and Phase Estimation method (BAPES). Ten volunteers were scanned over the carotid artery. From each dataset, 28 spectrograms were produced by combining four approaches (WM with a Hanning window (W.HAN), WM with a boxcar window (W.BOX), BPC and BAPES) and seven OWs (128, 64, 32, 16, 8, 4, 2). The full-width-at-half-maximum (FWHM)
High Resolution Ultrasound Imaging Using Adaptive Beamforming with Reduced Number of Active Elements

In this paper, the adaptive, minimum variance (MV) beamformer is applied to ultrasound data. Due to near-field properties, the energy of the ultrasound data reduces towards the edges of the transducer. The influence of this near-field effect is demonstrated, and a method to reduce this influence is proposed. By reducing the number of active sensor elements, an increased resolution can be obtained with the MV beamformer. This observation is directly opposite the well-known relation between the spatial extent of the aperture and the achievable resolution. The investigations are based on Field II simulated data using a 128-element transducer with a large spatial extent. The results show that an increased resolution can be obtained, when using only the central part of the transducer compared to using the entire spatial extent. Using the central 32 or 48 elements provides an increased resolution compared to using all 128 elements.

In vivo comparison of three ultrasound vector velocity techniques to MR phase contrast angiography

The objective of this paper is to validate angle independent vector velocity methods for blood velocity estimation. Conventional Doppler ultrasound (US) only estimates the blood velocity along the US beam direction where the estimate is angle corrected assuming laminar flow parallel to vessel boundaries. This results in incorrect blood velocity estimates, when angle of insonation approaches 90° or when blood flow is non-laminar. Three angle independent vector velocity methods are evaluated in this paper: directional beamforming (DB), synthetic aperture flow imaging (STA) and transverse...
The performances of the three methods were investigated by measuring the stroke volume in the right common carotid artery of 11 healthy volunteers with magnetic resonance phase contrast angiography (MRA) as reference. The correlation with confidence intervals (CI) between the three vector velocity methods and MRA were: DB vs. MRA: \( R = 0.84 \) (\( p < 0.01 \), 95% CI: 0.49–0.96); STA vs. MRA: \( R = 0.71 \) (\( p < 0.05 \), 95% CI: 0.19–0.92) and TO vs. MRA: \( R = 0.91 \) (\( p < 0.01 \), 95% CI: 0.69–0.98). No significant differences were observed for any of the three comparisons (DB vs. MRA: \( p = 0.65 \); STA vs. MRA: \( p = 0.24 \); TO vs. MRA: \( p = 0.36 \)). Bland–Altman plots were additionally constructed, and mean differences with limits of agreements (LoA) for the three comparisons were: DB vs. MRA = 0.17 ml (95% CI: −0.61–0.95) with LoA = −2.11–2.44 ml; STA vs. MRA = −0.55 ml (95% CI: −1.54–0.43) with LoA = −3.42–2.32 ml; TO vs. MRA = 0.24 ml (95% CI: −0.32–0.81) with LoA = −1.41–1.90 ml. According to the results, reliable volume flow estimates can be obtained with all three methods. The three US vector techniques can yield quantitative insight into flow dynamics and visualize complex flow patterns, which potentially can give the clinician a novel tool for cardiovascular disease assessment.
In Vivo Validation of a Blood Vector Velocity Estimator with MR Angiography
Conventional Doppler methods for blood velocity estimation only estimate the velocity component along the ultrasound beam direction. This implies that a Doppler angle under examination close to 90° results in unreliable information about the true blood direction and blood velocity. The novel method transverse oscillation (TO), which combines estimates of the axial and the transverse velocity components in the scan plane, makes it possible to estimate the vector velocity of the blood regardless of the Doppler angle. The present study evaluates the TO method with magnetic resonance phase contrast angiography (MRA) by comparing in vivo measurements of stroke volume. Eleven healthy volunteers were included in this prospective study. From the obtained data sets recorded with the 2 modalities, vector velocity sequences were constructed and stroke volume calculated. Angle of insonation was approximately 90° for TO measurements. The correlation between the stroke volume estimated by TO and MRA was 0.91 (p <0.01) with the equation for the line of regression: MRA = 1.1•TO-0.4. A Bland-Altman plot was additionally constructed where the mean difference was 0.2 ml with limits of agreement at −1.4 ml and 1.9 ml. The results indicate that reliable vector velocity estimates can be obtained in vivo using the presented angle-independent 2-D vector velocity method. The TO method can be a useful alternative to conventional Doppler systems by avoiding the angle artifact, thus giving quantitative velocity information.
Non-invasive estimation of blood pressure using ultrasound contrast agents

Local blood pressure measurements provide important information on the state of health of organs in the body and can be used to diagnose diseases in the heart, lungs, and kidneys. This paper presents an experimental setup for investigating the ambient pressure sensitivity of a contrast agent using diagnostic ultrasound. The setup resembles a realistic clinical setup utilizing a single array transducer for transmit and receive. The ambient pressure sensitivity of SonoVue (Bracco, Milano, Italy) was measured twice using two different acoustic driving pressures, which were selected based on a preliminary experiment. To compensate for variations in bubble response and to make the estimates more robust, the relation between the energy of the subharmonic and the fundamental component was chosen as a measure over the subharmonic peak amplitude. The preliminary study revealed the growth stage of the subharmonic component to occur at acoustic driving pressures between 300 and 500 kPa. Based on this, the pressure sensitivity was investigated using a driving pressure of 485 and 500 kPa. At 485 kPa, a linear pressure sensitivity of 0.42 dB/kPa was found having a linear correlation coefficient of 0.94. The second measurement series at 485 kPa showed a sensitivity of 0.41 dB/kPa with a correlation coefficient of 0.89. Based on the measurements at 500 kPa, this acoustic driving pressure was concluded to be too high causing the bubbles to be destroyed. The pressure sensitivity for these two measurement series were 0.42 and 0.25 dB/kPa with linear correlation coefficients of 0.98 and 0.93, respectively.

Parameter sensitivity study of a Field II multilayer transducer model on a convex transducer

A multilayer transducer model for predicting a transducer impulse response has in earlier works been developed and combined with the Field II software. This development was tested on current, voltage, and intensity measurements on piezoceramics discs (Bæk et al. IUS 2008) and a convex 128 element ultrasound imaging transducer (Bæk et al. ICU 2009). The model benefits from its 1D simplicity and has shown to give an amplitude error around 1.7-2 dB. However, any prediction of amplitude, phase, and attenuation of pulses relies on the accuracy of manufacturer supplied material characteristics, which may be inaccurate estimates. The previous test cases have assumed the simulation parameters to be exact as received from the manufacturer. In this paper the influence of a deviation in the accuracy of the different
parameters is studied by comparing simulation and measurement. The long term objective is a quantitative calibrated model for a complete ultrasound system. This includes a sensitivity study as presented here.

Statement of Contribution/Methods
The study alters 35 different model parameters which describe a 128 element convex transducer from BK Medical Aps. The changes are within ±20 % of the values supplied by the manufacturer, which are considered the zero reference (ZR). Simulations of a system consisting of a transmit unit, a five material layer transducer, and the FIELD II predicted pressure are performed by altering in turn the value of a single parameter in steps of 2 %. The remaining simulation parameters are held fixed at the ZR. The influence of the parameter change is determined by calculating the pressure and the intensity at a distance of 112 mm on an element’s center axis and comparing it with hydrophone measurements. These are performed with a water bath hydrophone setup using an Agilent MSO6014A oscilloscope that is set to average consecutive pulses 48 times for noise reduction of the hydrophone output. A commercial transmitter unit is used to drive the transducer with a 10 cycle tone burst at a frequency of 4.0 MHz and a maximum excitation amplitude of 31 volt.

Results
Predictions using the ZR give a pressure pulse error (PPE) and an intensity error (IE) of 32 % and 23 %, respectively, relative to the measured. Altering the piezoelectric permittivity +12 % from ZR decreases the PPE to 30 % and the IE to 2 % relative to the measured. Changing the stiffness constant of the lens -4 % from ZR increases the PPE and the IE with 6 % and 1 %, respectively. Performing the same with the ceramic stiffness the PPE is lowered 1.5 % and the IE is lowered 12 %.

Discussion and Conclusions
PPEs are found mainly to be sensitive to lens properties and piezoceramic properties, but minor sensitive to changes in matching layers. IEs are mainly sensitive to the piezoceramic properties. The study shows that minor changes can improve predictions significantly.

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Performance of the Transverse Oscillation method using beamformed data from a commercial scanner
Blood velocity estimates using conventional color flow imaging (CFI) or Doppler techniques are angle dependent. One of the proposed techniques to overcome this limitation is the Transverse Oscillation (TO) method, which also estimates the lateral velocity components. The performance of this is evaluated on a commercial platform. Beamformed data are acquired using a commercial BK Medical scanner as opposed to the previously reported results obtained with the experimental scanner RASMUS. The implementation is evaluated using an in-house circulating flow rig by calculating the relative mean standard deviation and bias of the velocity components. The relative mean standard deviation decreases as the number of shots per estimate increases and a value of 5% is obtained for 64 shots per estimate. For a center frequency of 5 MHz at 60Å°, 75Å°, and 90Å°, the relative mean bias varies from 21% to 27% and is lowest at a transmit focal depth close to the center of the vessel. The present performance is comparable with the results from the experimental scanner and simulations. It is obtained with only few changes to the conventional CFI setup and further optimization can improve the performance. This illustrates the feasibility of implementing the TO method on a commercial platform for real-time estimation.

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Precise Time-of-Flight Calculation For 3-D Synthetic Aperture Focusing

Conventional linear arrays can be used for 3D ultrasound imaging, by moving the array in the elevation direction and stacking the planes in a volume. The point spread function (PSF) is larger in the elevation plane, as the aperture is smaller and has a fixed elevation focus. Resolution improvements in elevation can be achieved by applying synthetic aperture (SA) focusing to the beamformed in-plane RF-data. The proposed method uses a virtual source (VS) placed at the elevation focus for postbeamforming. This has previously been done in two steps, in plane focusing followed by SA post-focusing in elevation, because of a lack of a simple expression for the exact time of flight (ToF). This paper presents a new method for calculating the ToF for a 3D case in a single step using a linear array. This method is more flexible than the previously proposed method and is able to beamform a fewer number of points much more efficiently. The method is evaluated using both simulated data and phantom measurements using the RASMUS experimental scanner. Computational cost for the method is higher than the 2-step method for a full volume beamforming, but allows for a reduction by an order of magnitude if three planes are used for real-time visualization. In addition, the need for a temporary storage of beamformed data is removed.
Spatial resolution of the HRRT PET scanner using 3D-OSEM PSF reconstruction

The spatial resolution of the Siemens High Resolution Research Tomograph (HRRT) dedicated brain PET scanner installed at Copenhagen University Hospital (Rigshospitalet) was measured using a point-source phantom with high statistics. Further, it was demonstrated how the newly developed 3D-OSEM PSF reconstruction can improve the resolution in reconstructed images with high signal-to-noise-ratios.

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Coded Ultrasound for Blood Flow Estimation Using Subband Processing

This paper investigates the use of coded excitation for blood flow estimation in medical ultrasound. Traditional autocorrelation estimators use narrow-band excitation signals to provide sufficient signal-to-noise-ratio (SNR) and velocity estimation performance. In this paper, broadband coded signals are used to increase SNR, followed by subband processing. The received broadband signal is filtered using a set of narrow-band filters. Estimating the velocity in each of the bands and averaging the results yields better performance compared with what would be possible when transmitting a narrow-band pulse directly. Also, the spatial resolution of the narrow-band pulse would be too poor for brightness-mode (B-mode) imaging, and additional transmissions would be required to update the B-mode image. For the described approach in the paper, there is no need for additional transmissions, because the excitation signal is broadband and has good spatial resolution after pulse compression. This means that time can be saved by using the same data for B-mode imaging and blood flow estimation. Two different coding schemes are used in this paper, Barker codes and Golay codes. The performance of the codes for velocity estimation is compared with a conventional approach transmitting a narrow-band pulse. The study was carried out using an experimental ultrasound scanner and a commercial linear array 7 MHz transducer. A circulating flow rig was scanned with a beam-to-flow angle of 60°. The flow in the rig was laminar and had a parabolic flow-profile with a peak velocity of 0.09 m/s. The mean relative standard deviation of the velocity estimate using the reference method with an 8-cycle excitation pulse at 7 MHz was 0.544% compared with the peak velocity in the rig. Two Barker codes were tested with a length of 5 and 13 bits, respectively. The corresponding mean relative standard deviations were 0.367% and 0.310%, respectively. For the Golay coded experiment, two 8-bit codes were used, and the mean relative standard deviation was 0.335%.

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Duplex scanning using sparse data sequences

The velocity distribution in vessels can be displayed using duplex scanning where B-mode acquisitions are interspaced with the velocity data. This gives an image for orientation, but lowers the maximum detectable velocity by a factor of two. Other pulse sequences either omit the B-mode image or leaves gaps in the velocity data, which makes it difficult to output audio data. The near full velocity range can be maintained and B-mode images shown by using a sparse data sequence with velocity and B-mode samples intermixed. The B-mode samples are placed in a (sparse) periodical pattern, which makes reconstruction of the missing samples possible. The periodic pattern has the length $T = M + A$ samples, where $M$ are for B-mode and $A$ for velocity estimation. The missing samples can now be reconstructed using a filter bank. One filter bank reconstructs one missing sample, so the number of filter banks corresponds to $M$. The number of sub filters in every filter bank is the same as $A$. Every sub filter contains fractional delay (FD) filter and an interpolation function. Many different sequences can be selected to adapt the B-mode frame rate needed. The drawback of the method is that the maximum velocity detectable is scaled by the factor $A/T$. The approach has been investigated using in vivo RF data from the Hepatic vein, Carotid artery and Aorta from a 33 year old healthy male. A B-K Medical 3535 ultrasound scanner has been used in Duplex mode with a BK 8556, 3.2 MHz linear array probe. The sampling frequency, the fprf and the resolution are 15 MHz, 3.5 kHz, and 12 bit sample (8 kHz and 16 bit for the Carotid artery). The resulting data contains 8000 RF lines with 128 samples at a depth of 45 mm for the vein and 50 mm for Aorta. Sparse sequences are constructed from the full data sequences to have both a reference sequence and sparse data sequences. After reconstruction the reference and the reconstructed spectrum are almost identical when characterized by the Signal to Noise Ratio (SNR). This is investigated and optimized by altering the number of filter coefficients, the implementation of the fractional delay filter, and the sparse sequence. The Hepatic vein data are processed with 5 filter coefficients, a FD filter implemented with a Knab window and sequence length $T$ of 10 RF lines. By removing 7 lines the SNR is calculated to be 30 dB. When reconstruction over half the RF lines possible then two spectograms can be acquired at the same time. The investigation of Aorta shows, that because the spectrum is wider, it puts some restrains on the selection of the sequence. The shortest sequence for getting a good spectrum consists of 7 lines, with one missing line (14.3%, SNR = 31.6 dB). Using sparse sequences both B-mode and velocity data can be acquired with only a modest degradation in maximum velocity. The reconstruction gives errors below the normal noise level in velocity data, and the full audio signal is precisely reconstructed from the data.
Estimating 2-D Vector Velocities Using Multidimensional Spectrum Analysis

Wilson (1991) presented an ultrasonic wide-band estimator for axial blood flow velocity estimation through the use of the 2-D Fourier transform. It was shown how a single velocity component was concentrated along a line in the 2-D Fourier space, where the slope was given by the axial velocity. Later, it was shown that this approach could also be used for finding the lateral velocity component by also including a lateral sampling. A single velocity component would then be concentrated along a plane in the 3-D Fourier space, tilted according to the 2 velocity components. This paper presents 2 new velocity estimators for finding both the axial and lateral velocity components. The estimators essentially search for the plane in the 3-D Fourier space, where the integrated power spectrum is largest. The first uses the 3-D Fourier transform to find the power spectrum, while the second uses a minimum variance approach. Based on this plane, the axial and lateral velocity components are estimated. Several phantom measurements, for flow-to-depth angles of 60, 75, and 90 degrees, were performed. Multiple parallel lines were beamformed simultaneously, and 2 different receive apodization schemes were tried. The 2 estimators were then applied to the data. The axial velocity component was estimated with an average standard deviation below 2.8% of the peak velocity, while the average standard deviation of the lateral velocity estimates was between 2.0% and 16.4%. The 2 estimators were also tested on in vivo data from a transverse scan of the common carotid artery, showing the potential of the vector velocity estimation method under in vivo conditions.

Fast Blood Vector Velocity Imaging using ultrasound: In-vivo examples of complex blood flow in the vascular system

Conventional ultrasound methods for acquiring color flow images of the blood motion are restricted by a relatively low frame rate and angle dependent velocity estimates. The Plane Wave Excitation (PWE) method has been proposed to solve these limitations. The frame rate can be increased, and the 2-D vector velocity of the blood motion can be estimated. The transmitted pulse is not focused, and a full speckle image of the blood can be acquired for each emission. A 13 bit Barker code is transmitted simultaneously from each transducer element. The 2-D vector velocity of the blood is found using 2-D speckle tracking between segments in consecutive speckle images. The flow patterns of six bifurcations and two veins were investigated in-vivo. It was shown: 1) that a stable vortex in the carotid bulb was present opposed to other examined bifurcations, 2) that retrograde flow was present in the superficial branch of the femoral artery during diastole, 3) that retrograde flow was present in the subclavian artery and antegrade in the common carotid artery during diastole, 4) that vortices were formed in the buckets behind the venous valves in both antegrade and retrograde flow, and 5) that
secondary flow was present in various vessels. The in-vivo results have revealed complex flow patterns not previously visualized with ultrasound imaging and indicate a flow complexity in both simple and complex vessel geometries.

**Fast Parametric Beamformer for Synthetic Aperture Imaging**

This paper describes the design and implementation of a real-time delay-and-sum synthetic aperture beamformer. The beamforming delays and apodization coefficients are described parametrically. The image is viewed as a set of independent lines that are defined in 3-D by their origin, direction, and inter-sample distance. The delay calculation is recursive and inspired by the coordinate rotation digital computer (CORDIC) algorithm. Only 3 parameters per channel and line are needed for their generation. The calculation of apodization coefficients is based on a piecewise linear approximation. The implementation of the beamformer is optimized with respect to the architecture of a novel synthetic aperture real-time ultrasound scanner (SARUS), in which 4 channels are processed by the same set of field-programmable gate arrays (FPGA). In synthetic transmit aperture imaging, low-resolution images are formed after every emission. Summing all low-resolution images produces a perfectly focused high-resolution image. The design of the beamformer is modular, and a single beamformation unit can produce 4600 low-resolution images per second, each consisting of 32 lines and 1024 complex samples per line. In its present incarnation, 3 such modules fit in a single device. The summation of low-resolution images is performed internally in the FPGA to reduce the required bandwidth. The delays are calculated with a precision of 1/16th of a sample, and the apodization coefficients with 7-bit precision. The accumulation of low-resolution images is performed with 24-bit precision. The level of the side- and grating lobes, introduced by the use of integer numbers in the calculations and truncation of intermediate results, is below -86 dB from the peak.
Feasibility of non-linear simulation for Field II using an angular spectrum approach

Simulation of non-linear fields is most often restricted to single element, circularly symmetric sources, which is not used in clinical scanning. To obtain a general and valuable simulation, array transducers of any geometry with any excitation, focusing, and apodization should be modeled. Field II is restricted to simulate these for the linear case and the purpose of this paper is to develop a general framework for extending it to non-linear simulation. The extension to the non-linear domain is made by using the angular spectrum approach (ASA), where the field is calculated in a plane close to the transducer surface. This calculation is performed using Field II and, thus, includes modeling array transducers of any geometry with any excitation, focusing, and apodization. The propagation in the linear or non-linear medium is then performed using the angular spectrum approach. The first step in deriving this procedure is to find the accuracy of the approach for linear propagation, where the result can be validated using Field II simulations. The ASA calculations are carried out by 3D fast Fourier transform using Matlab, where lambda=2 is chosen as the spatial sampling rate to reduce aliasing errors. Zero-padding is applied to enlarge the source plane to a (4N - 1) times (4N - 1) matrix to overcome artifacts in terms of the circular convolution. The source plane covering an area of 9 times 9 mm² with N = 61 samples along both side, is 0.05 mm away from a 5 MHz planar piston transducer, which is simulated by Field II. To determine the accuracy, different sampling intervals and zero-paddings are compared and the errors are calculated with Field II as a reference. It can be seen that zero-padding with 4N - 1 and lambda=2 sampling can both reduce the errors from 25.7% to 12.9% for the near-field and from 18.1% to 5.8% for the far-field, and improve the price of an increase in computation time. The angular spectrum approach in combination with Field II opens for the possibility of simulating the non-linear acoustic propagation for any kind of array transducers.

Gas enhanced magnetic resonance angiography of the cerebrum using carbon dioxide and oxygen - preliminary results

Purpose/introduction Standard imaging of the cerebral arteries is performed using intravenous contrast in CT angiography and x-ray angiography. Magnetic resonance angiography (MRA) of the cerebral arteries using intravenous contrast media does not perform well. Contrast in the venous bed and the meninges may obscure the signal from the arteries of interest. It is known that oxygen enhances the T1-weighted signal and that carbon dioxide increases the arterial blood flow. This paper presents preliminary results of gas enhanced MRA using combinations of atmospheric air, O2 and CO2. Subjects and Methods Two healthy volunteers were scanned during inhalation of three different gas mixtures: Gas I (air), Gas II (5% CO2, 21 % O2, 74 % N2), Gas III (5% CO2, 95% O2). For each gas mixture a time of flight (TOF) series on the cerebral arteries was performed. Following each TOF series an ECG-gated phase contrast sequence was performed to calculate volume flow in the common carotid arteries. MRA data was acquired with a 1.5 T Siemens VISION MR-system (SIEMENS Medical Systems, Germany) using a standard circularly polarized head coil. Reconstructed images of TOF...
series and volume flow measurements were compared. Results The TOF series showed an increase in MRA signal and vessel conspicuousness, when adding CO2 to air (gas I vs. gas II) and an additional increase was seen on MRA when adding O2 to CO2 (gas II vs. gas III). The increase in MRA signal was present on both volunteers. The volume flow increased as a response to the added CO2 (gas II). Free oxygen (gas III) enhanced the MRA blood signal but invoked a slight decrease in the volume flow. Discussion/conclusion Inhaling gas mixture during MRA examination containing CO2 and O2 increased the cerebral MRA signal. These preliminary results indicate that improved MRA of the cerebrum can be gained when inhaling 5% CO2/95% O2 during examination bringing forth an alternative to CT and x-ray cerebral angiography. Furthermore, gas enhanced MRA could be an alternative to contrast enhanced MRA in other regions of interest than cerebrum.

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**High Frame-Rate Blood Vector Velocity Imaging Using Plane Waves: Simulations and Preliminary Experiments**
Conventional ultrasound methods for acquiring color images of blood velocity are limited by a relatively low frame-rate and are restricted to give velocity estimates along the ultrasound beam direction only. To circumvent these limitations, the method presented in this paper uses 3 techniques: 1) The ultrasound is not focused during the transmissions of the ultrasound signals; 2) A 13-bit Barker code is transmitted simultaneously from each transducer element; and 3) The 2-D vector velocity of the blood is estimated using 2-D cross-correlation. A parameter study was performed using the Field II program, and performance of the method was investigated when a virtual blood vessel was scanned by a linear array transducer. An improved parameter set for the method was identified from the parameter study, and a flow rig measurement was performed using the same improved setup as in the simulations. Finally, the common carotid artery of a healthy male was scanned with a scan sequence that satisfies the limits set by the Food and Drug Administration. Vector velocity images were obtained with a frame-rate of 100 Hz where 40 speckle images are used for each vector velocity image. It was found that the blood flow approximately followed the vessel wall, and that maximum velocity was approximately 1 m/s, which is a normal value for a healthy person. To further evaluate the method, the test person was scanned with magnetic resonance (MR) angiography. The volume flow derived from the MR scanning was compared with that from the ultrasound scanning. A deviation of 9% between the 2 volume flow estimates was found.

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Investigation of Sound Speed Errors in Adaptive Beamforming

Previous studies have shown that adaptive beam-formers provide a significant increase of resolution and contrast, when the propagation speed is known precisely. This paper demonstrates the influence of sound speed errors on two adaptive beamformers; the minimum variance (MV) beamformer and the amplitude and phase (APES) beamformer. Simulations of a single point target are carried out in Field II, and a percentage error is applied on the speed of sound. As the error increases, MV and APES provide amplitude drops of 17 dB and 3 dB on the signal strength. Two approaches to overcome this amplitude drop is proposed; diagonal loading (DL) and forward-backward (FB) averaging of the covariance matrix. The investigations show that DL provides a slightly decreased resolution and amplitude compared to FB. It is noted that APES provides more robust estimates than MV at the mere expense of a slight decrease of resolution. From the investigations, it is concluded the performance of the adaptive beamformers are not outperformed by the conventional delay-and-sum beamformer.

In vitro measurement of ambient pressure changes using a realistic clinical setup

In vitro measurement of ambient pressure changes using a realistic clinical setup Klaus Scheldrup Andersen and Jørgen Arendt Jensen

Motivation and objective: Many attempts to find a non-invasive procedure to measure the local blood pressure have been made. In the last decade independent experiments have indicated that the amplitude of the subharmonic response from contrast agents is sensitive to the ambient pressure. This paper presents results from a new experimental setup for measuring the subharmonic response of a contrast agent when subjected to ambient pressure. The setup is very flexible offering completely arbitrary excitation and data acquisition, fast and accurate ambient pressure control, and precise timing. More importantly, it resembles a realistic clinical setup using a single array transducer for transmit and receive. The standard signal processing steps usually seen for these experiments are moreover accompanied by steps to reduce dependence on factors as bubble concentration and time.

Contribution/Methods: Up to now ambient pressure measurements have been done using two single element transducers. The measurement setup for this experiment consisted of a single B-K Medical (Herlev, Denmark) phased array transducer with 64 elements and a -6 dB bandwidth between 2 and 4 MHz. The transducer was sealed to an airtight phantom with inlets for injection of Sonovue (Bracco, Milano, Italy) and regulation of the ambient pressure, which was automatically adjusted from Matlab using a custom made pressure controller (Alicat Scientific, Tucson, AZ). Data was acquired using the experimental scanner RASMUS. 100 focused lines were acquired with a pulse repetition frequency of 50 Hz at 6 different ambient pressures in the interval 0 to 25 kPa. To ensure subharmonic generation, a 32 cycles cosine tapered pulse with a center frequency of 4 MHz and an acoustic pressure of 485 kPa was used for excitation. 64 elements were used in receive and the RF data was filtered and beamformed before further processing. To compensate for variations in bubble response and to make the estimates more robust, each spectrum was normalized according to the fundamental before averaging and the energy of the respective components was chosen as measure over the peak amplitude. Results: The measurements showed that the energy of the subharmonic component decreased by 10.3 dB when the over pressure was increased from 0 to 25 kPa. In the same interval, the fundamental changed by less than 1 dB. Fitting a line to the six measuring points shows a linear correlation of 0.78 for the subharmonic reduction yielding a pressure sensitivity of 0.41 dB/kPa. Discussion and Conclusion: The experiment has for the first time shown it is possible to detect ambient pressure changes using a single array transducer setup as obligatory in a clinical situation. Moreover, suggestions for further signal processing was presented to increase the robustness of the estimates. The amount of subharmonic reduction obtained is
In good correspondence with results by Shi et al. 1999 and Adam et al. 2005 who both used a receiver separated from the emitting single element transducer.

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In-vivo evaluation of three ultrasound vector velocity techniques with MR angiography
In conventional Doppler ultrasound (US) the blood velocity is only estimated along the US beam direction. The estimate is angle corrected assuming laminar flow parallel to the vessel boundaries. As the now in the vascular system never is purely laminar, the velocities estimated with conventional Doppler US are always incorrect. Three angle independent vector velocity methods are evaluated in this paper: directional beamforming (DB), synthetic aperture flow imaging (STA) and transverse oscillation (TO). The performances of the three methods were investigated by measuring the stroke volume in the right common carotid artery of eleven healthy volunteers, with magnetic resonance phase contrast angiography (MRA) as reference. The correlation between the three vector velocity methods and MRA were: DB/MRA R=0.84 (p<0.01); STA/MRA R=0.95 (p<0.01); TO/MRA R=0.91 (p<0.01). Bland-Altman plots were additionally constructed and mean differences for the three comparisons were: DB/MRA = 0.17 ml; STA/MRA = 0.07 ml; TO/MRA = 0.24 ml. The three US vector velocity techniques yield quantitative insight in to flow dynamics and can potentially give the clinician a powerful tool in cardiovascular disease assessment.

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In-vivo validation of fast spectral velocity estimation techniques – preliminary results

Spectral Doppler is a common way to estimate blood velocities in medical ultrasound (US). The standard way of estimating spectrograms is by using Welch's method (WM). WM is dependent on a long observation window (OW) (about 100 transmissions) to produce spectrograms with sufficient spectral resolution and contrast. Two adaptive filterbank methods have been suggested to circumvent this problem: the Blood spectral Power Capon method (BPC) and the Blood Amplitude and Phase Estimation method (BAPES). Previously, simulations and flow rig experiments have indicated that the two adaptive methods can display sufficient spectral resolution for much shorter OWs than WM. The purpose of this paper is to investigate the methods on a larger population and letting a clinical expert evaluate the spectrograms. Ten volunteers were scanned over the right common carotid artery and four different approaches were used to estimate the spectrograms: WM with a Hanning window (WMhw), WM with a boxcar window (WMbw), BPC and BAPES. For each approach the window length was varied: 128, 64, 32, 16, 8, 4 and 2 emissions/estimate. Thus, from the same data set of each volunteer 28 spectrograms were produced. The artery was scanned using the experimental ultrasound scanner RASMUS and a B-K Medical 5 MHz linear array transducer with an angle of insonation not exceeding 60deg. All 280 spectrograms were then randomised and presented to a radiologist blinded for method and OW for visual evaluation: useful or not useful. WMbw and WMhw estimated less useful spectrograms compared to the adaptive methods at OW below 64. The BAPES method performed better than BPC at OW of 16 and 8. Furthermore, BAPES was the only method that estimated spectrograms equally well for OW of 16 compared to OW of 128. All four approaches failed at OW of 4 and 2. The preliminary results indicate that the OW can be reduced to 32 when using the BPC method and to 16 when using the BAPES method for spectral blood estimation. This will - - liberate processing time in spectral US examination and could be used to increase the frame rate of the interleaved B-mode image.

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Multi-Frequency Encoding for Fast Color Flow or Quadroplex Imaging

Ultrasonic color flow maps are made by estimating the velocities line by line over the region of interest. For each velocity estimate, multiple repetitions are needed. This sets a limit on the frame rate, which becomes increasingly severe when imaging deeper lying structures or when simultaneously acquiring spectrogram data for triplex imaging. This paper proposes a method for decreasing the data acquisition time by simultaneously sampling multiple lines for color flow maps, using narrow band signals with approximately disjoint spectral support. The signals are separated in the receiver by filters matched to the emitted waveforms, producing a number of data sets with different center frequencies. The autocorrelation estimator is then applied to each of the data sets. The method is presented, various side effects are considered, and the method is tested on data from a recirculating flow phantom. A mean standard deviation across the flow profile of 3.1, 2.5, and 2.1% of the peak velocity was found for bands at 5 MHz, 7 MHz, and 9 MHz, respectively. Alternatively, the method can be used for simultaneously sampling data for a color flow map and for multiple spectrograms using different spectral bands. Using three spectral bands, data for a color flow map and two independent spectrograms can be acquired at the time normally spent on acquiring data for a color flow map only. This yields an expansion of triplex imaging called multi-frequency quadroplex imaging, which enables study of the flow over an arterial stenosis by simultaneously acquiring spectrograms on both sides of the stenosis, while maintaining the color flow map. The method was tested in vivo on data from the common carotid artery of a healthy male volunteer, both for fast color flow mapping and for multi-frequency quadroplex imaging.

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Plane Wave Medical Ultrasound Imaging Using Adaptive Beamforming

In this paper, the adaptive, minimum variance (MV) beamformer is applied to medical ultrasound imaging. The significant resolution and contrast gain provided by the adaptive, minimum variance (MV) beamformer, introduces the possibility of plane wave (PW) ultrasound imaging. Data is obtained using Field H and a 7 MHz, 128-elements, linear array transducer with lambda/2-spacing. MV is compared to the conventional delay-and-sum (DS) beamformer with Boxcar and Hanning weights. Furthermore, the PW images are compared to the a conventional ultrasound image, obtained from a linear scan sequence. The four approaches, (Linear Scan, DS Boxcar, DS Hanning, MV), have full width at half maximum of {0.82, 0.71, 1.28, 0.12} mm and peak side-lobe levels of {-40.1, -16.8, -34.4, -57.0} dB.

Precision of Needle Tip Localization Using a Receiver in the Needle

Many medical procedures require the detection, tracking and guidance of (biopsy) needles. The detection of the position of the needle can be challenging because of specular reflection which deflects the sound in a direction away from the transducer surface. To visualize the tip of small needles often motion is introduced to the discomfort of the patient. Vilkomerson and co-workers suggested in 1981 the placement of an ultrasound receiver close to the needle tip. The
received echoes are detected by add-on hardware. The maximum echo is assumed to originate from a beam directly above the detector, and the time of flight determines the distance to the transducer. The feasibility of the method was demonstrated by the same group in-vivo. The precision of the method has not been previously discussed in literature. This paper introduces two methods for estimation of the position of the needle tip and investigates their precision. The first method uses conventional imaging. Instead of detecting the maximum echo, as previously suggested, the center of mass is found both across beams and along the received signals, thus decreasing the sensitivity to noise. The second method is based on synthetic aperture (SA) scanning. The position of the tip is found via triangulation which involves solving a system of linear equations. The robustness to noise is ensured through averaging a number of estimates. The sensor is a ring of piezoelectric film making it possible to receive waves from any direction. The results were obtained using simulations in Field II. The center frequency is 7 MHz. The transducer array is mechanically focused in elevation plane at 25 mm while the height of the elements is 4.5 mm. The transducer pitch is 202 microns. The sensor is a ring with height of 1 mm and 2 mm diameter. Positions were varied from 10 to 120 mm in depth and from 0 to 20 mm in lateral and elevation direction. The mean error of position estimation is for the case of conventional and SA imaging is 0.2 and 0.05 mm, respectively. The precision of two methods to determine the position of the needle tip is investigated. Using spherical transmissions yields higher accuracy. Both methods can be extended to 3D if the transmissions originate from transducer elements that are not placed on a line. Needles equipped with receivers can be used for deploying brachytherapy seeds ensuring high precision of the procedure.

Pulse Wave Velocity in the Carotid Artery
The pulse wave velocity (PWV) in the carotid artery (CA) has been estimated based on ultrasound data collected by the experimental scanner RASMUS at DTU. Data is collected from one test subject using a frame rate (FR) of 4000 Hz. The influence of FRs is also investigated. The PWV is calculated from distension wave forms (DWF) estimated using cross-correlation. The obtained velocities give results in the area between 3-4 m/s, and the deviations between estimated PWV from two beats of a pulse are around 10%. The results indicate that the method presented is applicable for detecting the local PWV. Additional studies with data collections from several test subjects are required to determine the accuracy of the approach. Based on a spectrum analysis it appears that there is no gain from using FRs above 1000 Hz, but it is shown that FRs below 1000 Hz do not give accurate PWVs.

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Pulse Wave Velocity in the Carotid Artery
The pulse wave velocity (PWV) in the carotid artery (CA) has been estimated based on ultrasound data collected by the experimental scanner RASMUS at DTU. Data is collected from one test subject using a frame rate (FR) of 4000 Hz. The influence of FRs is also investigated. The PWV is calculated from distension wave forms (DWF) estimated using cross-correlation. The obtained velocities give results in the area between 3-4 m/s, and the deviations between estimated PWV from two beats of a pulse are around 10%. The results indicate that the method presented is applicable for detecting the local PWV. Additional studies with data collections from several test subjects are required to determine the accuracy of the approach. Based on a spectrum analysis it appears that there is no gain from using FRs above 1000 Hz, but it is shown that FRs below 1000 Hz do not give accurate PWVs.

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Research interface for experimental ultrasound imaging - the CFU grabber project.

Purpose
The acquisition of ultrasound images using new calculation methods usually requires days of post processing. An ultrasound scanner with a research interface developed in collaboration between DTU and BK medicals has made it possible to process US images faster than the current research system RASMUS. Furthermore precise scanner settings are stored for inter- and intra-observer studies. The resulting images are used for clinical evaluation. Method and materials
The ultrasound scanners research interface is connected to a graphical grabber card in a Windows PC (Grabber PC). The grabber PC acquires pre processed data from the scanner in real time. Further post processing is required to create the final images. In house software (CFU Grabber tool) was developed to review and store the pre processed data. Using MatLab image processing with a new post post processing method the final image can be produced within 20-30 minutes depending on the method while RASMUS uses up to 72 hours for post processing. Results
With a post processing time of 30 minutes images using a new method (Synthetic Aperture Sequential Beamforming) and a conventional method (Dynamic Receive Focusing) was performed. The resulting 3 seconds of image sequences (video) will be evaluated by experts within medical ultrasound imaging. Conclusion
The setup makes the data acquisition fast and the scanner setting reproducible and the first in-vivo studies using the new research system are on-going.

Rocking convex array used for 3D synthetic aperture focusing

Volumetric imaging can be performed using 1D arrays in combination with mechanical motion. Outside the elevation focus of the array, the resolution and contrast quickly degrade compared to the azimuth plane, because of the fixed transducer focus. The purpose of this paper is to use synthetic aperture focusing (SAF) for enhancing the elevation focusing for a convex rocking array, to obtain a more isotropic point spread function. This paper presents further development of the SAF method, which can be used with curved array combined with a rocking motion. The method uses a virtual source (VS) for defocused multi-element transmit, and another VS in the elevation focus point. This allows a direct time-of-flight (ToF) to be calculated for a given 3D point. The method is evaluated using simulations from Field II and by measurements using the RASMUS experimental scanner with a 4.5 MHz convex array (GE Kretztechnik, Zipf, Austria). The array has an elevation focus at 60 mm of depth, and the angular rocking velocity is up to 140 deg/s. The scan sequence uses an fprf of 4500 - 7000 Hz allowing up to 15 cm of penetration. The full width at half max (FWHM) and main-lobe to side-lobe ratio (MLSL) is used as quantitative measurements. The elevation FWHM for simulated scatterers placed at depths of 30 to 140 mm of depth were improved by 26.4% on average, and the MLSL ratio was improved by an average of 8.49 dB for the scatterers using 3D SA focusing. The elevation FWHM for a measured wire phantom was improved by 33.8% on average by applying 3D SA focusing. In-Vivo measurements show an improvement in C-scans matching what is found in simulations and wire phantoms. The method has shown the ability to improve the elevation focus and contrast for a convex rocking array. This was shown for simulations and for phantom and In-Vivo measurements using commercially available equipment.
Simulation of microbubble response to ambient pressure changes

The theory on microbubbles clearly indicates a relation between the ambient pressure and the acoustic behavior of the bubble. The purpose of this study was to optimize the sensitivity of ambient pressure measurements, using the subharmonic component, through microbubble response simulations. The behavior of two different contrast agents was investigated as a function of driving pulse and ambient overpressure, pov. Simulations of Levovist using a rectangular driving pulse show an almost linear reduction in the subharmonic component as pov is increased. For a 20 cycles driving pulse, a reduction of 4.6 dB is observed when changing pov from 0 to 25 kPa. Increasing the pulse duration makes the reduction even more clear. For a pulse with 64 cycles, the reduction is 9.9 dB. This simulation is in good correspondence with measurement results presented by Shi et al. 1999, who found a linear reduction of 9.6 dB. Further simulations of Levovist show that also the shape and the acoustic pressure of the driving pulse are very important factors. The best pressure sensitivity of Levovist was found to be 0.88 dB/kPa. For Sonazoid, a sensitivity of 0.71 dB/kPa has been found, although the reduction is not completely linear as a function of the ambient pressure.

Spatial Encoding Using a Code Division Technique for Fast Ultrasound Imaging

This paper describes a method for spatial encoding in synthetic transmit aperture ultrasound imaging. This allows several ultrasonic sources to be active simultaneously. The method is based on transmitting pseudo-random sequences to spatially encode the transmitters. The data can be decoded after only one transmission using the knowledge of the transmitted code sequences as opposed to other spatial encoding techniques, such as Hadamard or Golay encoding. This makes the method less sensitive to motion, and data can be acquired using fewer transmissions. The aim of this paper is to analyze the underlying theory and to test the feasibility in a physical system. The method has been evaluated in simulations using Field II in which the point-spread functions were simulated for different depths for a 7 MHz linear array transducer. A signal-to-noise ratio (SNR) simulation also was included in the study in which an improvement in SNR of ∼1.5 dB was attained compared to the standard synthetic transmit aperture (STA) firing scheme. Considering the amount of energy transmitted, this value is low. A plausible explanation is given that is verified in simulation. The method also was tested in an experimental ultrasound scanner and compared to a synthetic transmit aperture ultrasound imaging scheme using a sinusoidal excitation. The performance of the proposed method was comparable to the reference with respect to axial and lateral resolution, but it displayed poorer contrast with sidelobe levels at ∼−40 dB compared to the mainlobe.
Synthetic Aperture Sequential Beamforming

A synthetic aperture focusing (SAF) technique denoted Synthetic Aperture Sequential Beamforming (SASB) suitable for 2D and 3D imaging is presented. The technique differ from prior art of SAF in the sense that SAF is performed on pre-beamformed data contrary to channel data. The objective is to improve and obtain a more range independent lateral resolution compared to conventional dynamic receive focusing (DRF) without compromising frame rate. SASB is a two-stage procedure using two separate beamformers. First a set of B-mode image lines using a single focal point in both transmit and receive is stored. The second stage applies the focused image lines from the first stage as input data. The SASB method has been investigated using simulations in Field II and by off-line processing of data acquired with a commercial scanner. The performance of SASB with a static image object is compared with DRF. For the lateral resolution the improvement in FWHM equals a factor of 2 and the improvement at -40 dB equals a factor of 3. With SASB the resolution is almost constant throughout the range. The resolution in the near field is slightly better for DRF. A decrease in performance at the transducer edges occur for both DRF and SASB, but is more profound for SASB.
Testing of a one dimensional model for Field II calibration

Field II is a program for simulating ultrasound transducer fields. It is capable of calculating the emitted and pulse-echoed fields for both pulsed and continuous wave transducers. To make it fully calibrated a model of the transducer’s electro-mechanical impulse response must be included. We examine an adapted one dimensional transducer model originally proposed by Willatzen [9] to calibrate Field II. This model is modified to calculate the required impulse responses needed by Field II for a calibrated field pressure and external circuit current calculation. The testing has been performed with Pz27 piezoceramic discs from Ferroperm Piezoceramics A/S, Kvistgaard, Denmark. The transmitted acoustic pressures from two sets of each five disc samples with 10.08 mm diameters were measured in an automatic water bath needle hydrophone setup together with the current flow through the driving circuit. Resonance frequencies at 2.1 MHz and 4 MHz were applied. Two types of circuits were considered, one circuit with a simple resistance load of 47.5 Ohm and one with an example of a LR tuning circuit typically found in commercial transducers. The measurements were averaged 128 times and afterwards compared to the calibrated Field II program for 1, 4, and 10 cycle excitations. Two parameter sets were applied for modeling, one real valued Pz27 parameter set, manufacturer supplied, and one complex valued parameter set found in literature, Algueró et al. [11]. The latter implicitly accounts for attenuation. Results show that the combination of the model and Field II can calculate the pressure within ~15 % to 5 % RMS error for long excitation bursts and 7 % to 23 % for short excitation bursts. Furthermore it is shown that current simulations can be done within 1 % to maximum 33 % RMS error, where best current simulations are found for 4 MHz long burst simulations and worst case is found for 2.1 MHz short bursts. Finally it is shown that maximum pressure deviation for the real parameter set and the complex parameter simulation is 3 % for pressure and 5.3 % for current.

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Transverse correlation: An efficient transverse flow estimator - initial results

Color flow mapping has become an important clinical tool, for diagnosing a wide range of vascular diseases. Only the velocity component along the ultrasonic beam is estimated, so to find the actual blood velocity, the beam to flow angle has to be known. Because of the unpredictable nature of vascular hemodynamics, the flow angle cannot easily be found as the angle is temporally and spatially variant. Additionally the precision of traditional methods is severely lowered for high flow angles, and they breakdown for a purely transverse flow. To overcome these problems we propose a new method for estimating the transverse velocity component. The method measures the transverse velocity component by estimating the transit time of the blood between two parallel lines beamformed in receive. The method has been investigated using simulations performed with Field II. Using 15 emissions per estimate, a standard deviation of 1.64% and a bias of 1.13% are obtained for a beam to flow angle of 90 degrees. Using the same setup a standard deviation of 2.21% and a bias of 1.07% are obtained for a beam to flow angle of 75 degrees. Using 20 emissions a standard deviation of 3.4% and a bias of 2.06% are obtained at 45 degrees. The method performs stable down to a signal-to-noise ratio of 0 dB, where a standard deviation of 5.5% and a bias of 1.2% is achieved.

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Adaptive blood velocity estimation in medical ultrasound
This paper investigates the use of data-adaptive spectral estimation techniques for blood velocity estimation in medical ultrasound. Current commercial systems are based on the averaged periodogram, which requires a large observation window to give sufficient spectral resolution. Herein, we propose a novel data-adaptive method to form the blood velocity spectral estimate. The method is evaluated using realistic field II simulations for both steady and unsteady flow. The latter representing the femoral artery with strong tissue interference. The method is compared to the averaged periodogram and a Capon-based estimator. The simulations indicate that the proposed method offer a significant performance gain, suggesting that the frame-rate may be increased dramatically by using adaptive spectral estimation techniques.

A novel method for direct localized sound speed measurement using the virtual source paradigm
Accurate sound speed estimates are desirable in a number of fields, particularly adaptive imaging, and tissue and phantom characterization. In an effort to increase the spatial resolution of sound speed estimates, a new method is proposed for direct measurement of sound speed between arbitrary spatial locations. The method utilizes the sound speed estimator developed by Anderson and Trahey. Their least-squares fit of the received waveform's curvature provides the
wave's point of origin. The point of origin and the delay profile calculated from the fit are used to arrive at a spatially registered virtual detector. Between a pair of registered virtual detectors a spherical wave is propagated. By beamforming the received data the time of flight between the two virtual sources can be calculated. From this information the local sound speed can be estimated. Validation of the estimator used both phantom and simulation results. The phantom consisted of two wire targets located near the transducer's axis at depths of 17 and 28 mm. Using this phantom the sound speed between the wires was measured for a homogeneous (water) medium and for two inhomogeneous (DB-grade castor oil and water) mediums. The inhomogeneous mediums were arranged as an oil layer, one 6 mm thick and the other 11 mm thick, on top of a water layer. To complement the phantom studies, sources of error for spatial registration of virtual detectors were simulated. The sources of error presented here are multiple sound speed layers, and signal-to-noise ratio. Results are shown for 3 different media. The local sound speed estimates had mean relative errors and standard deviations of 0.0991% plusmn0.655% for a homogeneous medium, and -0.0673%plusmn0.279% and -0.0343%plusmn0.119% for inhomogeneous media with an oil layer of 6 mm and 11 mm respectively. Simulations are shown as well.

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**Coded excitation and sub-band processing for blood velocity estimation in medical ultrasound**
This paper investigates the use of broadband coded excitation and subband processing for blood velocity estimation in medical ultrasound. In conventional blood velocity estimation a long (narrow-band) pulse is emitted and the blood velocity is estimated using an auto-correlation based approach. However, the axial resolution of the narrow-band pulse is too poor for brightness-mode (B-mode) imaging. Therefore, a separate transmission sequence is used for updating the B-mode image, which lowers the overall frame-rate of the system. By using broad-band excitation signals, the backscattered received signal can be divided into a number of narrow frequency bands. The blood velocity can be estimated in each of the bands and the velocity estimates can be averaged to form an improved estimate. Furthermore, since the excitation signal is broadband, no secondary B-mode sequence is required, and the frame rate can be increased. To increase the SNR for the broad-band excitation waveforms, coding is proposed. Three different coding methods are investigated: nonlinear frequency modulation, complementary (Golay) codes, and Barker codes. Code design is described for the three different methods as well as different ways of pulse compression for restoring axial resolution. The different methods were studied using an experimental ultrasound scanner and a circulating flow rig.

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Coded ultrasound for blood flow estimation using subband processing

This paper further investigates the use of coded excitation for blood flow estimation in medical ultrasound. Traditional autocorrelation estimators use narrow-band excitation signals to provide sufficient signal-to-noise-ratio (SNR) and velocity estimation performance. In this paper, broadband coded signals are used to increase SNR, followed by sub-band processing. The received broadband signal, is filtered using a set of narrow-band filters. Estimating the velocity in each of the bands and averaging the results yields better performance compared to what would be possible when transmitting a narrow-band pulse directly. Also, the spatial resolution of the narrow-band pulse would be too poor for brightness-mode (B-mode) imaging and additional transmissions would be required to update the B-mode image. In the described approach, there is no need for additional transmissions, because the excitation signal is broadband and has good spatial resolution after pulse compression. Two different codin-schemes are used in this paper, Barker codes and Golay codes. The performance of the codes for velocity estimation is compared to a conventional approach transmitting a narrow-band pulse. The study was carried out using an experimental ultrasound scanner and a commercial linear array 7 MHz transducer. A circulating flow rig was scanned with a beam-to-flow angle of 60 degrees. The flow in the rig was laminar and had a parabolic flow-profile with a peak velocity of 0.09 m/s. The mean relative standard deviation of the reference method using an eight cycle excitation pulse at 7 MHz was 0.544% compared to the peak velocity in the rig. Two Barker codes were tested with a length of 5 and 13 bits, respectively. The corresponding mean relative standard deviations were 0.367% and 0.310%, respectively. For the Golay coded experiment, two 8 bit codes were used, and the mean relative standard deviation was 0.335%.

Designing waveforms for temporal encoding using a frequency sampling method

In this paper a method for designing waveforms for temporal encoding in medical ultrasound imaging is described. The method is based on least squares optimization and is used to design nonlinear frequency modulated signals for synthetic transmit aperture imaging. By using the proposed design method, the amplitude spectrum of the transmitted waveform can be optimized, such that most of the energy is transmitted where the transducer has large amplification. To test the design method, a waveform was designed for a BK8804 linear array transducer. The resulting nonlinear frequency modulated waveform was compared to a linear frequency modulated signal with amplitude tapering, previously used in clinical studies for synthetic transmit aperture imaging. The latter had a relatively flat spectrum which implied that the waveform tried to excite all frequencies including ones with low amplification. The proposed waveform, on the other hand, was designed so that only frequencies where the transducer had a large amplification were excited. Hereby, unnecessary heating of the transducer could be avoided and the signal-to-noise ratio could be increased. The experimental ultrasound scanner RASMUS was used to evaluate the method experimentally. Due to the careful waveform design optimized for the transducer at hand, a theoretic gain in signal-to-noise ratio of 4.9 dB compared to the reference excitation was found, even though the energy of the nonlinear frequency modulated signal was 71% of the energy of the reference signal. This was supported by a signal-to-noise ratio measurement and comparison in penetration depth, where an increase of 1 cm was found in favor for the proposed waveform. Axial and lateral resolutions at full-width halfmaximum were compared in a water phantom at depths of 42, 62, 82, and 102 mm. The axial resolutions of the nonlinear frequency modulated signal were 0.62, 0.69, 0.60, and 0.60 mm, respectively. The corresponding axial resolutions for the reference waveform were 0.58, 0.65, 0.62, and 0.60 mm, respectively. The compression properties of the matched filter (mismatched filter for the linear frequency modulated signal) were tested for both waveforms in simulation with respect to the Doppler frequency shift occurring when probing moving objects. It was concluded that the Doppler effect of moving targets does not significantly degrade the filtered output. Finally, in vivo measurements are shown for both methods, wherein the common
Effective and versatile software beamformation toolbox

Delay-and-sum array beamforming is an essential part of signal processing in ultrasound imaging. Although the principles are simple, there are many implementation details to consider for obtaining a reliable and computational efficient beamforming. Different methods for calculation of time-delays are used for different waveforms. Various inter-sample interpolation schemes such as FIR-filtering, polynomial, and spline interpolation can be chosen. Apodization can be any preferred window function of fixed size applied on the channel signals or it can be dynamic with an expanding and contracting aperture to obtain a preferred constant F-number. An effective and versatile software toolbox for off-line beamformation designed to address all of these issues has been developed. It is capable of exploiting parallelization of computations on a Linux cluster and is written in C++ with a MATLAB (Math Works Inc.) interface. It is an aid to support simulations and experimental investigation of 3D imaging, synthetic aperture imaging, and directional flow estimation. A number of parameters are necessary to fully define the spatial beamforming and some parameters are optional. All spatial specifications are given in 3D space such as the physical positions of the transducer elements during transmit and receive and the positions of the points to beamform. The points of focus are defined as a collection of lines each having an origin, a direction, a distance between points and a length. The transducer, the points to beamform, and the apodization are defined as individual objects and a combination of these define the actual beamforming. Once the beamforming is defined, the time-delays and apodization values for every combination of transmit elements, receive elements and focus points can be calculated and stored in lookup-tables (LUT). Parametric beamforming can also be applied where calculations are done by demand, thus, reducing the storage demand dramatically. On a standard PC with a Pentium 4, 2.66 GHz processor running Linux the toolbox can beamform 100,000 points in lines of various directions in 20 seconds using a transducer of 128 elements, dynamic apodization and 3rd order polynomial interpolation. This is a decrease in computation time of at least a factor of 15 compared to an implementation directly in MATLAB of a similar beamformer.
Examples of in-vivo blood vector velocity estimation.

In this paper examples of in-vivo blood vector velocity images of the carotid artery are presented. The transverse oscillation (TO) method for blood vector velocity estimation has been used to estimate the vector velocities and the method is first evaluated in a circulating flow rig where performance as function of flow angle is found. At 90 [deg] beam to flow angle the TO method can estimate the transverse velocity with a mean standard deviation of 2.8 % and with a mean absolute bias of 11.8 %. A carotid artery is scanned in-vivo at three different positions by experienced sonographers. The scanning regions are: 1) The common carotid artery at 88 [deg] beam to flow angle, 2) The common carotid artery and the Jugular vein at ~90 [deg] beam to flow angle and 3) The bifurcation of the carotid artery. The resulting velocity estimates are displayed as vector velocity images where the velocity vector is superimposed on a B-mode image showing the tissue structures. The volume flow is found for case 1) and when compared with MRI from the literature, a bias of approximately ~20% is found. The maximum flow velocities within the carotid artery is found to be 0.8 m/s, which is normal for a healthy person. In case 3) the estimated vector velocities are compared with numerical simulations. Qualitatively the same flow pattern can be seen in both simulations and in the vector velocity images. Furthermore a vortex is identified in the carotid sinus at the deceleration phase after the peak systole. This vortex is seen in all of the three acquired cardiac cycles.
Fast Blood Vector Velocity Imaging: Simulations and Preliminary In Vivo Results

I Background: Conventional ultrasound methods for acquiring color flow images of the blood velocity are limited by a relatively low frame rate and are restricted to only give velocity estimates along the ultrasound beam direction. To circumvent these limitations, we propose a method where the frame rate can be significantly increased, and the full 2-D vector velocity of the blood can be estimated. II Method: The method presented in this paper uses three techniques: 1) The ultrasound is not focused during the transmit of the ultrasound signals, and a full speckle image of the blood can be acquired for each pulse emission. 2) The transmitted pulse consists of a 13 bit Barker code which is transmitted simultaneously from each transducer element. 3) The 2-D vector velocity of the blood is found using 2-D speckle tracking between segments in consecutive speckle images. III Results: The method was tested with a 5.5 MHz linear array transducer scanning a flow phantom. Standard deviation and bias of the velocity estimates were evaluated when six parameters were changed around an initial point. The conclusions drawn from the simulations were then used in a scanning with our experimental RASMUS scanner. The same setup as in the simulations was used, and the standard deviation and bias were found. Finally, the common carotid artery of a healthy 36 year old male was scanned for 1.29 sec. with the RASMUS scanner, and 129 independent vector velocity images were acquired with a frame rate of 100 Hz. The derived volume flow estimates were compared with MR angiography, and a deviation of 9 $\%$ was found.

Fast Spectral Velocity Estimation Using Adaptive Techniques: In-Vivo Results

Adaptive spectral estimation techniques are known to provide good spectral resolution and contrast even when the observation window (OW) is very short. In this paper two adaptive techniques are tested and compared to the averaged periodogram (Welch) for blood velocity estimation. The Blood Power spectral Capon (BPC) method is based on a standard minimum variance technique adapted to account for both averaging over slowtime and depth. The Blood Amplitude and Phase Estimation technique (BAPES) is based on finding a set of matched filters (one for each velocity component of interest) and filtering the blood process over slow-time and averaging over depth to find the power spectral density estimate. In this paper, the two adaptive methods are explained, and performance is assessed in controlled steady How experiments and in-vivo measurements. The three methods were tested on a circulating How rig with a blood mimicking fluid flowing in the tube. The scanning section is submerged in water to allow ultrasound data acquisition. Data was recorded using a BK8804 linear array transducer and the RASMUS ultrasound scanner. The controlled experiments showed that the OW could be significantly reduced when applying the adaptive methods without compromising spectral resolution or contrast. The in-vivo data was acquired using a BK8812 transducer. OWs of 128, 64, 32 and 16 slow-time samples were tested. Spectrograms with duration of 2 seconds were generated. Welch's method required 128 samples to give a reasonable spectrogram, whereas the BPC only required 32 samples before the SNR became a limiting factor. The BAPES managed to display the spectrogram with sufficient quality at 16 slow-time samples.
Improved Beamforming for Lateral Oscillations in Elastography Using Synthetic Aperture Imaging

In this paper we present a beamforming technique based on synthetic aperture imaging that enables to improve the radio-frequency (RF) ultrasound images with lateral oscillations for lateral displacement estimation. As described in previous work, in order to increase the accuracy of the lateral displacement estimation using images with lateral oscillations, it is necessary to reduce both the wavelength of the lateral oscillations and the width of the point spread function (PSF). This is reached in this work, by doing emit and receive beamforming using synthetic aperture data. We show that the wavelength of the lateral oscillations can be reduced by a factor 2, and the width of the PSF can be reduced by a factor $\sqrt{2}$. We have used the images obtained by this beamforming technique for lateral displacement estimation in the field of elastography. We show that with this new approach it is possible to improve the lateral displacement estimation by nearly 25% by reducing the standard deviation of the error of the lateral estimation.

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In-vivo evaluation of convex array synthetic aperture imaging

This paper presents an in-vivo study of synthetic transmit aperture (STA) imaging in comparison to conventional imaging, evaluating whether STA imaging is feasible in-vivo, and whether the image quality obtained is comparable to traditional scanned imaging in terms of penetration depth, spatial resolution, contrast resolution, and artifacts. Acquisition was performed using our research scanner RASMUS and a 5.5 MHz convex array transducer. STA imaging was acquired using circular wave emulation by 33-element subapertures and a 20 us linear FM signal as excitation pulse. For conventional imaging a 64 element aperture was used in transmit and receive with a 1.5 cycle sinusoid excitation pulse. Conventional and STA images were acquired interleaved ensuring that the exact same anatomical location was scanned. Image sequences were recorded in real-time and processed off-line. Seven male volunteers were scanned abdominally, and resulting images were compared by three medical doctors using randomized blinded presentation. Penetration and image quality were scored and evaluated statistically. Results showed slightly but significantly (0.48 cm, $p=0.008$) increased penetration using STA. Image quality was also highly significantly (P
In-vivo examples of synthetic aperture vector flow imaging

The majority of the commercial ultrasound scanners feature blood flow velocity estimation based on the autocorrelation method, yielding estimates of the axial velocity component only. For studying complex flow patterns like arterial bifurcations or venous confluences, 2-D vector velocity estimates would be needed. Synthetic aperture vector flow imaging could potentially provide this. The purpose of this paper is to test the synthetic aperture vector flow imaging method on challenging in-vivo data. Two synthetic aperture in-vivo data sets are acquired using a commercial linear array transducer and our RASMUS experimental ultrasound scanner. The first data set covers the femoral artery and the confluence of the femoral and saphenous vein of a healthy 26-year-old male volunteer. The second shows the carotid bifurcation of a healthy 32-year-old male volunteer. Both 2 second long data sets are processed, and movies of full vector flow images are generated. This paper presents still frames from different time instances of these movies. The movie from the femoral data tracks the accelerating velocity in the femoral artery during systole and a backwards flow at the end of the systole. A complex flow pattern is seen at the junction of the femoral and saphenous vein. The movie of the carotid bifurcation shows high velocities close to the separating wall between the internal and external carotid, and a vortex tendency at the outermost wall. The volume flow through the femoral artery is extracted from the velocity estimates of the femoral data set by assuming the artery is rotational symmetric. An average volume flow just above 500 ml/min was found for the 26-year-old volunteer. This is in agreement with values found in literature.
In Vivo Vector Flow Imaging Using Improved Directional Beamforming

Directional beamforming has shown promising results for creating vector flow images. The method measures both the flow angle and the magnitude of the velocity. The flow angle is estimated by focusing lines in a range of angles from 0 to 180 degrees. The true angle is identified as the angle that produces the largest correlation coefficient across emissions. The magnitude of the velocity is found by cross-correlating consecutive lines focused along the direction of flow, to find the spatial shift corresponding to the velocity. In initial in vivo experiments, the method has however shown weaknesses by yielding outliers when a substantial clutter signal is present after clutter filtering. This is especially a problem when the flow angle is close to 90 degrees as the slow time frequencies from the flow signal is similar to that of the clutter, making clutter filtration difficult. When the angle determination fails, the correct velocity can no longer be found. The purpose of this work is to improve the robustness of the directional beamforming method, making precise in vivo measurement possible. A more robust angle estimator is proposed. Spatial averaging in the axial direction is applied over a depth of 2 wavelengths. Instead of traditionally beamforming a single line, three-lines are beamformed with an interline distance of a wavelength. To improve clutter filtering a post correlation clutter filter is applied, by removing peaks in the correlation functions corresponding to low velocities, since these peaks are believed not to be a result of the measured flow. The method has been tested on a flow phantom, using the RASMUS experimental scanner. The flow had a parabolic velocity distribution with a peak velocity of 0.1 m/s, and a flow angle of 90 degrees. The measurement were made with a 6.2 MHz linear array transducer, using 30 emissions and 128 transducer elements for each estimate. Using the same measurement setup, an initial in vivo study has been carried out. The measurements have been performed on the carotid artery of 11 human volunteers. To validate the method MR angiography has been performed on all human volunteers as a gold standard. For the phantom measurement 76.30 % of the angle estimates are within +/- 5 degrees of the actual angle, when using the traditional setup. Using our new approach 98.32 % of the angle estimates are within +/- 5 degrees from the true angle. The comparison between the stroke volume measurements in the carotid artery calculated using directional beamforming and MR angiography, gives a correlation coefficient of 0.84. Phantom and in vivo measurements has been carried out with a more robust implementation of the directional beamforming method. With the applied changes, the method has shown improved results for in vivo measurements.

Medical ultrasound imaging

The paper gives an introduction to current medical ultrasound imaging systems. The basics of anatomic and blood flow imaging are described. The properties of medical ultrasound and its focusing are described, and the various methods for two- and three-dimensional imaging of the human anatomy are shown. Both systems using linear and non-linear propagation of ultrasound are described. The blood velocity can also be non-invasively visualized using ultrasound and the basic signal processing for doing this is introduced. Examples for spectral velocity estimation, color flow imaging and the new vector velocity images are presented.
Minimum Variance Beamforming for High Frame-Rate Ultrasound Imaging

This paper investigates the application of adaptive beamforming in medical ultrasound imaging. A minimum variance (MV) approach for near-field beamforming of broadband data is proposed. The approach is implemented in the frequency domain, and it provides a set of adapted, complex apodization weights for each frequency sub-band. As opposed to the conventional, Delay and Sum (DS) beamformer, this approach is dependent on the specific data. The performance of the proposed MV beamformer is tested on simulated synthetic aperture (SA) ultrasound data, obtained using Field II. For the simulations, a 7 MHz, 128-element, phased array transducer with lambda/2-spacing was used. Data is obtained using a single element as the transmitting aperture and all 128 elements as the receiving aperture. A full SA sequence consisting of 128 emissions was simulated by gliding the active transmitting element across the array. Data for 13 point targets and a circular cyst with a radius of 5 mm were simulated. The performance of the MV beamformer is compared to DS using boxcar weights and Hanning weights, and is quantified by the Full Width at Half Maximum (FWHM) and the peak-side-lobe level (PSL). Single emission (DS Boxcar, DS Hanning, MV) provide a PSL of {-16,-36,-49} dB and a FWHM of {0.79,1.33,0.08} mm = {3.59 lambda, 6.05 lambda, 0.36 lambda}. Using all 128 emissions, (DS Boxcar, DS Hanning, MV) provide a PSL of {1.32, -49, -65} dB, and a FWHM of {0.63, 0.97, 0.08} mm = {2.86 lambda, 4.41 lambda, 0.36 lambda}. The contrast of the beamformed single emission responses of the circular cyst were calculated to {-18, -37, -40} dB. The simulations have shown that the frequency sub-band MV beamformer provides a significant increase in lateral resolution compared to DS, even when using considerably fewer emissions. An increase in resolution is seen when using only one single emission. Furthermore, it is seen that an increase of the number of emissions does not alter the FWHM. Thus, the MV beamformer introduces the possibility for high frame-rate imaging with increased resolution.
Multi-dimensional spectrum analysis for 2-D vector velocity estimation

Wilson (1991) presented a wide-band estimator for axial blood flow velocity estimation through the use of the two-dimensional (2-D) Fourier transform. It was shown how a single velocity component was concentrated along a line in the 2-D Fourier space, where the slope was given by the axial velocity. This paper presents an expansion of this study. If data are sampled within a region, instead of along a line, a three-dimensional (3-D) data matrix is created along lateral space, axial space, and pulse repetitions. It is shown, that a single velocity component will be concentrated along a plane in the 3-D Fourier space, where the integrated power spectrum is largest. The first uses the 3-D Fourier transform to find the power spectrum, while the second uses a minimum variance approach. Based on this plane, the axial and lateral velocity components are estimated. A number of phantom flow measurements, for flow-to-beam angles of 60, 75, and 90 degrees, were performed to test the estimator. The data were collected using our RASMUS experimental ultrasound scanner and a 128 element commercial linear array transducer. The receive apodization function was manipulated, creating an oscillation in the lateral direction, and multiple parallel lines were beamformed simultaneously. The two estimators were then applied to the data. Finally, an in-vivo scan of the common carotid artery was performed. The average standard deviation was found across the phantom tube, for both the axial and the lateral velocity estimate. Twenty independent estimates were made for each position. The average standard deviation of the lateral velocity estimates ranged from 16.4 % to 2.1 %, relative to the peak velocity, while the average standard deviation of the axial velocity ranged from 2.0 % to 0.2 %. Both estimators performed best for flow-to-beam angles of 90 degrees. The in-vivo scan showed the potential of the method, yielding an estimate of the velocity magnitude Independent of vessel orientation.

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Multi-Frequency Encoding for Rapid Color Flow and Quadroplex Imaging

Ultrasonic color flow maps are made by estimating the velocities line by line over the region of interest. For each velocity estimate, multiple repetitions are needed. This sets a limit on the frame rate, which becomes increasingly severe when imaging deeper lying structures or when simultaneously acquiring spectrogram data for triplex imaging. This paper proposes a method for decreasing the data acquisition time by simultaneously sampling multiple lines at different spatial positions for the color flow map using narrow band signals with disjoint spectral support. The signals are separated in the receiver by filters matched to the emitted waveforms and the autocorrelation estimator is applied. Alternatively, one spectral band can be used for creating a color flow map, while data for a number of spectrograms are acquired simultaneously. Using three disjoint spectral bands, this will result in a multi-frequency quadroplex imaging mode featuring a color flow map and two spectrograms at the same frame rate as a normal color flow map. The method is presented, various side-effects are considered, and the method is tested on data from a re-circulating flow phantom where a constant parabolic flow with a peak of 0.1 m/s is generated with a flow angle of 60 degrees. A commercial linear array transducer is used and data are sampled using our RASMUS multi-channel sampling system. An in-vivo multi-frequency quadroplex movie of the common carotid artery of a healthy male volunteer was created. The flow phantom measurements gave a mean standard deviation across the flow profile of 3.1%, 2.5%, and 2.1% of the peak velocity for bands at 5 MHz, 7 MHz, and 9 MHz, respectively. The in-vivo multi-frequency quadroplex movie showed the color flow map, and the two independent spectrograms at different spatial positions. This enables studying the flow over an arterial stenosis by simultaneously acquiring spectrograms on both sides of the stenosis, while maintaining the color flow map. A frame rate of 21.4 frames per second was achieved in this in-vivo experiment.
Precise Time-of-Flight Calculation For 3D Synthetic Aperture Focusing

Conventional linear arrays can be used for 3D ultrasound imaging, by moving the array in the elevation direction and stacking the planes in a volume. The point spread function (PSF) is larger in the elevation plane, as the aperture is smaller and has a fixed elevation focus. Resolution improvements in elevation can be achieved by applying synthetic aperture (SA) focusing to the beamformed in-plane RF-data. The method uses a virtual source (VS) placed at the elevation focus for post-beamforming. This has previously been done in two steps, in plane focusing followed by SA post-focusing in elevation, because of a lack of a simple expression for the exact time of flight (ToF). This paper presents a new method for calculating the ToF for a 3D case in a single step using a spherical defocused emission from a linear array. The method is evaluated using both simulated data obtained by Field II and phantom measurements using the RASMUS experimental scanner. For the simulation, scatterers were placed from 20 to 120 mm of depth. A point and a cyst phantom were scanned by translating a 7 MHz linear array in the elevation direction. For a point placed at (25.8, 75) mm relative to the transducer, the mean error between the calculated and estimated ToF is 0.0129 μs (0.09%), and the standard deviation of the ToF error is 0.0049A. SA focusing improves both contrast and resolution. For simulated scatterers at depths of 40 and 70 mm the FWHM is 83.6% and 46.8% of the FWHM without elevation SA focusing. The main-lobe to side-lobe energy ratio (MLSLR) for the scatterers is 32.3 dB and 29.1 dB. The measurement of a PSF phantom at a depth of 65 mm shows a relative FWHM of 27.8%. For an elevation sampling distance of 0.63 mm, the MLSLR for the two simulated scatterers is 26.4 dB and 27.9 dB. For the point phantom the MLSLR is 16.3 dB. If the elevation sampling distance is increased to 0.99 mm, the two simulated scatterers have a MLSLR of 21.1 dB and 15.8 dB respectively, and the point phantom has an MLSLR of 5.2 dB. The cyst phantom shows an improvement of 5.8 dB in contrast to noise ratio, for a 4 mm cyst, when elevation focusing is applied.
PSF dedicated to estimation of displacement vectors for tissue elasticity imaging with ultrasound

This paper investigates a new approach devoted to displacement vector estimation in ultrasound imaging. The main idea is to adapt the image formation to a given displacement estimation method to increase the precision of the estimation. The displacement is identified as the zero crossing of the phase of the complex cross-correlation between signals extracted from the lateral direction of the ultrasound RF image. For precise displacement estimation, a linearity of the phase slope is needed as well as a high phase slope. Consequently, a particular point spread function (PSF) dedicated to this estimator is designed. This PSF, showing oscillations in the lateral direction, leads to synthesis of lateral RF signals. The estimation is included in a 2-D displacement vector estimation method. The improvement of this approach is evaluated quantitatively by simulation studies. A comparison with a speckle tracking technique is also presented. The lateral oscillations improve both the speckle tracking estimation and our 2-D estimation method. Using our dedicated images, the precision of the estimation is improved by reducing the standard deviation of the lateral displacement error by a factor of 2 for speckle tracking and more than 3 with our method compared to using conventional images. Our method performs 7 times better than speckle tracking. Experimentally, the improvement in the case of a pure lateral translation reaches a factor of 7. Finally, the experimental feasibility of the 2-D displacement vector estimation is demonstrated on data acquired from a Cryogel phantom.

Synthetic Aperture Focusing Applied to Imaging Using a Rotating Single Element Transducer

This paper applies the concept of virtual sources and mono-static synthetic aperture focusing (SAF) to 2-dimensional imaging with a single rotating mechanically focused concave element with the objective of improving lateral resolution and signal-to-noise ratio (SNR). The geometrical focal point of the concave element can be considered as a point source emitting a spherical wave in a limited angular region. The SAF can be formulated as creating a high resolution line as a sum over low resolution tines (LRL). A LRL is the contribution from a single emission. Simulation in Field 11 is based on moving the concave element of radius 2.5 mm along a circle of radius 10 mm. Elements with different concave curvatures are used to obtain geometrical focusing depths at 10 mm, 15 mm, and 20 mm. Point targets in the range from 5 mm to 65 mm are used as image objects. The high resolution images (HRI) are shown and the radial and angular resolution are extracted at -6 dB and -40 dB. The performance of the setup with a VS at 20 mm is superior to the other setups. Due to the rotation, the synthesized aperture only experiences a moderate expansion, which is not sufficient to reduce the extent of the wide point spread function of a single emission. The effect of SAF with focal depth at 20 mm is negligible, caused by the small number of LRL applied. The great profit of the SAF is the increase in SNR. For the setup with focal depth at 20 mm the SAF SNR gain is 11 dB. The SNR gain of a setup with a VS at radius 10 mm or 15 mm over conventional imaging
with a VS at 20 mm, is also 11 dB.

System Architecture of an Experimental Synthetic Aperture Real-Time Ultrasound System

Synthetic Aperture (SA) ultrasound imaging has many advantages in terms of flexibility and accuracy. One of the major drawbacks is, however, that no system exists, which can implement SA imaging in real time due to the very high number of calculations amounting to roughly 1 billion complex focused samples per second per receive channel. Real time imaging is a key aspect in ultrasound, and to truly demonstrate the many advantages of SA imaging, a system usable in the clinic should be made. The paper describes a system capable of real time SA B-mode and vector flow imaging. The Synthetic Aperture Real-time Ultrasound System (SARUS) has been developed through the last 2 years and can perform real time SA imaging and storage of RF channel data for multiple seconds. SARUS consists of a 1024 channel analog front-end and 64 identical digital boards. Each has 16 transmit channels and 16 receive channels both with a sampling frequency of 70 MHz/12 bits for arbitrary waveform emission and reception. The board holds five Virtex 4FX100 FPGAs, where one houses a PowerPC CPU used for control. The remaining four are used for generation of transmit signals, receive storage and matched filter processing, and focusing and summing of data. Each FPGA can perform 80 billion multiplications/s and the full system can perform 25,600 billion multiplications/s. The FPGAs are connected through multiple 3.2 Gbit Rocket 10 links, which makes it possible to send more than 1.6 GBytes/s of data between the FPGAs and between boards. The system can concurrently sample in 1024 channels, thus, generating 140 GBytes/s of data, which also can be processed in real time or stored. The system is controlled over a 1 Gbit/s Ethernet link to each digital board that runs Linux. The control and processing are divided into functional units that are accessed through an IP numbering scheme in a hierarchical order. A single controlling mechanism can, thus, be used to access the whole system from any PC. It is also possible for the controlling PowerPCs to access all other boards, which enables advanced adaptive imaging. The software is written in C++ and runs under Matlab for high level access to the system in a command structure similar to the Field 11 simulation program. This makes it possible for the user to specify imaging in very few lines of code and the set-up is fast due to the employment of the 64 PowerPCs in parallel. Focusing is done using a parametric beamformer. Code synthesized for a Xilinx V4FX100 speed grade 11 FPGA can operate at a maximum clock frequency of 167.8 MHz producing 1 billion I and Q samples/second sufficient for real time SA imaging. The system is currently in production, and all boards have been laid out. VHDL and C++ code for the control has been written and the code for real time beamformation has been made and has obtained a sufficient performance for real-time imaging.
Validation of Transverse Oscillation Vector Velocity Estimation In-Vivo

Conventional Doppler methods for blood velocity estimation only estimate the velocity component along the ultrasound (US) beam direction. This implies that a Doppler angle under examination close to 90° results in unreliable information about the true blood direction and blood velocity. The novel method Transverse Oscillation (TO), which combines estimates of the axial and the transverse velocity components in the scan plane, makes it possible to estimate the vector velocity of the blood regardless of the Doppler angle. The present study evaluates the TO method with magnetic resonance angiography (MRA) by comparing in-vivo measurements of stroke volume (SV) obtained from the right common carotid artery. Angle of insonation was 90° for the TO measurements. Eleven healthy volunteers were scanned with the TO method and MRA. The overall results were as follows: mean SV +/- STD for TO: 5.5 ml +/- 1.7 ml and for MRA: 5.8 ml +/- 2.0 ml with the full range for TO: 3.4 ml - 9.5 ml and for MRA 3.0 ml - 10.8 ml. The correlation between the SV estimated by TO and MRA was 0.91 (p < 0.01; 95% CI: 0.69 to 0.98) with the equation for the line of regression MRA = 1.1ldrTO - 0.4. A Bland-Altman plot was constructed where the mean difference was 0.2 ml with limits of agreement at -1.4 ml and 1.9 ml (95% CI for mean difference: -0.3 ml to 0.8 ml). The strong correlation and the low mean difference between the TO method and MRA indicates that reliable vector velocity estimates can be obtained in vivo using the presented angle independent 2-D vector velocity method. The results give reason to believe that the TO method can be a useful alternative to conventional Doppler systems bringing forth new information to the US examination of blood flow.

Spectral velocity estimation using autocorrelation functions for sparse data sets

The distribution of velocities of blood or tissue is displayed using ultrasound scanners by finding the power spectrum of the received signal. This is currently done by making a Fourier transform of the received signal and then showing spectra in an M-mode display. It is desired to show a B-mode image for orientation, and data for this has to acquired interleaved with the flow data. The power spectrum can be calculated from the Fourier transform of the autocorrelation function Ry(k), where its span of lags k is given by the number of emission N in the data segment for velocity estimation. The lag corresponds to the difference in pulse number, so that for lag k data from emission i is correlated with i + k. The autocorrelation for lag k can be averaged over N-k pairs of emissions. It is possible to calculate Ry(k) for a sparse set of emissions, as long as all combinations of emissions cover all lags in Ry(k). A sparse set of emissions inter-spaced with B-mode emissions can, therefore, be used for estimating Ry(k) The sequence 'v B v v B!' gives 2 B-mode emissions (B) for every 3 velocity emissions (v) and is denoted a 3:2 sequence. All combinations on lags are present k=0123...l, if the sequence is continually repeated. The variance on the estimate of Ry(k) is determined by the number of emission pairs for the value of k, and it can be lowered by averaging the RF data over the range gate. Many other sequences can be devised with this property giving 3:3, 3:4, and 5:8 or even random sequences, so that the ratio between B-mode frame
A Frequency Splitting Method For CFM Imaging

The performance of conventional CFM imaging will often be degraded due to the relatively low number of pulses (4-10) used for each velocity estimate. To circumvent this problem we propose a new method using frequency splitting (FS). The FS method uses broad band chirps as excitation pulses instead of narrow band pulses as in conventional CFM imaging. By appropriate filtration, the returned signals are divided into a number of narrow band signals which are approximately disjoint. After clutter filtering the velocities are found from each frequency band using a conventional autocorrelation estimator. Finally the velocity estimates from each frequency band are averaged to obtain an improved velocity estimate. The FS method has been evaluated in simulations using the Field II program and in flow phantom experiments using the experimental ultrasound scanner RASMUS. In both simulations and experiments, a 5 MHz linear array transducer was used to scan a vessel situated at 30 mm depth with a maximum flow velocity of 0.1 m/s. The pulse repetition frequency was 1.8 kHz and the angle between the flow and the beam was 60 deg. A 15 mus chirp was used as excitation pulse and 40 independent velocity estimates were obtained using the FS method with 10 pulse transmissions used for each estimate. For comparison, a 8 cycles sinusoid pulse at 5 MHz was used to acquire 40 independent velocity estimates, each derived from 10 pulse emissions. Here the velocity was found using a conventional autocorrelation estimator. In the simulation, the relative mean standard deviation of the velocity estimates over the vessel was 2.43% when using the FS method and the relative mean absolute bias was 1.84%. For the reference 8 oscillation pulse, the relative mean standard deviation over the vessel was 4.91 % and the relative mean absolute bias was 1.78%. In the experiments the relative mean standard deviation of the velocity estimates over the vessel was 2.41 % when using the FS method and the relative-mean absolute bias was 1.56%. For the reference 8 oscillation pulse, the relative mean standard deviation over the vessel was 4.76% and the relative mean absolute bias was 3.12%.

Cardiac In-vivo Measurements Using Synthetic Transmit Aperture Ultrasound

This paper investigates the feasibility of acquiring cardiac images using synthetic transmit aperture (STA) ultrasound. Focusing in STA is done by beamforming all points in the image for every emission, creating a low-resolution image. The low-resolution images for each emission are summed, effectively achieving dynamic transmit and receive focusing. The purpose of this paper is to acquire in-vivo cardiac images using STA to investigate image quality and the effect of tissue motion. For the in-vivo experiments, a 3 MHz and a 3.5 MHz transducers were used with 64 and 128 elements,
respectively, together with the RASMUS experimental ultrasound scanner. Both transducers have a pitch of half a wavelength. To ensure an adequate signal-to-noise ratio, a 20 μs non-linear frequency modulated chirp and a 7-element de-focused virtual source were used for transmission. The number of virtual sources used in each scan sequence is equal to the number of transducer elements. A pulse repetition frequency of 4500 Hz was used, allowing a frame rate of 78 and 39 frames/s for the 64 and 128 element transducer. As the heart walls move with a speed of up to 80 mm/s, a movement of the tissue of several wavelengths is possible during an STA scan sequence using 64 emissions. To investigate the possibility of reducing the susceptibility to tissue motion, a sparse scan sequence using only 9 virtual source emissions is used to reduce the required scan-time. A shorter scan sequence will reduce the tissue motion between the first and last emission, and allows a frame rate of up to 555 frames/s. The sparse sequence is interleaved with the full sequence to allow a better comparison between the two techniques. A measurement of a point spread phantom shows a FWHM for the full scan sequences of 1.29 mm and 0.66 mm for the 64 and 128 element transducers, and an average side-lobe level of -47.25 dB and -58.42 dB respectively. The sparse scan sequences have a FWHM of 1.24 mm and 1.10 mm for the 64 and -128 element transducers, and an average side-lobe level of -39.48 dB and -42.13 dB respectively. The four image sequences presented in this paper show a cross-section of the ventricle and atrium, where the walls of the ventricles and the atrioventricular valves are visible. The dynamic of the beating heart is visible during the recorded sequences. Distortions are seen in the images created by the full scan sequence, which are attributed to be caused by tissue motion. The images created by the sparse sequence show a reduced contrast, but also a reduction of the distortion caused by tissue motion.

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Designing Non-linear Frequency Modulated Signals For Medical Ultrasound Imaging
In this paper a new method for designing non-linear frequency modulated (NLFM) waveforms for ultrasound imaging is proposed. The objective is to control the amplitude spectrum of the designed waveform and still keep a constant transmit amplitude, so that the transmitted energy is maximized. The signal-to-noise-ratio can in this way be optimized. The waveform design is based on least squares optimization. A desired amplitude spectrum is chosen, hereafter the phase spectrum is chosen, so that the instantaneous frequency takes on the form of a third order polynomial. The finite energy waveform is derived by minimizing the summed squared error between the desired spectrum and the obtained spectrum of the waveform. Having total control of the waveform spectrum has two advantages: First, it facilitates efficient use of the transducer passband, so that the amount of energy converted to heat in the transducer can be decreased. Secondly, by choosing an appropriate amplitude spectrum, no additional temporal tapering has to be applied to the matched filter to achieve sufficient range sidelobe suppression. Proper design results in waveforms with a range sidelobe level beyond -80 dB. The design method is tested experimentally using the RASMUS ultrasound system with a 7 MHz linear array transducer. Synthetic transmit aperture ultrasound imaging is applied to acquire data. The proposed design method was compared to a linear FM signal. Due to more efficient spectral usage, a gain in SNR of 4.3±1.2 dB was measured resulting in an increase of 1 cm in penetration depth. Finally, in-vivo measurements are shown for both methods, where the common carotid artery on a 27 year old healthy male was scanned.

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Directional velocity estimation using a spatio-temporal encoding technique based on frequency division for synthetic transmit aperture ultrasound

This paper investigates the possibility of flow estimation using spatio-temporal encoding of the transmissions in synthetic transmit aperture imaging (STA). The spatial encoding is based on a frequency division approach. In STA, a major disadvantage is that only a single transmitter (denoting single transducer element or a virtual source) is used in every transmission. The transmitted acoustic energy will be low compared to a conventional focused transmission in which a large part of the aperture is used. By using several transmitters simultaneously, the total transmitted energy can be increased. However, to focus the data properly, the signals originating from the different transmitters must be separated. To do so, the pass band of the transducer is divided into a number of subbands with disjoint spectral support. At every transmission, each transmitter is assigned one of the subbands. In receive, the signals are separated using a simple filtering operation. To attain high axial resolution, broadband spectra must be synthesized for each of the transmitters. By multiplexing the different waveforms on different transmitters over a number of transmissions, this can be accomplished. To further increase the transmitted energy, the waveforms are designed as linear frequency modulated signals. Therefore, the full excitation amplitude can be used during most of the transmission. The method has been evaluated for blood velocity estimation for several different velocities and incident angles. The program Field II was used. A 128-element transducer with a center frequency of 7 MHz was simulated. The 64 transmitting elements were used as the transmitting aperture and 128 elements were used as the receiving aperture. Four virtual sources were created in every transmission. By beamforming lines in the flow direction, directional data were extracted and correlated. Hereby, the velocity of the blood was estimated. The pulse repetition frequency was 16 kHz. Three different setups were investigated with flow angles of 45, 60, and 75 degrees with respect to the acoustic axis. Four different velocities were simulated for each angle at 0.10, 0.25, 0.50, and 1.00 m/s. The mean relative bias with respect to the peak flow for the three angles was less than 2%, 2%, and 4%, respectively.
Estimation of velocity vector angles using the directional cross-correlation method

A method for determining both velocity magnitude and angle in any direction is suggested. The method uses focusing along the velocity direction and cross-correlation for finding the correct velocity magnitude. The angle is found from beamforming directional signals in a number of directions and then select the angle with the highest normalized correlation between directional signals. The approach is investigated using Field II simulations and data from the experimental ultrasound scanner RASMUS and a circulating flow rig with a parabolic flow having a peak velocity of 0.3 m/s. A 7 MHz linear array transducer is used with a normal transmission of a focused ultrasound field. In the simulations the relative standard deviation of the velocity magnitude is between 0.7% and 7.7% for flow angles between 45 deg and 90 deg. The study showed that angle estimation by directional beamforming can be estimated with a high precision. The angle estimation performance is highly dependent on the choice of the time ktprf Tprf (correlation-time) between signals to correlate. One performance example is given with a fixed value of ktprf for all flow angles. The angle estimation on measured data for flow at 60 to 90 deg, yields a probability of valid estimates between 68% and 98%. The optimal value of ktprf for each flow angle is found from a parameter study and with these values the performance on simulated data yields angle estimates with no outlier estimates and with standard deviations below 2 deg.

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Estimation of velocity vectors in synthetic aperture ultrasound imaging

A method for determining both velocity magnitude and angle in a synthetic aperture ultrasound system is described. The approach uses directional beamforming along the flow direction and cross-correlation to determine velocity magnitude. The angle of the flow is determined from the maximum normalized correlation calculated as a function of angle. This assumes the flow direction is within the imaging plane. Simulations of the angle estimation method show both biases and standard deviations of the flow angle estimates below 3 deg for flow angles from 20 deg to 90 deg (transverse flow). The method is also investigated using data measured by an experimental ultrasound scanner from a flow rig. A commercial 128 element 7 MHz linear array transducer is used, and data are measured for flow angles of 60 deg and 90 deg. Data are acquired using the RASMUS experimental ultrasound scanner, which samples 64 channels simultaneously. A 20 us chirp
was used during emission and 8 virtual transmit sources were created behind the transducer using 11 transmitting elements. Data from the 8 transmissions are beamformed and coherently summed to create high resolution lines at different angles for a set of points within the region of flow. The velocity magnitude is determined with a precision of 0.36% (60 deg) and 1.2% (90 deg), respectively. The 60 deg angle is estimated with a bias of 0.54 deg and a standard deviation of 2.1 deg. For 90 deg the bias is 0.0003 deg and standard deviation 1.32 deg. A parameter study with regard to correlation length and number of emissions is performed to reveal the accuracy of the method. Real time data covering 2.2 seconds of the carotid artery of a healthy 30-year old male volunteer is acquired and then processed off-line using a computer cluster. The direction of flow is estimated using the above mentioned method. It is compared to the flow angle of 106 deg with respect to the axial direction, determined visually from the B-mode image. For a point in the center of the common carotid artery, 76% of the flow angle estimates over the 2.2 seconds were within 10 deg of the visually determined flow angle. The standard deviation of these estimates was below 2.7 deg. Full color flow maps from different parts of the cardiac cycle are presented, including vector arrows indicating both estimated flow direction and velocity magnitude.

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Frequency division transmission imaging and synthetic aperture reconstruction
In synthetic transmit aperture imaging only a few transducer elements are used in every transmission, which limits the signal-to-noise ratio (SNR). The penetration depth can be increased by using all transmitters in every transmission. In this paper, a method for exciting all transmitters in every transmission and separating them at the receiver is proposed. The coding is done by designing narrow-band linearly frequency modulated signals, which are approximately disjointed in the frequency domain and assigning one waveform to each transmitter. By designing a filterbank consisting of the matched filters corresponding to the excitation waveforms, the different transmitters can be decoded at the receiver. The matched filter of a specific waveform will allow information only from this waveform to pass through, thereby separating it from the other waveforms. This means that all transmitters can be used in every transmission, and the information from the different transmitters can be separated instantaneously. Compared to traditional synthetic transmit aperture (STA) imaging, in which the different transmitters are excited sequentially, more energy is transmitted in every transmission, and a better signal-to-noise-ratio is attained. The method has been tested in simulation, in which the resolution and contrast was compared to a standard synthetic transmit aperture system with a single sinusoid excitation. The resolution and contrast was comparable for the two systems. The method has also been tested using the experimental ultrasound scanner RASMUS. The resolution was evaluated using a string phantom. The method was compared to a conventional STA using both sinusoidal excitation and linear frequency modulated (FM) signals as excitation. The system using the FM signals and the frequency division approach yielded the same performance concerning both axial (of ap 3 lambda) and lateral resolution (of ap 4.5 lambda). A SNR measurement showed an increase in SNR of 6.5 dB compared to the system using the conventional STA method and FM signal excitation.

General information
Conventional ultrasound scanners can only display the axial component of the blood velocity vector, which is a significant limitation when vessels nearly parallel to the skin surface are scanned. The transverse oscillation method (TO) overcomes this limitation by introducing a transverse oscillation and an axial oscillation in the pulse echo field. The theory behind the creation of the double oscillation pulse echo field is explained as well as the theory behind the estimation of the vector velocity. A parameter study of the method is performed, using the ultrasound simulation program Field II. A virtual linear array transducer with center frequency 7 MHz and 128 active elements is created, and a virtual blood vessel of radius 6.4 mm is simulated. The performance of the TO method is found around an initial point in the parameter space. The parameters varied are: flow angle, transmit focus depth, receive apodization, pulse length, transverse wave length, number of emissions, signal to noise ratio, and type of echo canceling filter used. Using the experimental scanner
RASMUS, the performance of the TO method is evaluated. An experimental flowrig is used to create laminar parabolic flow in a blood mimicking fluid and the fluid is scanned under different flow-to-beam angles. The relative standard deviation on the transverse velocity estimate is found to be less than 10% for all angles between 50 deg. and 90 deg. Furthermore the TO method is evaluated in the flowrig using pulsatile flow which resembles the flow in the femoral artery. The estimated volume flow as a function of time is compared to the volume flow derived from a conventional axial method at an angle between 60 deg. It is found that the method is highly sensitive to the angle between the flow and the beam direction. Also the choice of echo canceling filter affects the performance significantly.
Parameter study of 3D synthetic aperture post-beamforming procedure.

A method to increase the image resolution and dynamic range is to use the acquired data from several emissions (lines) and to beamform the collected RF signals treating the focal point in transmit as a virtual source of a spherical wave. The transducer is swept mechanically over the region of interest to scan a full volume. The same beamformation procedure is applied both in the azimuth and the elevation planes. This paper presents a study of the influence of the position of the transmit focus on the image resolution, the signal-to-noise ratio and penetration depth. The investigation is based on simulations and measurements. The system used in this work is a research scanner developed at the department. The transducer is a 7.5 MHz linear array with a pitch of 208 µm and a fixed focus in the elevation direction at 25 mm. The field is simulated for points placed at every 5 mm between 10 and 150 mm depths. 100 different positions of the transmit focus are investigated. For every transmit focus the image is beamformed and evaluated. Finally the gain in signal-to-noise ratio and penetration depth are investigated experimentally for the setup, with which the best resolution is achieved. Simulations indicate that the size of the point spread function at a depth of 60 mm is decreased from 3 mm to 0.66 mm and from 4 mm to 2.5 mm in the azimuth and elevation planes, respectively. The gain in signal-to-noise ratio measured in a tissue mimicking phantom is 10 dB. The penetration depth increases from 70 to 100 mm. The method can be applied in applications, where the image quality is of prime importance, such as in the classification of atherosclerotic lesions in the carotid artery.

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Parametric Beamformer for Synthetic Aperture Ultrasound Imaging

In this paper a parametric beamformer, which can handle all imaging modalities including synthetic aperture imaging, is presented. The image lines and apodization coefficients are specified parametrically, and the lines can have arbitrary orientation and starting point in 3D coordinates. The beamformer consists of a number of identical beamforming blocks, each processing data from several channels and producing part of the image. A number of these blocks can be accommodated in a modern field-programmable gate array device (FPGA), and a whole synthetic aperture system can be
implemented using several FPGAs. For the current implementation, the input data is sampled at 4 times the center frequency of the excitation pulse and is match-filtered in the frequency domain. In-phase and quadrature data are beamformed with a sub-sample precision of the focusing delays of 1/16th of the sampling period. Each line is completely specified by 3 input parameters. The focusing delays are calculated iteratively in a 8-stage deep pipeline, and focusing information for 8 different lines is interleaved to produce delays at every clock cycle. The apodization is specified using piecewise linear approximation with 255 levels. A beamforming block uses input data from 4 elements and produces a set of 10 lines. Linear interpolation is used to implement sub-sample delays. The VHDL code for the beamformer has been synthesized for a Xilinx V4FX100 speed grade 11 FPGA, where it can operate at a maximum clock frequency of 167.8 MHz. Each beamformation block requires 12 multipliers, 5 buffers for parameters, 8 buffers for input data and 32 buffers for output data (I and Q). Furthermore double-buffering is used for the input data, thus simplifying the synchronization. Up to six beamforming blocks can fit in one FPGA. Clocked at 150 MHz they produce 900 x 106 I and Q samples/second. Assuming a pulse repetition frequency of 5000 Hz, these blocks can be configured to beamform in real time 256 B-mode lines of synthetic aperture data from 4 transducer elements, or 64 lines from 16 elements.

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**Plane wave fast color flow mode imaging: Parameter study**
A new Plane wave fast color flow imaging method (PWM) has been investigated, and performance evaluation of the PWM based on experimental measurements has been made. The results show that it is possible to obtain a CFM image using only 8 echo-pulse emissions for beam to flow angles between 45 degrees and 75 degrees. Compared to the conventional ultrasound imaging the frame rate is similar to 30 - 60 times higher. The bias, B-est of the velocity profile estimate, based on 8 pulse-echo emissions, is between 3.3% and 6.1% for beam to flow angles between 45 degrees and 75 degrees, and the standard deviation, sigma(est) of the velocity profile estimate is around 2% for beam to flow angles between 45 degrees and 75 degrees relative to the peak velocity, when the flow angle is known in advance. A study is performed to investigate how different parameters influence the blood velocity estimation. The results confirmed expectations for beam to flow angles between 45 degrees and 75 degrees. The parameter study shows that the PWM using Directional velocity estimation gives the best results using spatial sampling interval <= lambda/10, correlation range >= 10A, and number of directional signals => 6. It is hereby shown that, by carefully choosing the set of parameters, PWM is feasible for fast CFM imaging with an acceptable bias and standard deviation.

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Preliminary In-vivo Results For Spatially Coded Synthetic Transmit Aperture Ultrasound Based On Frequency Division

This paper investigates the possibility of using spatial coding based on frequency division for in-vivo synthetic transmit aperture (STA) ultrasound imaging. When using spatial encoding for STA, it is possible to use several transmitters simultaneously and separate the signals at the receiver. This increases the maximum transmit power compared to conventional STA, where only one transmitter can be active. The signal-to-noise-ratio can therefore he increased and better penetration can be obtained. For frequency division, the coding is achieved by designing a number of transmit waveforms with disjoint spectral support, spanning the passband of the ultrasound transducer. The signals can therefore be separated at the receiver using matched filtering. The method is tested using a commercial linear array transducer with a center frequency of 9 MHz and 68% fractional bandwidth. In this paper, the transmit waveforms are designed as non-linear frequency modulated signals. This allows for efficient design of the amplitude spectrum of the signals. The duration of the signals was 25 µs and the bandwidth of each frequency band was 2.8 MHz. Eight frequency bands were designed which allowed for four transmitters to be active simultaneously. The method is compared to traditional STA with linear frequency modulation as means of temporal coding. The reference waveform was a 20 ps chirp at 9.37 MHz with a bandwidth of 11.3 MHz. Penetration and resolution is evaluated using a tissue mimicking phantom. The increase in penetration for the frequency division method was approximately 2 cm. The SNR was measured in the same type of phantom and an increase in SNR at depths between 3 cm and 10 cm of 7.2 +/- 3.6 dB was found. In-vivo experiments were carried out by an experienced sonographer. First, the common carotid artery was scanned on a 27 year old healthy male volunteer. The image quality was comparable for the two methods. To compare penetration depth of the two methods, the vesica fellea was scanned on the same volunteer. The frequency division method exhibited approximately 2 cm improvement in penetration compared to conventional STA.

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Real-time synthetic aperture imaging: opportunities and challenges

Synthetic aperture (SA) ultrasound imaging has not been introduced in commercial scanners mainly due to the computational cost associated with the hardware implementation of this imaging modality. SA imaging redefines the term beamformed line. Since the acquired information comes from all points in the region of interest it is possible to beamform the signals along a desired path, thus, improving the estimation of blood flow. The transmission of coded excitations makes it possible to achieve higher contrast and larger penetration depth compared to "conventional" scanners. This paper presents the development and implementation of the signal processing stages employed in SA imaging: compression of received data acquired using codes, and beamforming. The goal was to implement the system using commercially available field programmable gate arrays. The compression filter operates on frequency modulated pulses with duration of up to 50 mus sampled at 70 MHz. The beamformer can process data from 256 channels at a pulse
repetition frequency of 5000 Hz and produces 192 lines of 1024 complex samples in real time. The lines are described by
their origin, direction, length and distance between two samples in 3D. This parametric description makes it possible to
quickly change the image geometry during scanning, thus enabling adaptive imaging and precise flow estimation. The
paper addresses problems such as large bandwidth and computational load and gives the solutions that have been
adopted for the implementation.

Recursive Delay Calculation Unit for Parametric Beamformer
This paper presents a recursive approach for parametric delay calculations for a beamformer. The suggested calculation
procedure is capable of calculating the delays for any image line defined by an origin and arbitrary direction. It involves
only add and shift operations making it suitable for hardware implementation. One delay calculation unit (DCU) needs 4
parameters, and all operations can be implemented using fixed-point arithmetics. An N-channel system needs N + 1
DCUs per line - one for the distance from the transmit origin to the image point and N for the distances from the image
point to each of the receivers. Each DCU recursively calculates the square of the distance between a transducer element
and a point on the beamformed line. Then it finds the approximate square root. The distance to point i is used as an initial
guess for point i + 1. Using fixed-point calculations with 36-bit precision gives an error in the delay calculations on the
order of 1/64 samples, at a sampling frequency of fs = 40 MHz. The circuit has been synthesized for a Virtex II Pro device
speed grade 6 in two versions - a pipelined and a non-pipelined producing 150 and 30 million delays per second,
respectively. The non-pipelined circuit occupies about 0.5% of the FPGA resources and the pipelined one about 1%.
When the square root is found with a pipelined CORDIC processor, 2% of the FPGA slices are used to deliver 150 million
delays per second.

Spectral velocity estimation in ultrasound using sparse data sets

Velocity distributions in blood vessels can be displayed using ultrasound scanners by making a Fourier transform of the received signal and then showing spectra in an M-mode display. It is desired to show a B-mode image for orientation, and data for this have to be acquired interleaved with the flow data. This either halves the effective pulse repetition frequency fprf or gaps appear in the spectrum from B-mode emissions. This paper presents a techniques for maintaining the highest possible fprf and at the same time show a B-mode image. The power spectrum can be calculated from the Fourier transform of the autocorrelation function, and it is shown that the autocorrelation function can be calculated for a sparse set of data where flow and B-mode emissions are inter-spaced. Both short deterministic sequences of emissions and full random sequences can be used. The dynamic range of the sparse sequence is reduced compared to a full sequence. Typically a reduction of 20 dB is found when using 66% of the data compared to using all data. The theory of the method and examples from simulations of flow in arteries are presented. The audio signal can also be generated from the spectrogram.
Vector blood velocity estimation in medical ultrasound

Two methods for making vector velocity estimation in medical ultrasound are presented. All of the techniques can find both the axial and transverse velocity in the image and can be used for displaying both the correct velocity magnitude and direction. The first method uses a transverse oscillation in the ultrasound field to find the transverse velocity. In-vivo examples from the carotid artery are shown, where complex turbulent flow is found in certain parts of the cardiac cycle. The second approach uses directional beam forming along the flow direction to estimate the velocity magnitude. Using a correlation search can also yield the direction, and the full velocity vector is thereby found. An examples from a flow rig is shown.

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Vector Velocity Imaging Using Cross-Correlation and Virtual Sources

Previous investigations have shown promising results in using the directional cross-correlation method to estimate velocity vectors. The velocity vector estimate provides information on both velocity direction and magnitude. The direction is estimated by beamforming signals along directions in the range $[0^\circ; 180^\circ]$ and identifying the direction that produces the largest correlation across emissions. An estimate of the velocity magnitude is obtained from the spatial shift between signals beamformed along the estimated direction. This paper expands these investigations to include estimations of the vector velocities of a larger region by combining the estimations along several scan lines. In combination with a B-mode image, the vector velocities are displayed as an image of the investigated region with a color indicating the magnitude, and arrows showing the direction of the flow. Using the RASMUS experimental ultrasound scanner, measurements have been carried out in a water tank using a 7-MHz transducer. A 6-mm tube contained the flow and a Danfoss, MAG-3000, magnetic flow meter measured the volume flow. The tube has a parabolic flow profile with a peak velocity of 0.29 m/s. During the experiments fixed beam-to-flow angles at $\{60^\circ, 75^\circ, 90^\circ\}$ were applied. The images are obtained using a pulse repetition frequency of 15 kHz, and the images contain 33 lines with 60 emissions for each line. Corresponding to the three fixed beam-to-flow angles, the angle estimates along the center scan line have a bias of $\{-3.9^\circ, -12.8^\circ, -18.1^\circ\}$ and standard deviation of $\{10.0^\circ, 18.2^\circ, 32.2^\circ\}$. The estimates of the velocity magnitude have bias of $\{4.4\%, 8.1\%, -5.4\%\}$ and standard deviation of $\{9.7\%, 14.3\%, 13.4\%\}$ relative to the peak velocity. The amount of in-tube angle estimates in the range of $\pm 10^\circ$ from the true angle are $\{74\%, 77\%, 66\%\}$. In-vivo measurements are carried out on a
A simple method to reduce aliasing artifacts in color flow mode imaging.

It is a well known limitation in conventional blood velocity estimation using a phase estimation approach, that aliasing artifacts are present, when the blood velocities exceed a value determined by half the pulse repetition frequency (the Nyquist frequency). This paper proposes a simple anti-aliasing discriminator (AAD) method based on using two different pulse repetition frequencies to increase the aliasing limit to twice the Nyquist frequency. The method is evaluated in simulations using the Field II program. The axial velocity in a virtual blood vessel is found along one axial line, where N=10 emissions are used for each velocity estimate. Mean standard deviation and mean absolute bias are 4.9% and 23.8%, respectively, when no attempt is done to suppress the aliasing. When the AAD is used the corresponding values are 3.4% and 1.0%. When median filtering is applied, the values are 1.1% and 0.6%. The method is evaluated experimentally using the ultrasound scanner RASMUS and a circulating flowrig with parabolic flow. The mean standard deviation and mean absolute bias are 4.0% and 20.3%, respectively, when no attempt is done to suppress the aliasing. When the anti-aliasing discriminator is used the corresponding values are 3.6% and 1.2%. The values are 1.0% and 0.8%, when median filtering is performed.

Blood vector velocity estimation using an autocorrelation approach: In vivo Investigation.

In conventional techniques for blood velocity estimation, only the axial component of the velocity vector is found. We have previously shown that it is possible to estimate the 2-D blood velocity vector both in simulations and in flow phantom experiments using a fast and inexpensive method (the transverse oscillation (TO) method) based on an autocorrelation approach. The TO method makes use of a double oscillating pulse-echo field which is created by manipulating the receive apodization function. Two receive beams are beamformed, where the lateral distance between the two beams corresponds to a 90 deg phase shift in the lateral direction. The TO method works at angles where conventional methods fails to estimate any blood movement, i.e. when the angle between the ultrasound beam and the velocity vector is approximately 90 deg. In this paper the first in-vivo color flow map (CFM) images are presented using the TO method. A 128 element 5 MHz linear array transducer was used together with the experimental ultrasound scanner RASMUS.
operating at a sampling frequency of 40 MHz with a pulse repetition frequency of 24 kHz. After sampling the received channel data were beamformed off-line, and a transverse oscillation period of 1 mm was created in the lateral pulse-echo field by manipulating the receive apodization function. Echo-canceling was performed by subtracting a line from the sampled data, where the line was a linear fit to the sampled data. Three different scan areas were selected: 1) The common carotid artery, 2) the common carotid artery and the jugular vein, 3) the bifurcation of the common carotid artery. In all three cases the angle between the ultrasound beams and the blood velocity vector is larger than 60 deg. i.e. the conventional Doppler velocity estimator degrades significantly in terms of standard deviation and bias. The velocity direction and magnitude could be estimated for all cases and it was found that the blood flow is within the values given by the literature.

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Blood velocity estimation using spatio-temporal encoding based on frequency division approach
In this paper a feasibility study of using a spatial encoding technique based on frequency division for blood flow estimation is presented. The spatial encoding is carried out by dividing the available bandwidth of the transducer into a number of narrow frequency bands with approximately disjoint spectral support. By assigning one band to one virtual source, all virtual sources can be excited simultaneously. The received echoes are beamformed using Synthetic Transmit Aperture beamforming. The velocity of the moving blood is estimated using a cross-correlation estimator. The simulation tool Field II was used to carry out the study. Three different flow angles were investigated: 45 ◦, 60 ◦ and 75 ◦, and all setups were investigated for four different velocities: 0.10, 0.25, 0.50, 1.00 m/s. The mean relative bias was below 4% in all simulations and the mean relative standard deviation was below 3%

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Compact FPGA-based beamformer using oversampled 1-bit A/D converters
A compact medical ultrasound beamformer architecture that uses oversampled 1-bit analog-to-digital (A/D) converters is presented. Sparse sample processing is used, as the echo signal for the image lines is reconstructed in 512 equidistant focal points along the line through its in-phase and quadrature components. That information is sufficient for presenting a B-mode image and creating a color flow map. The high sampling rate provides the necessary delay resolution for the focusing. The low channel data width (1-bit) makes it possible to construct a compact beamformer logic. The signal reconstruction is done using finite impulse response (FIR) filters, applied on selected bit sequences of the delta-sigma
modulator output stream. The approach allows for a multichannel beamformer to fit in a single field programmable gate array (FPGA) device. A 32-channel beamformer is estimated to occupy 50% of the available logic resources in a commercially available midrange FPGA, and to be able to operate at 129 MHz. Simulation of the architecture at 140 MHz provides images with a dynamic range approaching 60 dB for an excitation frequency of 3 MHz.

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Comparing interpolation schemes in dynamic receive ultrasound beamforming.
In medical ultrasound interpolation schemes are of ten applied in receive focusing for reconstruction of image points. This paper investigates the performance of various interpolation scheme by means of ultrasound simulations of point scatterers in Field II. The investigation includes conventional B-mode imaging and synthetic aperture (SA) imaging using a 192-element, 7 MHz linear array transducer with λ pitch as simulation model. The evaluation consists primarily of calculations of the side lobe to main lobe ratio, SLMLR, and the noise power of the interpolation error. When using conventional B-mode imaging and linear interpolation, the difference in mean SLMLR is 6.2 dB. With polynomial interpolation the ratio is in the range 6.2 dB to 0.3 dB using 2nd to 5th order polynomials, and with FIR interpolation the ratio is in the range 5.8 dB to 0.1 dB depending on the filter design. The SNR is between 21 dB and 45 dB with the polynomial interpolation and between 37 dB and 43 dB with FIR filtering. In the synthetic aperture imaging modality the difference in mean SLMLR ranges from 14 dB to 33 dB and 6 dB to 31 dB for the polynomial and FIR filtering schemes respectively. By using a proper interpolation scheme it is possible to reduce the sampling frequency and avoid a decrease in performance. When replacing linear interpolation with a more advanced interpolation scheme it is possible to obtain a reduction of 18 dB and 33 dB in the SLMLR for the B-mode and SA imaging, respectively, and an improvement in SNR of 24 dB.

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Determination of velocity vector angles using the directional cross-correlation method.

A method for determining both velocity magnitude and angle in any direction is suggested. The method uses focusing along the velocity direction and cross-correlation for finding the correct velocity magnitude. The angle is found from beamforming directional signals in a number of directions and then select the angle with the highest normalized correlation between directional signals. The approach is investigated using Field II simulations and data from the experimental ultrasound scanner RASMUS and with a parabolic flow having a peak velocity of 0.3 m/s. A 7 MHz linear array transducer is used with a normal transmission of a focused ultrasound field. The velocity profile estimates from simulations have relative mean standard deviations between 0.7% and 7.7% for flow between 45° and 90°. The angle estimation performance is highly dependent on the choice of the time k tprf · T prf (correlation-time) between signals to correlate, and a proper choice varies with flow angle and flow velocity. One performance example is given with a fixed value of k tprf for all flow angles. The angle estimation on measured data for flow at 60° to 90°, yields a probability of valid estimates between 68% and 98% and with standard deviations between 1° and 4°. The optimal value of k tprf for each flow angle is found from a parameter study to reveal the potential of the method and with these values the performance on simulated data yields angle estimates with no outlier estimates and with standard deviations below 2°.

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Experimental investigation of synthetic aperture flow angle estimation
Currently synthetic aperture flow methods can find the correct velocity magnitude, when the flow direction is known. To make a fully automatic system, the direction should also be estimated. Such an approach has been suggested by Jensen (2004) based on a search of the highest cross-correlation as a function of velocity and angle. This paper presents an experimental investigation of this velocity angle estimation method based on a set of synthetic aperture flow data measured using our RASMUS experimental ultrasound system. The measurements are performed for flow angles of 60, 75, and 90 deg. with respect to the axial direction, and for constant velocities with a peak of 0.1 m/s and 0.2 m/s. The implemented synthetic aperture imaging method uses virtual point sources in front of the transducer, and recursive imaging is used to increase the data rate. A 128 element linear array transducer is used for the experiments, and the emitted pulse is a 20 micro sec. chirp, linearly sweeping frequencies from approximately 3.5 to 10.5 MHz. The flow angle could be estimated with an average bias up to 5.0 deg., and a average standard deviation between 0.2 deg. and 5.2 deg. Using the angle estimates, the velocity magnitudes were estimated with average standard deviations no higher than 6.5% relative to the peak velocity.

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Fast color flow mode imaging using plane wave excitation and temporal encoding

In conventional ultrasound color flow mode imaging, a large number (~500) of pulses have to be emitted in order to form a complete velocity map. This lowers the frame-rate and temporal resolution. A method for color flow imaging in which a few (~10) pulses have to be emitted to form a complete velocity image is presented. The method is based on using a plane wave excitation with temporal encoding to compensate for the decreased SNR, resulting from the lack of focusing. The temporal encoding is done with a linear frequency modulated signal. To decrease lateral sidelobes, a Tukey window is used as apodization on the transmitting aperture. The data are beamformed along the direction of the flow, and the velocity is found by 1-D cross correlation of these data. First the method is evaluated in simulations using the Field II program. Secondly, the method is evaluated using the experimental scanner RASMUS and a 7 MHz linear array transducer, which scans a circulating flowrig. The velocity of the blood mimicking fluid in the flowrig is constant and parabolic, and the center of the scanned area is situated at a depth of 40 mm. A CFM image of the blood flow in the flowrig is estimated from two pulse emissions. At the axial center line of the CFM image, the velocity is estimated over the vessel with a mean relative standard deviation of 2.64% and a mean relative bias of 6.91%. At an axial line 5 mm to the right of the center of the CFM image, the velocity is estimated over the vessel with a relative standard deviation of 0.84% and a relative bias of 5.74%. Finally the method is tested on the common carotid artery of a healthy 33-year-old male.

Spatio-temporal encoding using narrow-band linear frequency modulated signals in synthetic aperture ultrasound imaging

In this paper a method for spatio-temporal encoding is presented for synthetic transmit aperture ultrasound imaging (STA). The purpose is to excite several transmitters at the same time in order to transmit more acoustic energy in every single transmission. When increasing the transmitted acoustic energy, the signal to noise ratio will increase. However, to focus the data properly using the STA approach, the transmitters have to be separated from each other. This is done by dividing the available spectrum into several subbands with a small overlap. Separating different transmitters can be done by bandpass filtering. Therefore, the separation can be done instantaneously without the need for further transmissions, unlike spatial encoding relying on Hadamard or Golay coding schemes, where several transmissions have to be made before the decoding can be done. Motion artifacts from the decoding can, thus, be avoided. To further increase the transmitted energy, the excitation waveforms are designed as linear frequency modulated (FM) signals. This makes it possible to maintain the full excitation amplitude during most of the transmission. The design of the separation filters will also be discussed. The method was tested using the experimental ultrasound scanner RASMUS and evaluated using a reference setup with a linear FM excitation waveform and STA beamforming. The point spread function (PSF) was measured on a wire phantom in water. A wire phantom with an attenuating medium was also measured, where the proposed method achieved approximately 2 cm improvement in penetration depth. The signal to noise ratio was also measured, where the gain was ~ 7 dB in comparison to the reference.
Spectral Velocity Estimation using the Autocorrelation Function and Sparse data Sequences

Ultrasound scanners can be used for displaying the distribution of velocities in blood vessels by finding the power spectrum of the received signal. It is desired to show a B-mode image for orientation and data for this has to be acquired interleaved with the flow data. Techniques for maintaining both the B-mode frame rate, and at the same time have the highest possible $f_{prf}$ only limited by the depth of investigation, are, thus, of great interest. The power spectrum can be calculated from the Fourier transform of the autocorrelation function $R_r(k)$. The lag $k$ corresponds to the difference in pulse number, so that for lag $k$ data from emission $i$ is correlated with $i+k$. It is possible to calculate $R_r(k)$ for a sparse set of emissions, as long as all combinations of emissions cover all lags in $R_r(k)$. A sparse set of emissions interleaved with B-mode emissions can, therefore, be used for estimating $R_r(k)$. The approach has been investigated using Field II simulation of the flow in the carotid and femoral arteries. A 5 MHz linear array transducer with 128 elements, a pitch of $\lambda$ and an element height of 5 mm was simulated. The autocorrelation was calculated from the sparse sequence and averaged over a pulse length. The 1:2 sequence using 2 flow emission for one B-Mode emissions showed a nearly indistinguishable spectrum compared to a Fourier spectrum calculated on the full data. The sparser sequences give a higher noise in the spectrum proportional to the sparseness of the sequence. The audio signal has also been synthesized from the autocorrelation data by passing white, Gaussian noise through a filter designed from the power spectrum of the autocorrelation function. The results show that both the full velocity range can be maintained at the same time as a B-mode image is shown in real time, where the trade-off between B-mode frame rate and spectral accuracy can be selected.

Synthetic aperture flow angle estimation on in-vivo data from the carotid artery

In conventional ultrasound velocity estimation systems only the velocity projected onto the direction of the steered ultrasound beam is found. It has previously been shown how true blood flow velocity magnitudes can be found using synthetic transmit aperture imaging. The method is based on crosscorrelation between lines beamformed along the flow direction. This method assumes the direction of flow is known. Jensen (2004) presented a method for estimating the direction of flow [1]. The angle determination method is based on a search for the maximum normalized cross-correlation as a function of angle. It assumes the largest correlation is seen for the angle of flow. Previously, this method has only been validated using data from a circulating flow rig. This paper presents an In-Vivo investigation of the method. Real time data covering 2.2 seconds of the carotid artery of a healthy 30-year old male volunteer is acquired and then processed off-line using a large computer cluster. Data are acquired using our RASMUS experimental ultrasound scanner and a 128 element 6.2 MHz linear array transducer. A 20 µs chirp was used during emission and virtual transmit sources were
created behind the transducer using 11 transmitting elements. Data from 8 transmissions with each 64 receiving elements are beamformed and coherently summed to create high resolution lines at different angles for a set of points within the region of flow. The pulse repetition frequency was set to 10 kHz. The direction of flow is estimated using the above mentioned method. It is compared to the flow angle of $106^\circ$ with respect to the axial direction, determined visually from the B-mode image. For a point in the center of the common carotid artery, 76 % of the flow angle estimates over the 2.2 seconds were within $\pm 10^\circ$ of the visually determined flow angle. The standard deviation of these estimates was below $2.7^\circ$. Full color flow maps from different parts of the cardiac cycle are presented, including vector arrows indicating both estimated flow direction and velocity magnitude.

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**Ultrasound Research Scanner for Real-time Synthetic Aperture Data Acquisition**

Conventional ultrasound systems acquire ultrasound data sequentially one image line at a time. The architecture of these systems is therefore also sequential in nature and processes most of the data in a sequential pipeline. This often makes it difficult to implement radically different imaging strategies on the platforms and makes the scanners less accessible for research purposes. For a system designed for imaging research flexibility is the prime concern. The possibility of sending out arbitrary signals and the storage of data from all transducer elements for 5 to 10 seconds allows clinical evaluation of synthetic aperture and 3D imaging. This paper describes a real-time system specifically designed for research purposes. The system can acquire multi-channel data in real-time from multi-element ultrasound transducers, and can perform some real-time processing on the acquired data. The system is capable of performing real-time beamforming for conventional imaging methods using linear, phased, and convex arrays. Image acquisition modes can be intermixed, and this makes it possible to perform initial trials in a clinical environment with new imaging modalities for synthetic aperture imaging, 2D and 3D B-mode and velocity imaging using advanced coded emissions. The system can be used with 128 element transducers and can excite 128 transducer elements and receive and sample data from 64 channels simultaneously at 40 MHz with 12 bits precision. Two-to-one multiplexing in receive can be used to cover 128 receive channels. Data can be beamformed in real time using the system’s 80 signal processing units, or it can be stored directly in RAM. The system has 16 Gbytes RAM and can, thus, store more than 3.4 seconds of multi-channel data. It is fully software programmable and its signal processing units can also be reconfigured under software control. The control of the system is done over a 100 Mbit/s Ethernet using C and Matlab. Programs for doing e.g. B-mode imaging can directly be written in Matlab and executed on the system over the net from any workstation running Matlab. The overall system concept is presented along with its implementation and examples of B-mode and in-vivo synthetic aperture flow imaging.

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Use of modulated excitation signals in medical ultrasound. Part III: High frame rate imaging

For pt.II, see ibid., vol.52, no.2, p.192-207 (2005). This paper, the last from a series of three papers on the application of coded excitation signals in medical ultrasound, investigates the possibility of increasing the frame rate in ultrasound imaging by using modulated excitation signals. Linear array-coded imaging and sparse synthetic transmit aperture imaging are considered, and the trade-offs between frame rate, image quality, and SNR are discussed. It is shown that FM codes can be used to increase the frame rate by a factor of two without a degradation in image quality and by a factor of 5, if a slight decrease in image quality can be accepted. The use of synthetic transmit aperture imaging is also considered, and it is here shown that Hadamard spatial encoding in transmit with FM emission signals can be used to increase the frame rate by 12 to 25 times with either a slight or no reduction in signal-to-noise ratio and image quality. By using these techniques, a complete ultrasound-phased array image can be created using only two emissions.

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Use of modulated excitation signals in ultrasound. Part I: Basic concepts and expected benefits

This paper, the first from a series of three papers on the application of coded excitation signals in medical ultrasound, discusses the basic principles and ultrasound-related problems of pulse compression. The concepts of signal modulation and matched filtering are given, and a simple model of attenuation relates the matched filter response with the ambiguity function, known from radar. Based on this analysis and the properties of the ambiguity function, the selection of coded waveforms suitable for ultrasound imaging is discussed. It is shown that linear frequency modulation (FM) signals have the best and most robust features for ultrasound imaging. Other coded signals such as nonlinear FM and binary complementary Golay codes also have been considered and characterized in terms of signal-to-noise ratio (SNR) and sensitivity to frequency shifts. Using the simulation program Field II, it is found that in the case of linear FM signals, a SNR improvement of 12 to 18 dB can be expected for large imaging depths in attenuating media, without any depth-dependent filter compensation. In contrast, nonlinear FM modulation and binary codes are shown to give a SNR improvement of only 4 to 9 dB when processed with a matched filter. Other issues, such as depth-dependent matched filtering and use of filters other than the matched filter (inverse and Wiener filters) also are addressed.
Use of modulated excitation signals in ultrasound. Part II: Design and performance for medical imaging applications

For pt.I, see ibid., vol.52, no.2, p.177-91 (2005). In the first paper, the superiority of linear FM signals was shown in terms of signal-to-noise ratio and robustness to tissue attenuation. This second paper in the series of three papers on the application of coded excitation signals in medical ultrasound presents design methods of linear FM signals and mismatched filters, in order to meet the higher demands on resolution in ultrasound imaging. It is shown that for the small time-bandwidth (TB) products available in ultrasound, the rectangular spectrum approximation is not valid, which reduces the effectiveness of weighting. Additionally, the distant range sidelobes are associated with the ripples of the spectrum amplitude and, thus, cannot be removed by weighting. Ripple reduction is achieved through amplitude or phase predistortion of the transmitted signals. Mismatched filters are designed to efficiently use the available bandwidth and at the same time to be insensitive to the transducer's impulse response. With these techniques, temporal sidelobes are kept below 60 to 100 dB, image contrast is improved by reducing the energy within the sidelobe region, and axial resolution is preserved. The method is evaluated first for resolution performance and axial sidelobes through simulations with the program Field II. A coded excitation ultrasound imaging system based on a commercial scanner and a 4 MHz probe driven by coded sequences is presented and used for the clinical evaluation of the coded excitation/compression scheme. The clinical images show a significant improvement in penetration depth and contrast, while they preserve both axial and lateral resolution. At the maximum acquisition depth of 15 cm, there is an improvement of more than 10 dB in the signal-to-noise ratio of the images. The paper also presents acquired images, using complementary Golay codes, that show the deleterious effects of attenuation on binary codes when processed with a matched filter, also confirmed by the presented simulated images.
A Code Division Technique for Multiple Element Synthetic Aperture Transmission

In conventional synthetic transmit aperture imaging (STA) the image is built up from a number of low resolution images each originating from consecutive single element firings to yield a high resolution image. This may result in motion artifacts making flow imaging problematic. This paper describes a method in which all transmitting centers can be excited at the same time and separated at the receiver. Hereby the benefits from traditional STA can be utilized and a high frame rate can be maintained and the images are not influenced by motion artifacts. The different centers are excited using mutually orthogonal codes. The total signal at the receiver is then a linear combination of the transmitted signals convolved with the corresponding pulse-echo impulse response. The pulse-echo impulse responses for the different elements are modeled as FIR channels and estimated using a maximum likelihood technique. The method was verified using Field II. A 7 MHz transducer was simulated with 128 receiving elements and 64 transmitting elements divided into subapertures so that 4 virtual transmission centers were formed. The point spread function was measured and the axial resolution was 0.2312 mm (-3dB) and 0.3083 mm (-6dB), lateral resolution 0.5301 mm (-3dB) and 0.7068 mm (-6dB) and maximum lateral sidelobe level less than 44 dB. Conventional STA is given as a reference with the same setup excited with a single cycle sinusoid at 7 MHz with axial resolution 0.2312 mm (-3dB) and 0.3083 mm (-6dB), lateral resolution 0.5301 mm (-3dB) and 0.7068 mm (-6dB) and maximum lateral sidelobe level less than 44 dB.

An In-vivo investigation of transverse flow estimation

Conventional ultrasound scanners are restricted to display the blood velocity component in the ultrasound beam direction. By introducing a laterally oscillating field, signals are created from which the transverse velocity component can be estimated. This paper presents velocity and volume flow estimates obtained from flow phantom and in-vivo measurements with a relative standard deviation of 13.0 % and a relative mean bias of 3.4 %. The in-vivo experiment is performed on the common carotid artery of a healthy 25 year old male. The same transducer and setup is used as in the flow phantom experiment, and the data is acquired using the RASMUS scanner. The peak velocity of the carotid flow is estimated to 1.2 m/s and the volume flow to 290 ml/min. This is within normal physiological range.
Compact implementation of dynamic receive apodization in ultrasound scanners

The image quality in medical ultrasound scanners is determined by several factors, one of which is the ability of the receive beamformer to change the aperture weighting function with depth and beam angle. In digital beamformers, precise dynamic apodization can be achieved by representing the function by numeric sequences. For a 15 cm scan depth and 100 lines per image, a 64-channel, 40 MHz ultrasound beamformer may need almost 50 million coefficients. A more coarse representation of the aperture relieves the memory requirements but does not enable compact and precise beamforming. Previously, the authors have developed a compact beamformer architecture, which utilizes sigma-delta A/D conversion, recursive delay generation, and sparse sample reconstruction using FIR filters. The channel weights were here fixed. In this paper, a compact implementation of dynamic receive apodization is presented. It allows precise weighting coefficient generation and utilizes a recursive algorithm, which shares its starting parameters with the recursive delay generation logic. Thus, only a separate calculation block, consisting of 5 adders and 5 registers, is necessary. A VHDL implementation for a Xilinx XCV2000E-7 FPGA device has been made for the whole receive beamformer for assessing the necessary hardware resources and the achievable performance for that platform. The code implements dynamic apodization with an expanding aperture for either linear or phased array imaging. A complete 32-channel beamformer can operate at 129.82 MHz and occupies 1.28 million gates. Simulated in Matlab, a 64-channel beamformer provides gray scale image with around 55 dB dynamic range. The beamformed data can also be used for flow estimation.

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Directional synthetic aperture flow imaging

A method for flow estimation using synthetic aperture imaging and focusing along the flow direction is presented. The method can find the correct velocity magnitude for any flow angle and full color flow images can be measured using only 32 to 128 pulse emissions. The approach uses spherical wave emissions using a number of defocused elements and a linear frequency modulated pulse (chirp) to improve the signal-to-noise ratio. The received signals are dynamically focused along the flow direction and these signals are used in a cross-correlation estimator for finding the velocity magnitude. The flow angle is manually determined from the B-mode image. The approach can be used for both tissue and blood velocity determination. The approach was investigated using both simulations and a flow system with a laminar flow. The flow profile was measured with a commercial 7.5 MHz linear array transducer. A plastic tube with an internal diameter of 17 mm was used with an EcoWatt 1 pump generating a laminar, stationary flow. The velocity profile was measured for flow angles of 90 and 60 degrees. The RASMUS research scanner was used for acquiring RF data from 128 elements of the array using 8 emissions with 11 elements in each emission. A 20 us chirp was used during emission. The RF data were subsequently beamformed off-line and stationary echo canceling was performed. The 60 degrees flow with a peak velocity of 0.15 m/s was determined using 16 groups of 8 emissions and the relative standard deviation was 0.36% (0.65 mm/s). Using the same set-up for the purely transverse flow gave a std. of 1.2% (2.1 mm/s). Variation of the different parameters has been done to reveal the sensitivity to number of lines, angle deviations, length of correlation interval, and sampling interval. An in-vivo image of the carotid artery and jugular vein of a healthy 29 years old volunteer was acquired. A full color flow image using only 128 emissions could be made with a high velocity precision.

General information
Identification of pulse echo impulse responses for multi source transmission

In this paper a method for acquiring data from several simultaneously transmitting elements in synthetic transmit aperture (STA) ultrasound imaging is proposed. Several transmitters are excited simultaneously using pseudo-random sequences. The received signal at a given time point and receiver is a mixture of the information corresponding to several transmitters. There is, thus, no direct way of determining which information corresponds to which transmitter, preventing proper focusing. In this paper we decode the received signal by estimating the pulse echo impulse responses between every transmitter and receiver pair, using a least squares estimator. The decoding is done instantaneously, making information from several transmitters available after only one transmission. This limits the influence of motion artifacts both in the decoding step and when the STA focusing scheme is applied. The method is evaluated using the simulation tool Field II. Three point spread functions are simulated where axial movement of 1 m/s is present. The axial resolution for the moving scatterer is 0.249 mm (-3dB) and 0.291 mm (-6dB), which is compared to a standard STA transmission scheme with sequential excitation of the transmitters using a chirp excitation. The axial resolution was in this case 0.260 mm (-3dB) and 0.611 mm (-6dB). Also a blood vessel is simulated with an angle of 45° to the acoustic axis with a peak flow of 1 m/s. The velocity is estimated with a mean bias of 2.57% and a mean standard deviation of 0.505% relative to the peak velocity of the flow.
Maximum Likelihood Blood Velocity Estimator Incorporating Properties of Flow Physics

The aspect of correlation among the blood velocities in time and space has not received much attention in previous blood velocity estimators. The theory of fluid mechanics predicts this property of the blood flow. Additionally, most estimators based on a cross-correlation analysis are limited on the maximum velocity detectable. This is due to the occurrence of multiple peaks in the cross-correlation function. In this study a new estimator (CMLE), which is based on correlation (C) properties inherited from fluid flow and maximum likelihood estimation (MLE), is derived and evaluated an a set of simulated and in vivo data from the carotid artery. The estimator is meant for two-dimensional (2-D) color flow imaging. The resulting mathematical relation for the estimator consists of two terms. The first term performs a cross-correlation analysis on the signal segment in the radio frequency (RF)-data under investigation. The flow physic properties are exploited in the second term, as the range of velocity values investigated in the cross-correlation analysis are compared to the velocity estimates in the temporal and spatial neighborhood of the signal segment under investigation. The new estimator has been compared to the cross-correlation (CC) estimator and the previously developed maximum likelihood estimator (MLE). The results show that the CMLE can handle a larger velocity search range and is capable of estimating even low velocity levels from tissue motion. The CC and the MLE produce incorrect velocity estimates due to the multiple peaks, when the velocity search range is increased above the maximum detectable velocity. The root-mean square error (RMS) on the velocity estimates for the simulated data is on the order of 7 cm/s (14%) for the CMLE, and it is comparable to the RMS for the CC and the MLE. When the velocity search range is set to twice the limit of the CC and the MLE, the number of incorrect velocity estimates are 0, 19.1, and 7.2% for the CMLE, CC, and MLE, respectively. The ability to handle a larger search range and estimating low velocity levels was confirmed on in vivo data.

Method for In-vivo Synthetic Aperture B-flow Imaging

B-flow techniques introduced in commercial scanners have been useful is visualizing places of flow. The method is relatively independent of flow angle and can give a good perception of vessel location and turbulence. This paper introduces a technique for making a synthetic aperture B-flow system. Data is acquired over a number of pulse emissions, where a set of elements synthesizes a spherical wave and the received signal on all elements are acquired. The sequence is repeated and a full new image can always be formed from the last set of emissions, thus making the frame rate very...
The data is continuously available at all places in the image and any kind of echo canceling filter can therefore be used without the usual initialization problems. The B-flow images are then formed by displaying the gray level image after echo canceling. A fast moving scatterer will give a bright echo and slower moving scatterers will yield a dark echo. The approach is demonstrated through in-vivo images. A 128 elements 7 MHz probe with lambda pitch is used together with the RASMUS experimental scanner. Eleven elements are used per emission and the eight emissions are spread evenly over the 128 elements of the array. The signal received by the 64 elements closest to the en-fission is sampled at 40 MHz and 12 bits at a pulse repetition frequency of 3 kHz. A full second of data is acquired from a healthy 29 years old male volunteer from the carotid artery. The data is beamformed, combined, and echo canceled off-line. High-pass filters designed by the Remez exchange algorithm, have been used for the B-flow processing. The image is displayed after each set of emissions yielding 375 frames per second. Both the flow in the carotid artery and the jugular vein can be seen along with an indication of the acceleration and spatial variation of the velocity.
Simulation of advanced ultrasound systems using Field II
The background and basic features of the Field II simulation program are described. It can simulate any linear ultrasound system, which can use single or multi-element transducers. Any kind of apodization, focusing, and excitation can be used. The basic theory behind the program's use of spatial impulse responses is explained. A simulation example for a synthetic aperture spread spectrum flow systems is described. It is shown how the advanced coded excitation can be set up, and how the simulation can be parallelized to reduce the simulation time from 17 months to 391 hours using a 32 CPU Linux cluster.

Synthetic Aperture Imaging in Medical Ultrasound
Synthetic Aperture (SA) ultrasound imaging is a relatively new and unexploited imaging technique. The images are perfectly focused both in transmit and receive, and have a better resolution and higher dynamic range than conventional ultrasound images. The blood flow can be estimated from SA images with high precision, and the imaging is easily extended to real-time 3D scanning. This paper presents the work done at the Center for Fast Ultrasound Imaging in the area of SA imaging. Three areas that benefit from SA imaging are described. Firstly a preliminary in-vivo evaluation comparing conventional B-mode imaging with STAI is presented. In this study 7 male volunteers were scanned abdominally, and resulting images were compared by 3 medical doctors using randomized blinded presentation. All 3 examiners scored a significant better image quality in STA images (P-value <0.001). Secondly the performance of a flow estimator is evaluated in a flow rig and in-vivo scans are shown. The method uses beamforming along the flow direction, which has the advantage that the signals are strongly correlated. A 7.5 MHz commercial transducer was used to measure the flow in a plastic tube with an entrance length of 1 m and a diameter of 17 mm. The velocity profile was measured for flow angles of 60 and 90 degrees. The standard deviation of the measurements was 0.36% (0.65 mm/s) for 60 degrees and 1.2 % (2.1 mm/s) for the purely transverse flow. Finally the application of SA imaging to real-time 3D scanning is presented. The method uses a combination of a rotating transducer and STA imaging. Due to the rotation of the transducer, a 2D array is synthesized. Images from point targets in a tissue mimicking phantom show that the -6 dB resolution is 1.5 deg. in both elevation and azimuth planes, and that the side-lobes are 50 dB below the peak. The system can potentially acquire 10 fully focused volumes per second.
Velocity vector estimation in synthetic aperture flow and B-mode imaging

A method for determining both velocity magnitude and angle in a synthetic aperture ultrasound system is described. The approach uses directional beamforming along the flow direction and cross-correlation to determine velocity magnitude. The angle of the flow is determined from the maximum normalized correlation calculated as a function of angle. The method is investigated using data measured by an experimental ultrasound scanner from a flow rig. A commercial 7 MHz linear array transducer is used and data are measured for flow angles of 60° and 90°. The velocity magnitude is determined with a precision of 0.36 % (60°) and 1.2 % (90°), respectively. The 60° angle is estimated with a bias of 0.54° and a standard deviation of 2.1°. For 90° the bias is 0.0003° and standard deviation 1.32°.

Apparatus and method for velocity estimation in synthetic aperture imaging

The invention relates to an apparatus for flow estimation using synthetic aperture imaging. The method uses a Synthetic Transmit Aperture, but unlike previous approaches a new frame is created after every pulse emission. In receive mode parallel beam forming is implemented. The beam formed RF data is added to the previously created RF lines obtained by the same transmit sequence. The apparatus comprises a pulser (1) to generate a pulsed voltage signal, that is fed to the emit beam former (2). The emit beam former (2) is connected to the emitting transducer array (3). The ultrasound is reflected by the object (4) and received by the elements of the transducer array (5). All of these signals are then combined in the beam processor (6) to focus all of the beams in the image in both transmit and receive mode and the simultaneously focused signals are used for updating the image in the processor (7). The update signals are used in the velocity estimation processor (8) to correlate the individual measurements to obtain the displacement between high-resolution images and thereby determine the velocity.
A method for real-time three-dimensional vector velocity imaging

The paper presents an approach for making real-time three-dimensional vector flow imaging. Synthetic aperture data acquisition is used, and the data is beamformed along the flow direction to yield signals usable for flow estimation. The signals are cross-related to determine the shift in position and thereby velocity. The data can be beamformed after reception in any direction and any vectorial velocity can be found. More than 60 independent velocity volumes can be made per second with this approach. A 3 MHz 2D matrix transducer consisting of 64 × 64 elements with λ/2 pitch are used. The emissions are done using 16 × 16 = 256 elements at a time and the received signals from the same elements are sampled. Access to the individual elements is done through 16-to-1 multiplexing, so that only a 256 channels transmitting and receiving system are needed. The method has been investigated using Field II. Parabolic flow in a 10 mm radius vessel inclined at 60 degrees to the acoustical axis of the transducer was simulated. The mean standard deviation of the estimates was 0.0098 m/s over the whole vessel cross-section, which is 3.3% relative to the peak velocity. The bias was 0.023 m/s (7.5%). False peaks were found mainly at the edges of the vessel due to the echo-cancelling, and the probability of false detection was 2.2%.

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Clinical evaluation of coded excitation in medical ultrasound

Despite the enormous development in medical ultrasound (US) imaging over the last decades, penetration depth with satisfying image quality is often a problem in clinical practice. Coded excitation, used for years in radar techniques to increase signal-to-noise ratio (SNR), has recently been introduced in medical US scanning. In the present study, coded excitation using frequency-modulated US signals is implemented and evaluated in vivo. A total of nine male volunteers were scanned in three different abdominal locations, using both conventional pulsed and coded excitation. A modified scanner (B-K Medical model 3535) with transmitter and receiver boards developed in our group and a mechanical 4 MHz transducer were used. The system acquired coded and conventional US image frames interleaved, yielding identical acquisitions with the two techniques. Cine-loop sequences were evaluated by three experienced sonographers estimating penetration depth and scoring image quality of both conventional and coded imaging. The results showed a significant (p <0.001) increase in penetration depth around 2 cm. Image quality was significantly (p <0.001) better using codes at full usable depth and slightly, but also significantly (p <0.05), better above depths, where the effect of coded excitation was noticeable to the sonographers. We conclude that the higher SNR offered by coded excitation gives improved image quality and provides increased penetration in medical US imaging. This increased SNR can, alternatively, be used to allow imaging at higher frequencies and thereby increase spatial resolution without any loss of penetration. (E-mail: mhp@dadinet.dk)

Delay generation methods with reduced memory requirements

Modern diagnostic ultrasound beamformers require delay information for each sample along the image lines. In order to avoid storing large amounts of focusing data, delay generation techniques have to be used. In connection with developing a compact beamformer architecture, recursive algorithms were investigated. These included an original design and a technique developed by another research group. A piecewise-linear approximation approach was also investigated. Two imaging setups were targeted - conventional beamforming with a sampling frequency of 40 MHz and subsample precision of 2 bits, and an oversampled beamformer that performs a sparse sample processing by reconstructing the in-phase and quadrature components of the echo signal for 512 focal points. The algorithms were synthesized for a FPGA device XCV2000E-7, for a phased array image with a depth of 15 cm. Their performance was as follows: 1) For the best parametric approach, the gate count was 2095, the maximum operation speed was 131.9 MHz, the power consumption at 40 MHz was 10.6 mW, and it requires 4 12-bit words for each image line and channel. 2) For the piecewise-linear approximation, the corresponding numbers are 1125 gates, 184.9 MHz, 7.8 mW, and 15 16-bit words.
Directional velocity estimation using focusing along the flow direction II: Experimental investigation

A new method for directional velocity estimation is investigated through a number of flow rig measurements. The method uses beamforming along the flow direction to generate data, where the correct velocity magnitude can directly be estimated from the shift in position of the received consecutive signals. The shift is found by cross-correlating the beamformed lines. The approach can find the velocity in any direction, including transverse to the traditionally emitted ultrasound beam. The method is investigated using a flow rig with a peak velocity of 0.15 m/s. A 7-MHz linear array transducer is used together with a dedicated sampling system to acquire signals from 64 transducer elements simultaneously. A technique for obtaining 128-element data using multiplexing is also presented. The data is beamformed off-line on a PC. A relative standard deviation of 1.4% can be obtained for a beam-to-flow angle of 45 degrees and 4.3% at 90 degrees. Color flow images are displayed showing that the correct velocity magnitude can be obtained with the method for beam-to-flow angles of 60 and 90 degrees with an accuracy of 3 to 4%.

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Directional velocity estimation using focusing along the flow direction - I: Theory and simulation

A new method for directional velocity estimation is presented. The method uses beamformation along the flow direction to generate data in which the correct velocity magnitude can be directly estimated from the shift in position of the received consecutive signals. The shift is found by cross-correlating the beamformed lines. The approach can find the velocity in any direction, including transverse to the traditionally emitted ultrasound beam. The velocity estimation is studied through extensive simulations using Field H. A 128-element, 7-MHz linear array is used. A parabolic velocity profile with a peak velocity of 0.5 m/s is simulated for different beam-to-flow angles and for different emit foci. At 45 degrees the relative standard deviation over the profile is 1.6% for a transmit focus at 40 mm. At 90 degrees the approach gave a relative standard deviation of 6.6% with a transmit focus of 80 mm, when using 8 pulse-echo lines and stationary echo canceling. Pulsatile flow in the femoral artery was also simulated using Womersley's flow model. A purely transverse flow profile could be obtained with a relative standard deviation of less than 10% over the whole cardiac cycle using 8 pulse emissions for each imaging direction, which is sufficient to show clinically relevant transverse color flow images.

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Duplex synthetic aperture imaging with tissue motion compensation

This paper investigates a method for tissue motion estimation and compensation in synthetic transmits aperture imaging. The approach finds the tissue velocity and the direction of the motion at very tissue region by cross-correlating high resolution lines beamformed along multiple directions at each image points. Compensation is applied in the beamformer by tracking the image points using the velocity and angle estimates from the closest estimation point. Simulation results using Field II show nearly perfect motion compensation with no appreciable difference in contrast resolution after compensation. Phantom measurements show similar performance with differences in contrast resolution of 29% and 0.61% before and after compensation, respectively.

Experimental investigation of transverse flow estimation using transverse oscillation

Conventional ultrasound scanners can only display the blood velocity component parallel to the ultrasound beam. Introducing a laterally oscillating field gives signals from which the transverse velocity component can be estimated using 2:1 parallel receive beamformers. To yield the performance of the approach, this paper presents simulated and experimental results, obtained at a blood velocity angle transverse to the ultrasound beam. The Field II program is used to simulate a setup with a 128 element linear array transducer. At a depth 27 mm a virtual blood vessel of radius 2.4 mm is
situated perpendicular to the ultrasound beam. The velocity profile of the blood is parabolic, and the speed of the blood in the center of the vessel is 1.1 m/s. An extended autocorrelation algorithm is used for velocity estimation for 310 trials, each containing 32 beamformed signals. The velocity can be estimated with a mean relative bias of 6.3% and a mean relative standard deviation of 5.4% over the entire vessel length. With the experimental ultrasound scanner RASMUS the simulations are reproduced in an experimental flow phantom using a linear array transducer and vessel characteristics as in the simulations. The flow is generated with the Compuflow 1000 programmable flow pump giving a parabolic velocity profile of the blood mimicking fluid in the flow phantom. The profiles are estimated for 310 trials each containing of 32 data vectors. The relative mean bias over entire blood vessel is found to be 10.0% and the relative mean standard deviation is found to be 9.8%. With the Compuflow 1000 programmable flow pump a color flow mode image is produced of the experimental setup for a parabolic flow. Also the flow of the human femoralis is reproduced and it is found that the characteristics of the flow can be estimated.

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Further development of synthetic aperture real-time 3D scanning with a rotating phased array
In a previous paper we have presented an approach combing synthetic transmit aperture imaging with a rotating phased array. The method is implemented on a specially made Vermon transducer capable of rotating at 5 Hz. The center frequency of the transducer is 3.2 MHz, and the pitch is 0.22 mm. The array active diameter in 16mm and the number of elements is 64. The method is capable of scanning 10 volume/sec. The order in which the transmit elements were fired made it possible to achieve lateral resolution of a 0.94 mm at 45 mm depth, which is comparable to a standard B-mode scan. The penetration depth was > 10 cm due to the use of 20 μs long frequency modulated (FM) pulses. The dynamic range was limited to 45 dB because of the nonoptimized FM pulse and grating lobes. This paper presents the work on improving the image quality of the approach: (1) instead of defocusing conventional focusing with an f-number of 1 is used to transmit to create spherical waves, (2) virtual receive elements are synthesized to decrease noise and grating lobes, (3) the compression filter for the FM pulses was modified to suppress the range lobes (4) additional hardware for synchronization is built.

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Investigation of the feasibility for 3D synthetic aperture imaging

This paper investigates the feasibility of implementing real-time synthetic aperture 3D imaging on the experimental system developed at the Center for Fast Ultrasound Imaging using a 2D transducer array. The target array is a fully populated 32 × 32 3 MHz array with a half wavelength pitch. The elements of the array are grouped in blocks of 16 × 8, which can simultaneously be accessed by the 128 channels of the scanner. Using 8-to-1 high-voltage analog multiplexors, any group of 16 × 8 elements can be accessed. Simulations are done using Field II using parameters from a 32 x 32 elements experimental array made by Vermon with a center frequency of 2.93 MHz, fractional bandwidth of 58 %, and a pitch of 300 µm. The simulations show, that using all of the 128 elements a spherical wave within ±50 degrees sector can be created. The level of the edge waves is reduced by applying apodization with an elliptic footprint. The results of simulations show that the angular resolution at -6dB is 2.7 degrees, and is determined by the distance between the outer-most transmit elements. The peak gratinglobe levels are −23.5, −25, 27.2, −44.5 dB below the main peak for 64, 100, 144, and 169 transmit events, respectively. The number of scanned volumes per second for these cases are 78, 50, 34 and 30, respectively.

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In-vivo synthetic aperture flow imaging in medical ultrasound

A new method for acquiring flow images using synthetic aperture techniques in medical ultrasound is presented. The new approach makes it possible to have a continuous acquisition of flow data throughout the whole image simultaneously, and this can significantly improve blood velocity estimation. Any type of filter can be used for discrimination between tissue and blood flow without initialization, and the number of lines used for velocity estimation is limited only by the nonstationarity of the flow. The new approach is investigated through both simulations and measurements. A flow rig is used for generating a parabolic laminar flow, and a research scanner is used for acquiring RF data from individual transducer elements. A reference profile is calculated from a mass flow meter. The parabolic velocity profile is estimated using the new approach with a relative standard deviation of 2.2% and a mean relative bias of 3.4% using 24 pulse emissions at a flow angle of 45
degrees. The 24 emissions can be used for making a full-color flow map image. An in-vivo image of How in the carotid artery for a 29-year-old male also is presented. The full image is acquired using 24 emissions.

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K-space model of motion artifacts in synthetic transmit aperture ultrasound imaging
Synthetic transmit aperture (STA) imaging gives the possibility to acquire an image with only few emissions and is appealing for 3D ultrasound imaging. Even though the number of emissions is low, the change in position of the scatterers prohibits the coherent summations of ultrasound echoes and leads to distortions in the image. In order to develop motion compensation and/or velocity estimation algorithms a thorough and intuitive understanding of the nature of motion artifacts is needed. This paper proposes a simple 2D broadband model for STA images, based on the acquisition procedure and the beamformation algorithm. In STA imaging a single element transmits a cylindrical wave. All elements are used in receive, and by applying different delays a low resolution image (LRI) is beamformed. A Fourier relation exists between the aperture function and all points in the beamformed LRI. This relation is used to develop an approximation of the point spread function (PSF) of a LRI. It is shown that the PSF of LRIs obtained by transmitting with different elements can be viewed as rotated versions of each other. Summing several LRIs gives a high resolution image. The model approximates the PSF of a high resolution image as a sum of rotated PSFs of a single LRI. The approximation is validated with a Field II simulation. The model predicts and explains the motion artifacts, and gives an intuitive feeling of what would happen for different velocities.

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Multi element synthetic aperture transmission using a frequency division approach

In synthetic aperture imaging an image is created by a number of single element defocused emissions. A low resolution image is created after every emission and a high resolution image is formed when the entire aperture has been covered. Since only one element is used at a time the energy transmitted into the tissue is low. This paper describes a novel method in which the available spectrum is divided into $2N$ overlapping subbands. This will assure a smooth broadband high resolution spectrum when combined. The signals are grouped into two subsets in which all signals are fully orthogonal. The transmitting elements are excited so that $N$ virtual sources are formed. All sources are excited using one subset at a time. The signals can be separated by matched filtration, and the corresponding information is extracted. The individual source information is hence available in every emission and the method can therefore be used for flow imaging, unlike with Hadamard and Golay coding. The frequency division approach increases the SNR by a factor of $N^2$ compared to conventional pulsed synthetic aperture imaging, provided that $N$ transmission centers are used. Simulations and phantom measurements are presented to verify the method.

Multielement Synthetic Transmit Aperture Imaging Using Temporal Encoding

A new method to increase the signal-to-noise ratio (SNR) of synthetic transmit aperture imaging is investigated. The approach utilizes multiple elements to emulate a spherical wave, and the conventional short excitation pulse is replaced by a linear frequency-modulated (FM) signal. The approach is evaluated in terms of image quality parameters in comparison to linear array imaging. Field II simulations using an 8.5-MHz linear array transducer with 128 elements show an improvement in lateral resolution of up to 30% and up to 10.75% improvement in contrast resolution for the new approach. Measurements are performed using our experimental multichannel ultrasound scanning system, RASMUS. The designed linear FM signal obtains temporal sidelobes below -55 dB, and SNR investigations show improvements of 4-12 dB. A 30 turn (approximate to 45%) increase in penetration depth is obtained on a multitarget phantom with 0.5 dB/[cm MHz] attenuation. Furthermore, in vivo images of the abdomen are presented, which demonstrate the clinical application of the new approach.
Parallel Multi-Focusing Using Plane Wave Decomposition

In conventional phased-array imaging, identical short single-carrier pulses are emitted from the entire aperture, and focusing is done in one direction at a time by applying simple geometric delays. This is a sequential and not optimal transmission scheme, which limits the frame rate and makes 3D imaging in real-time impossible. By using a transmit matrix with frequency and apodization variations across the aperture, it is possible to focus in several directions simultaneously (5 or more), significantly increasing the frame rate to 170 frames/s or more. The algorithm used for the determination of the transmitted pulses is based on the directivity spectrum method, a generalization of the angular spectrum method, containing no evanescent waves. The underlying theory is based on the Fourier slice theorem, and field reconstruction from projections. First a set of desired 2-D sensitivity functions is specified, for multi-focusing in a number of directions. The field along these directions is decomposed to a sufficiently large (for accurate specification) number of plane waves, which are then back-propagated to all transducer elements. The contributions of all plane waves result in one time function per element. The numerical solution is presented and discussed. It contains pulses with a variation in central frequency and time-varying apodization across the aperture (dynamic apodization). The RMS difference between the transmitted field using the calculated pulse-excitation and a designed multi-focused field in 3 focal directions at a depth corresponding to an F-number of 1.5 is 4%, and in increases with depth. These results demonstrate the close agreement between specified and actual acoustic fields. It is, then, shown how specification of long frequency-modulated desired field functions can yield more strongly focused fields or higher number of multi-focused beams, with the additional advantage of higher SNR.
Real time 3D visualization of ultrasonic data using a standard pc
This paper describes a flexible, software-based scan converter capable of rendering 3D volumetric data in real time on a standard PC. The display system is used in the remotely accessible and software-configurable multichannel ultrasound sampling system (RASMUS system) developed at the Center for Fast Ultrasound Imaging. The display system is split into two modules: data transfer and display. These two modules are independent and communicate using shared memory and a predefined set of functions. It is, thus, possible to use the display program with a different data-transfer module which is tailored to another source of data (scanner, database, etc.). The data-transfer module of the RASMUS system is based on a digital signal processor from Analog Devices-ADSP 21060. The beamformer is connected to a PC via the link channels of the ADSP. A direct memory access channel transfers the data from the ADSP to a memory buffer. The display module, which is based on OpenGL, uses this memory buffer as a texture map that is passed to the graphics board. The scan conversion, image interpolation, and logarithmic compression are performed by the graphics board, thus reducing the load on the main processor to a minimum. The scan conversion is done by mapping the ultrasonic data to polygons. The format of the image is determined only by the coordinates of the polygons allowing for any kind of geometry to be displayed on the screen. Data from color flow mapping is added by alpha-blending. The 3D data are displayed either as cross-sectional planes, or as a fully rendered 3D volume displayed as a pyramid. All sides of the pyramid can be changed to reveal B-mode or C-mode scans, and the pyramid can be rotated in all directions in real time.

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Simulation of RF data with tissue motion for optimizing stationary echo canceling filters
Blood velocity estimation is complicated by the strong echoes received from tissue surrounding the vessel under investigation. Proper blood velocity estimation necessitates use of a filter for separation of the different signal components. Development of these filters and new estimators requires RF-data, where the tissue component is known. In vivo RF-data does not have this property. Instead simulated data incorporating all relevant features of the measurement situation can be employed. One feature is the motion in the surrounding tissue induced by pulsation, heartbeat, and breathing. This study has developed models for the motions and incorporated them into the RF simulation program Field II, thereby obtaining realistic simulated data. A powerful tool for evaluation of different filters and estimators is then available. The model parameters can be varied according to the physical situation with respect to scan-site and the individual to be scanned. The nature of pulsation is discussed, and a relation between the pressure in the carotid artery and the experienced vessel wall motion is derived.

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Trade off study on different envelope detectors for B-mode imaging

Generation of B-mode images involves envelope detection of the RF-signals. Various detection algorithms are available. A trade off between performance, price, and complexity determines the choice of algorithm in an ultrasound system. A Hilbert Transform (HT) and a subsequent computation of the magnitude give the ideal envelope, but the approach (IDE) is expensive and complex. A rectifier (REC) is a simple, low-cost solution, but the performance is severely degraded (especially in dynamic imaging). This study has investigated the possibility of providing a detector with a complexity and cost close to REC, while maintaining a performance close to IDE. Two low-cost detectors have been implemented and evaluated on in-vivo data. The first approach is an expansion of the rectifier with a median filter (ERM). The second detector (TAS) approximates the HT by a time delay and the magnitude by a weighted sum of the real and imaginary signals. The four detectors were evaluated on in-vivo data acquired with a B-K Medical 2102 scanner interfaced to the sampling system RASMINE. Three data sets were acquired with three different center frequencies. Hundred images were acquired as the transducer was moved across the liver and the carotid artery of a 30 years old healthy male. The root-mean-square error (RMSE) relative to IDE, and a visual inspection determine performance. For the 3.5 MHz data set RMSE's of 15.7%, 1.6%, and 1.9% are obtained with REC, ERM, and TAS, respectively. The performance is similar for the two other data sets. Close to ideal envelope detection is therefore obtainable with a simple detector (ERM or TAS), which is less complex and costly.

A new coding concept for fast ultrasound imaging using pulse trains

Frame rate in ultrasound imaging can be increased by simultaneous transmission of multiple beams using coded waveforms. However, the achievable degree of orthogonality among coded waveforms is limited in ultrasound, and the image quality degrades unacceptably due to interbeam interference. In this paper, an alternative combined time-space coding approach is undertaken. In the new method all transducer elements are excited with short pulses and the high time-bandwidth (TB) product waveforms are generated acoustically. Each element transmits a short pulse spherical wave with a constant transmit delay from element to element, long enough to assure no pulse overlapping for all depths in the image. Frequency shift keying is used for "per element" coding. The received signals from a point scatterer are staggered pulse trains which are beamformed for all beam directions and further processed with a bank of matched filters (one for each beam direction). Filtering compresses the pulse train to a single pulse at the scatterer position with a number of spike axial sidelobes. Cancellation of the ambiguity spikes is done by applying additional phase modulation from one emission to the next and summing every two successive images. Simulation results presented for QLFM and Costas spatial encoding schemes show that the proposed method can yield images with range sidelobes down to -45 dB using only two emissions.
Clinical Comparison of Pulse and Chirp Excitation

Coded excitation (CE) using frequency modulated signals (chirps) combined with modified matched filtering has earlier been presented showing promising results in simulations and in-vitro. In this study an experimental ultrasound system is evaluated in a clinical setting, where image sequences are assessed by skilled medical doctors. The effect on penetration depth and image quality were measured. A modified clinical scanner with a 4 MHz single element mechanical transducer, and external transmitter and receiver boards (RASMUS system) were used. The system allowed rapid toggling between chirp and short pulse excitation to simultaneously produce identical image sequences using both techniques. Nine healthy male volunteers were scanned in abdominal locations. All sequences were evaluated by 3 skilled medical doctors, blinded to each other and to the technique used. They assessed the depth (1) in which image quality decreased and (2) in which the image would be insufficient for clinical diagnosis. Furthermore they compared image quality in matching pairs of conventional and CE images. The average increase in penetration depth were almost 2 cm. Side-by-side comparison showed that coded image quality was consistently rated better; significant (p≤0.05) when images were cropped at minimum the depth for good image quality and highly significant (p

Comparison between different encoding schemes for synthetic aperture imaging

Synthetic transmit aperture ultrasound (STAU) imaging can create images with as low as 2 emissions, making it attractive for 3D real-time imaging. Two are the major problems to be solved: (1) complexity of the hardware involved, and (2) poor image quality due to low signal to noise ratio (SNR). We have solved the first problem by building a scanner capable of acquiring data using STAU in real-time. The SNR is increased by using encoded signals, which make it possible to send more energy in the body, while preserving the spatial and contrast resolution. The performance of temporal, spatial and spatio-temporal encoding was investigated. Experiments on wire phantom in water were carried out to quantify the gain from the different encodings. The gain in SNR using an FM modulated pulse is 12 dB. The penetration depth of the images was studied using tissue mimicking phantom with frequency dependent attenuation of 0.5 dB/(cm MHz). The
Combination of spatial and temporal encoding have highest penetration depth. Images to a depth of 110 mm, can successfully be made with contrast resolution comparable to that of a linear array image. The in-vivo scans show that the motion artifacts do not significantly influence the performance of the STAU.

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**Complex pulsing schemes for high frame rate imaging**
High frame rate ultrasound imaging can be achieved by simultaneous transmission of multiple focused beams along different directions. However, image quality degrades by the interference among beams. An alternative approach is to transmit spherical waves of a basic short pulse with frequency coding and a constant transmit delay from channel to channel. In this way, transmit diversity is provided on a time and channel basis rather than on a beam direction basis. The non-focused transmitted acoustic waves carry spatial information from the entire imaging region. At a given imaging point, all pulses will add up to a pulse train. The acoustically generated high time-bandwidth (TB) product waveforms can be compressed by using a filter bank of matched filters one for every beam direction. Matched filtering compresses the pulse train to a single pulse at the scatterer position plus a number of spike axial sidelobes. Frequency and phase modulation of the transmitting pulses allows control and elimination of the ambiguous spikes. QLFM pulse trains are found to give the best performance. Simulation results and images are presented showing the feasibility of the method. The excitation consists of 32 pulses with linear frequency modulation along the transducer elements, that cover the 70% fractional bandwidth of the 7 MHz transducer. The resulted images (after beamforming and matched filtering) show an axial resolution at the same order as in conventional pulse excitation and axial sidelobes down to -45 dB. With the proposed imaging strategy of pulse train excitation, a whole image can be formed with only two emissions, making it possible to obtain high quality images at a frame rate of 20 to 25 times higher than that of conventional phased array imaging.

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**Equipment and methods for synthetic aperture anatomic and flow imaging**
Conventional ultrasound imaging is done by sequentially probing in each image direction. The frame rate is, thus, limited by the speed of sound and the number of lines necessary to form an image. This is especially limiting in flow imaging, since multiple lines are used for flow estimation. Another problem is that each receiving transducer element must be connected to a receiver, which makes the expansion of the number of receive channels expensive. Synthetic aperture (SA) imaging is a radical change from the sequential image formation. Here ultrasound is emitted in all directions and the image is formed in all directions simultaneously over a number of acquisitions. SA images can therefore be perfectly focused in both transmit and receive for all depths, thus significantly improving image quality. A further advantage is that very fast imaging can be done, since only a few emissions are needed for forming an image, and a novel approach of
recursive ultrasound imaging can be used to give several thousand images a second. A commercial SA imaging system has, however, not yet been introduced due to a number of problems. The fundamental problems are primarily that the signal-to-noise ratio and penetration depth are low and velocity imaging is thought not to be possible. This paper will address all the issues above and show that they can all be solved using various techniques. The SNR is increased significantly beyond that for normal systems by using coded imaging and grouping of elements to form larger defocused emitting apertures. It is also possible to have many more receive channels, since different elements can be sampled during different emissions. The paper also shows that velocity imaging can be performed by making a special grouping of the received signals without motion compensation by using recursive imaging. With this technique continuous imaging at all points in the image is possible, which can significantly improve velocity estimates, since the estimates can be formed from a large number of emissions (100-200). The research scanner RASMUS, capable of acquiring clinical SA images, has been constructed and will be described. A number of phantom and in-vivo images will be presented showing in-vivo SA B-mode and flow imaging.

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Experimental Study of Convex Coded Synthetic Transmit Aperture Imaging
Synthetic transmit aperture imaging is investigated using a convex array transducer. To increase the signal-to-noise ratio, a multi-element subaperture is used to emulate the spherical wave transmission, and the conventional short excitation pulse is replaced by a linear FM signal. The approach is compared to the conventional application of the convex array in commercial scanners. The array used is a commercial 5.5 MHz, 128 element array with 60% bandwidth and λ pitch. For conventional imaging a 64 element transmit aperture is used with a 2 cycle temporally weighted sinusoid as excitation signal. For synthetic aperture imaging an 11 element transmit aperture is used with a 20 μs linear FM signal as excitation. For both methods, 128 elements are used on receive. Measurements are done using our experimental multi-channel ultrasound scanner, RASMUS. Wire phantom measurements show an improvement in lateral resolution of about 30% throughout the image with lower near and far field sidelobe levels. Results from a cyst phantom show big improvements in contrast resolution, and an increase in penetration depth of about 2 cm. In-vivo images of the abdomen of a healthy 27 year old male show slight improvements in image quality, especially in the near field.

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Modeling of higher harmonics formation in medical ultrasound systems

The pressure field emitted from multi-element medical ultrasound transducers can be simulated with Field II in the linear regime. By expanding this program's application to the nonlinear regime, beamforming schemes can be studied under strong focusing and high pressure levels as well, providing a valuable tool for simulating ultrasound harmonic imaging. An extended version of Field II is obtained by means of operator splitting. The pressure field is calculated by propagation of the field from the transducer through a number of planes. Every plane serves as a virtual aperture for the next plane, and nonlinear distortion is accounted for by the lossless Burgers' Equation. This method has no plane-wave approximation and the full effects of diffusion, attenuation, and nonlinear wave propagation can be observed under electronic focusing of array transducers in medical ultrasound systems. A single example of the approach is demonstrated by comparing results from simulations and measurements from a convex array transducer. The new simulation tool is capable of simulating the formation of higher harmonics in water on the acoustical axis. The generation of nonlinear higher harmonic components can be predicted with an accuracy of 2.6 dB and 2.0 dB for the second and third harmonic, respectively.

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Multi-Element Synthetic Transmit Aperture Imaging using Temporal Encoding

A new method to increase the signal-to-noise-ratio (SNR) of synthetic transmit aperture (STA) imaging is investigated. The new approach is called temporally Encoded Multi-Element STA imaging (EMESTA). It utilizes multiple elements to emulate a single transmit element, and the conventional short excitation pulses are replaced by linear FM signals. Simulations using Field II and measurements are compared to linear array imaging. A theoretical analysis shows a possible improvement in SNR of 17 dB. Simulations are done using an 8.5 MHz linear array transducer with 128 elements. Spatial resolution results show better performance for EMESTA imaging after the linear array focus. Both methods have similar contrast performance. Measurements are performed using our experimental multi-channel ultrasound scanning system, RASMUS. The designed linear FM signal obtains temporal side lobes below -55 dB, and SNR investigations show improvements of 4-12 dB. The depth performance is investigated using a multi-target phantom. Results show a 30 mm increase in penetration depth with improved spatial resolution. In conclusion, EMESTA imaging significantly increases the SNR of STA imaging, exceeding that of linear array imaging.

General information

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Should compression of coded waveforms be done before or after focusing

In medical ultrasound signal-to-noise ratio improvements of approximately 15-20 dB can be achieved by using coded waveforms. Exciting the transducer with an encoded waveform necessitates compression of the response which is computationally demanding. This paper investigates the possibility of reducing the workload without introducing errors. Ne compression iterations (convolutions) can be saved by inverting the precedence of compression and beamforming (called post-compression), when Ne is the number of transducer elements. Postcompression with dynamic receive focusing will theoretically introduce errors. Simulations and measurements show that increasing the depth of the scatterers results in a decreased error. Transmit focus depth and the distance between focus points have a significant influence on the error. The size of the error is studied and a new scheme for correcting the error is proposed. The study is done by simulations in Field II and by measurements with our experimental scanner RASMUS. The measurements are done on a string phantom and in-vivo on the abdomen of a male volunteer.

Simulation of non-linear ultrasound fields

An approach for simulating non-linear ultrasound imaging using Field II has been implemented using the operator splitting approach, where diffraction, attenuation, and non-linear propagation can be handled individually. The method uses the Earnshaw/Poisson solution to Burgers' equation for the non-linear propagation. The speed of sound is calculated from the instantaneous pressure of the pulse and the nonlinearity B/A parameter of the medium. The harmonic field is found by introducing a number of virtual planes in front of the aperture and then propagating the pulse using Burgers' solution between the planes. Simulations on the acoustical axis of an array transducer were performed and compared to measurements made in a water tank. A 3 MHz convex array transducer with a pitch of 0.53 mm and a height of 13 mm was used. The electronic focus was at 45 mm and 16 elements were used for emission. The emitted pressure was 1.4 MPa measured 6 mm from the aperture by a Force Institute MH25-5 needle hydrophone in a water bath. The build-up of higher harmonics can here be predicted accurately up to the 5th harmonic. The second harmonic is simulated with an accuracy of ±2.6 dB and the third harmonic with ±2 dB compared to the water bath measurements. Point spread functions (PSFs) were also calculated and measured. They all showed that the second and third harmonic PSFs are narrower than for the first harmonic, with a good resemblance between the measured and simulated PSFs. The approach can also be extended to simulate non-linear ultrasound imaging in 3D using filters or pulse inversion for any kind of transducer, focusing, apodization, pulse emission and scattering phantom. This is done by first simulating the non-linear emitted field and assuming that the scattered field is weak and linear. The received signal is then the spatial impulse response in receive convolved with the emitted field at the given point.
Simulation of non-linear ultrasound imaging

Frame rate in ultrasound imaging can be dramatically increased by using sparse synthetic transmit aperture (STA) beamforming techniques. The two main drawbacks of the method are the low signal-to-noise ratio (SNR) and the motion artifacts, that degrade the image quality. In this paper we propose a spatio-temporal encoding for STA imaging based on simultaneous transmission of two quasi-orthogonal tapered linear FM signals. The excitation signals are an up- and a down-chirp with frequency division and a cross-talk of −55 dB. The received signals are first cross-correlated with the appropriate code, then spatially decoded and finally beamformed for each code, yielding two images per emission. The spatial encoding is a Hadamard encoding previously suggested by Chiao et al. [in: Proceedings of the IEEE Ultrasonics Symposium, 1997, p. 1679]. The Hadamard matrix has half the size of the transmit element groups, due to the orthogonality of the temporal encoded wavefronts. Thus, with this method, the frame rate is doubled compared to previous systems. Another advantage is the utilization of temporal codes which are more robust to attenuation. With the proposed technique it is possible to obtain images dynamically focused in both transmit and receive with only two firings. This reduces the problem of motion artifacts. The method has been tested with extensive simulations using Field II. Resolution and SNR are compared with uncoded STA imaging and conventional phased-array imaging. The range resolution remains the same for coded STA imaging with four emissions and is slightly degraded for STA imaging with two emissions due to the −55 dB cross-talk between the signals. The additional proposed temporal encoding adds more than 15 dB on the SNR gain, yielding a SNR at the same order as in phased-array imaging.

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Space-time encoding for high frame rate ultrasound imaging

Frame rate in ultrasound imaging can be dramatically increased by using sparse synthetic transmit aperture (STA) beamforming techniques. The two main drawbacks of the method are the low signal-to-noise ratio (SNR) and the motion artifacts, that degrade the image quality. In this paper we propose a spatio-temporal encoding for STA imaging based on simultaneous transmission of two quasi-orthogonal tapered linear FM signals. The excitation signals are an up- and a down-chirp with frequency division and a cross-talk of −55 dB. The received signals are first cross-correlated with the appropriate code, then spatially decoded and finally beamformed for each code, yielding two images per emission. The spatial encoding is a Hadamard encoding previously suggested by Chiao et al. [in: Proceedings of the IEEE Ultrasonics Symposium, 1997, p. 1679]. The Hadamard matrix has half the size of the transmit element groups, due to the orthogonality of the temporal encoded wavefronts. Thus, with this method, the frame rate is doubled compared to previous systems. Another advantage is the utilization of temporal codes which are more robust to attenuation. With the proposed technique it is possible to obtain images dynamically focused in both transmit and receive with only two firings. This reduces the problem of motion artifacts. The method has been tested with extensive simulations using Field II. Resolution and SNR are compared with uncoded STA imaging and conventional phased-array imaging. The range resolution remains the same for coded STA imaging with four emissions and is slightly degraded for STA imaging with two emissions due to the −55 dB cross-talk between the signals. The additional proposed temporal encoding adds more than 15 dB on the SNR gain, yielding a SNR at the same order as in phased-array imaging.

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Three-dimensional real-time synthetic aperture imaging using a rotating phased array transducer

Current 3D real-time imaging is done either with sparse 2D arrays, or with mechanically moved phased arrays. The former results in a poor resolution and contrast due to a limited amount of elements. The latter has the disadvantage of low frame rates due to the sequential acquisition of the volume line-by-line and plane-by-plane. This paper describes an approach which combines mechanically moved phased array with synthetic transmit aperture imaging, resulting in high volume acquisition rates without a trade-off in image quality. The scan method uses a conventional fully populated 64 element phased array, which is rotated over the volume of interest. The data is acquired using coded signals and synthetic transmit aperture imaging. Only one group of elements transmits at a time. The delays are set such as to form a cylindrical wave. The back-scattered signal carries information not only from the plane located directly below the transducer, but also from neighboring planes. A complete dataset for all elements for the whole rotation is acquired and stored. The volume is then focused from this complete data set in order to obtain dynamic transmit and receive focusing in all directions.

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Transverse flow imaging using synthetic aperture directional beamforming
Current ultrasound scanners only determine the velocity along the ultrasound beam, since data is only focused along the emitted beam. Synthetic aperture ultrasound systems have the capability of focusing simultaneously in all directions. This is used here to focus along the flow direction and then cross-correlate these measurements to obtain the correct velocity magnitude. The approach was investigated in a flow system with a laminar flow. The velocity profile was measured with a B-K Medical 8804 7.5 MHz linear array transducer. A plastic tube with an entrance length of 1 m and a diameter of 17 nm was used with an EcoWatt 1 pump generating a laminar, stationary flow. The velocity profile was measured for flow angles of
90 and 60 degrees. The RASMUS research scanner was used for acquiring RF data from 128 elements of the array using 8 emissions with 11 elements in each emission. A 20μs chirp was used during emission. The RF data were subsequently beamformed off-line and stationary echo canceling was performed. The 60 degrees flow was determined using 16 groups of 8 emissions and the relative standard deviation was 0.36 % (0.65 mm/s). Using the same setup for the purely transverse flow gave a std. of 1.2 % (2.1 mm/s). An in-vivo image of the carotid artery and jugular vein of a healthy 29 years old volunteer. A full color flow image using only 128 emissions could be made with a high velocity precision.

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**Ultrasound Imaging and its modeling**
Modern medical ultrasound scanners are used for imaging nearly all soft tissue structures in the body. The anatomy can be studied from gray-scale B-mode images, where the reflectivity and scattering strength of the tissues are displayed. The imaging is performed in real time with 20 to 100 images per second. The technique is widely used, since it does not use ionizing radiation and is safe and painless for the patient.

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**Virtual ultrasound sources in high-resolution ultrasound imaging**
This paper investigates the concept of virtual source elements. It suggests a common framework for increasing the resolution, and penetration depth of several imaging modalities by applying synthetic aperture focusing (SAF). SAF is used either as a post focusing procedure on the beamformed data, or directly on the raw signals from the transducer elements. Both approaches increase the resolution. The paper shows that in one imaging situation, there can co-exist...
different virtual sources for the same scan line - one in the azimuth plane, and another in the elevation. This property is
used in a two stage beamforming procedure for 3D ultrasound imaging. The position of the virtual source, and the created
waveform are investigated with simulation, and with pulse-echo measurements. There is good agreement between the
estimated waveform and the theoretically fitted one. Several examples of the use of virtual source elements are considered.
Using SAF on data acquired for a conventional linear array imaging improves the penetration depth for the particular
imaging situation from 80 to 110 mm. The independent use of virtual source elements in the elevation plane decreases the
respective size of the point spread function at 100 mm below the transducer from 7 mm to 2 mm.

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A new architecture for a single-chip multi-channel beamformer based on a standard FPGA
A new architecture for a compact medical ultrasound beamformer has been developed. Combination of novel and known
principles has been utilized, leading to low processing power requirements and simple analog circuitry. Usage of a field
programmable gate array (FPGA) for the digital signal processing provides programming flexibility. First, sparse sample
processing is performed by generating the in-phase and quadrature beamformed signals. Hereby only 512 samples are
beamformed for each line in an image. That leads to a 15-fold decrease in the number of operations and enables the use
of Delta-Sigma (ΔΣ) modulation analog-to-digital converters (ADC). Second, simple second-order ΔΣ modulation ADC
with classic topology is used. This allows for simple analog circuitry and a very compact design. Several tens of these
together with the corresponding preamplifiers can be fitted together onto a single analog integrated circuit. Third,
parameter driven delay generation is used, using 3 input parameters per line per channel for either linear array imaging or
phased array imaging. The delays are generated on the fly. The delay generation logic also determines the digital
apodization by using 2 additional parameters. The control logic consists of few adders and counters and requires very
limited resources. Fourth, the beamformer is fully programmable. Any channel can be set to use an arbitrary delay curve,
and any number of these channels can be used together in an extendable modular multi-channel system. A prototype of
the digital logic is implemented using a Xilinx Virtex-E series FPGA. A 5 MHz center frequency is used along with an
oversampling ratio of 14. The sampling clock frequency used is 140 MHz and the number of channels in a single Xilinx 1
million gate FPGA XC600E is 32. The beamformer utilizes all of the BlockRAM of the device and 33% of its Core Logic
Block (CLB) resources. Both simulation results and processed echo data from a phantom are presented.

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A new estimator for vector velocity estimation [medical ultrasonics]

A new estimator for determining the two-dimensional velocity vector using a pulsed ultrasound field is derived. The estimator uses a transversely modulated ultrasound field for probing the moving medium under investigation. A modified autocorrelation approach is used in the velocity estimation. The new estimator automatically compensates for the axial velocity when determining the transverse velocity. The estimation is optimized by using a lag different from one in the estimation process, and noise artifacts are reduced by averaging RF samples. Further, compensation for the axial velocity can be introduced, and the velocity estimation is done at a fixed depth in tissue to reduce the influence of a spatial velocity spread. Examples for different velocity vectors and field conditions are shown using both simple and more complex field simulations. A relative accuracy of 10.1% is obtained for the transverse velocity estimates for a parabolic velocity profile for flow transverse to the ultrasound beam and a SNR of 20 dB using 20 pulse-echo lines. The overall bias in the estimates was -4.3%.

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A new maximum likelihood blood velocity estimator incorporating spatial and temporal correlation

The blood flow in the human cardiovascular system obeys the laws of fluid mechanics. Investigation of the flow properties reveals that a correlation exists between the velocity in time and space. The possible changes in velocity are limited, since the blood velocity has a continuous profile in time and space. This paper presents a new estimator (STC-MLE), which incorporates the correlation property. It is an expansion of the maximum likelihood estimator (MLE) developed by Ferrara et al. With the MLE a cross-correlation analysis between consecutive RF-lines on complex form is carried out for a range of possible velocities. In the new estimator an additional similarity investigation for each evaluated velocity and the available velocity estimates in a temporal (between frames) and spatial (within frames) neighborhood is performed. An a priori probability density term in the distribution of the observations gives a probability measure of the correlation between the velocities. Both the MLE and the STC-MLE have been evaluated on simulated and in-vivo RF-data obtained from the carotid artery. Using the MLE 4.1% of the estimates deviate significantly from the true velocities, when the performance is evaluated on the simulated data. These deviating estimates arise, as the search range in the correlation analysis exceeds one wavelength. By performing a similar investigation with the STC-MLE, no highly deviating estimates occur. The allowed search range is therefore larger with the STC-MLE. The performance evaluation on in-vivo data further reveals that the
number of highly deviating velocity estimates in the tissue parts of the RF-signals are reduced with the STC-MLE. In general the resulting profiles are continuous and more consistent with the true velocity profile, and the introduction of the correlation property has improved the estimates.

Efficient focusing scheme for transverse velocity estimation using cross-correlation

The blood velocity can be estimated by cross-correlation of received RF signals, but only the velocity component along the beam direction is found. A previous paper showed that the complete velocity vector can be estimated, if received signals are focused along lines parallel to the direction of the flow. Here a weakly focused transmit field was used along with a simple delay-sum beamformer. A modified method for performing the focusing by employing a special calculation of the delays is introduced, so that a focused emission can be used. The velocity estimation was studied through extensive simulations with Field II. A 64-elements, 5 MHz linear array was used. A parabolic velocity profile with a peak velocity of 0.5 m/s was considered for different angles between the flow and the ultrasound beam and for different emit foci. At 60 degrees the relative standard deviation was 0.58 % for a transmit focus at 40 mm. For 90 degrees the new approach gave a relative standard deviation of 8.3 % with a focus at 40 mm and 8.0 % at a transmit focus of 150 mm. Pulsatile flow in the femoral artery was also simulated. A purely transverse flow profile could be obtained with a relative standard deviation of less than 10 % over the whole cardiac cycle, which is sufficient to show clinically relevant transverse color flow images.
Experimental investigation of transverse velocity estimation using cross-correlation

A technique for estimating the full flow velocity vector has previously been presented by our group. Unlike conventional estimators, that only detect the axial component of the flow, this new method is capable of estimating the transverse velocity component. The method uses focusing along the flow direction to produce signals that are influenced by the shift of the scatterer's position. The signals are then cross-correlated to find the shift in position and thereby the velocity. The performance of the method is investigated using both a flow phantom and in-vivo measurements.

A flow phantom capable of producing a parabolic flow profile was measured with a B-K Medical 8804 7.5 MHz linear array transducer. A plastic tube with an entrance length of 130 cm and a diameter of 17 mm. was used with an EcoWatt 1 pump generating a volume flow of 93.4 l/h corresponding to a peak velocity in the tube of 0.23 m/s. The volume flow was determined by a Danfoss MAG 1100 flow meter. The velocity profiles were measured for different beam-to-flow angles of 90, 65, and 45 degrees. A Harming apodized beam focused at the vessel was transmitted using 64 elements and the received signals on all elements were sampled at 40 MHz and 12 bits in parallel using our experimental ultrasound scanner. Three hundred and seventy pulse echo measurements were acquired for each angle at a pulse repetition frequency of 5 kHz. The field in a number of points on lines parallel to the flow was calculated by focusing the 64 channels of data. A mean parabolic velocity profile was obtained for purely transverse flow with a mean bias to the true profile of -2.5% relative to the peak velocity and a standard deviation of 13.3% relative to the peak velocity. Twenty pulse-echo lines were used for each estimate and 18 profiles were obtained. For a beam-to-flow angles of 45 and 65 degrees the corresponding numbers were a mean relative bias of less than 4.0% and a relative standard deviation of 3.0% or less, when using 10 pulse-echo lines and 36 profiles. In-vivo measurements have also been performed on the carotid artery on a male volunteer and the flow at an angle of 701 was successfully estimated.

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Joint probability discrimination between stationary tissue and blood velocity signals

In CFM-mode the blood velocity estimates are overlaid onto the B-mode image. The velocity estimation gives non-zero velocity estimates in both the surrounding tissue and the vessels. A discrimination algorithm is needed to determine, which estimates represent blood flow and should be displayed. This study presents a new statistical discriminator. Investigation of the RF-signals reveals that features can be derived that distinguish the segments of the signal, which do and do not carry information on the blood flow. In this study 4 features, have been determined: (a) the energy content in the segments before and after echo-canceling, and (b) the amplitude variations between samples in consecutive RF-signals before and after echo-canceling. The statistical discriminator was obtained by computing the probability density functions (PDFs) for each feature through histogram analysis of data. The discrimination is performed by determining the joint probability of the features for the segment under investigation and choosing the segment type that is most likely. The method was tested on simulated data resembling RF-signals from the carotid artery.

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Performance of velocity vector estimation using an improved dynamic beamforming setup

Estimation of velocity vectors using transverse spatial modulation has previously been presented. Initially, the velocity estimation was improved using an approximated dynamic beamformer setup instead of a static combined with a new velocity estimation scheme. A new beamformer setup for dynamic control of the acoustic field, based on the Pulsed Plane Wave Decomposition (PPWD), is presented. The PPWD gives an unambiguous relation between a given acoustic field and the time functions needed on an array transducer for transmission. Applying this method for the receive beamformation results in a set-up of the beamformer with different filters for each channel for each estimation depth. The method of the PPWD is illustrated by analytical expressions of the decomposed acoustic field and these results are used for simulation. Results of velocity estimates using the new setup are given on the basis of simulated and experimental data. The simulation setup is an attempt to approximate the situation present when performing a scanning of the carotid artery with a linear array. Measurement of the flow perpendicular to the emission direction is possible using the approach of transverse spatial modulation. This is most often the case in a scanning of the carotid artery, where the situation is handled by an angled Doppler setup in the present ultrasound scanners. The modulation period of 2 mm is controlled for a range of 20-40 mm which covers the typical range of the carotid artery. A 6 MHz array on a 128-channel system is simulated. The flow setup in the simulation is based on a vessel with a parabolic flow profile for a 60 and a 90-degree flow angle. The experimental results are based on the backscattered signal from a sponge mounted in a stepping device. The bias and std. dev. of the velocity estimate are calculated for four different flow angles (50, 60, 75 and 90 degrees). The velocity vector is calculated using the improved 2-D estimation approach at a range of depths.

Spatial filters for focusing ultrasound images

Traditionally focusing is done by taking out one sample in the received signal from each transducer element and then sum these signals. This method does not take into account the temporal or spatial spread of the received signal from a point
scatterer and does not make an optimal focus of the data. A new method for making spatial matched filter focusing of RF ultrasound data is proposed based on the spatial impulse response description of the imaging. The response from a scatterer at any given point in space relative to the transducer can be calculated, and this gives the spatial matched filter for beamforming the received RF signals from the individual transducer elements. The matched filter is applied on RF signals from individual transducer elements, thus properly taking into account the spatial spread of the received signal. The method can be applied to any transducer and can also be used for synthetic aperture imaging for single element transducers. It is evaluated using the Field II program. Data from a single 3 MHz transducer focused at a distance of 80 mm is processed. Far from the transducer focal region, the processing greatly improves the image resolution: the lateral slice of the autocovariance function of the image shows a -6 dB width reduction by a factor of 3.3 at 20 mm and by a factor of 1.8 at 30 mm. Other simulations use a 64 elements, 3 MHz, linear array. Different receiving conditions are compared and this shows that the effect of the filter is progressively lower, but the approach always yields point spread functions better or equal to a traditional dynamically focused image. Finally, the process was applied to in-vivo clinical images of the liver and right kidney from a 28 years old male. The data was obtained with a single element transducer focused at 100 mm. The improvement in resolution was in this case less evident and further optimization is needed.

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Speed-accuracy trade-offs in computing spatial impulse responses for simulating medical ultrasound imaging
Medical ultrasound imaging can be simulated realistically using linear acoustics. One of the most powerful approaches is to employ spatial impulse responses. Hereby both emitted fields and pulse-echo responses from point scatterers can be determined. Also any kind of dynamic focusing and apodization can be incorporated, as has been done in the Field II simulation program. Here the transducer is modeled through a set of either rectangles, triangles, or bounding lines, so that any geometry can be simulated. The response from the transducer is found by summing the spatial impulse responses from the individual elements. One of the problems in using spatial impulse responses is the abrupt changes in the responses due to the sharp transducer boundaries. Sampling the responses directly therefore have to be done at very high sampling frequencies to keep the shape and energy of the response. The high sampling frequency is unnecessary in the final signals, since the transducers used in medical ultrasound are band limited. Approaches to reduce the sampling frequency are, thus, needed to make efficient simulation programs. Field II uses time integration of the spatial impulse responses using a continuous rather than discrete time-axis. This preserves the energy in the responses and makes it possible to make sub-sample interval delays for focusing. The paper discusses the consequence of the integration for the rectangular elements that uses an approximative calculation of the spatial impulse responses. Data for the accuracy as a function of sampling frequency is given, and it is shown how a sampling frequency of 100 MHz gives similar results to using 2 GHz sampling of the analytic solution for rectangular elements. The spatial impulse responses for the triangular and bounding line elements are found analytically, and an iterative integration routine has to be used. The Romberg integration routine is used, and the accuracy versus sampling frequency for bounding line is shown. An increased accuracy is attained for the lines compared to the rectangles, but the simulation times are significantly higher. Line elements should therefore, in this implementation, only be used very close to the transducer, and if a very high precision is needed in the calculation.

General information
Velocity estimation using synthetic aperture imaging

In a previous paper we have demonstrated that the velocity can be estimated for a plug flow using recursive ultrasound imaging [1]. The approach involved the estimation of the velocity at every emission and using the estimates for motion compensation. An error in the estimates, however, would lead to an error in the compensation further increasing the error in the estimates.

In this paper the approach is further developed such that no motion compensation is necessary. In recursive ultrasound imaging a new high resolution image is created after every emission. The velocity was estimated by cross correlating RF lines from two successive emissions \( n \) and \( n + 1 \), and then average over a number of lines. In the new approach images \( n \) and \( n + N \), \( n + 1 \) and \( n + N + 1 \) are cross correlated, where \( N \) is the number of emissions for one image. These images experience the same phase distortion due to motion and therefore have a high correlation without motion compensation. The advantage of the approach is that a color flow map can be created for all directions in the image simultaneously at every emission, which makes it possible to average over a large number of lines. This makes stationary echo canceling easier and significantly improves the velocity estimates. The approach is verified using simulations with the program Field II and measurements on a blood-mimicking phantom. The estimates from the simulations have a bias of -3.5% and a mean standard deviation less than 2.0% for a parabolic velocity profile. The estimates from the measurements for the same setup exhibit a larger bias -11%, but the standard deviation is comparable to the simulations (sigma similar to 2.5%).

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Velocity estimation using synthetic aperture imaging [blood flow]
Presented an approach for synthetic aperture blood flow ultrasound imaging. Estimates with a low bias and standard deviation can be obtained with as few as eight emissions. The performance of the new estimator is verified using both simulations and measurements. The results demonstrate that a fully functioning synthetic aperture scanner can be made
3D synthetic aperture imaging using a virtual source element in the elevation plane

The conventional scanning techniques are not directly extendable for 3D real-time imaging because of the time necessary to acquire one volume. Using a linear array and synthetic transmit aperture, the volume can be scanned plane by plane. Up to 1000 planes per second can be scanned for a typical scan depth of 15 cm and speed of sound of 1540 m/s. Only 70 to 90 planes must be acquired per volume, making this method suitable for real-time 3D imaging without compromising the image quality. The resolution in the azimuthal plane has the quality of a dynamically focused image in transmit and receive. However, the resolution in the elevation plane is determined by the fixed mechanical elevation focus. This paper suggests to post-focus the RF lines from several adjacent planes in the elevation direction using the elevation focal point of the transducer as a virtual source element, in order to obtain dynamic focusing in the elevation plane. A 0.1 mm point scatterer was mounted in an agar block and scanned in a water bath. The transducer is a 64 elements linear array with a pitch of 209 μm. The transducer height is 4 mm in the elevation plane and it is focused at 20 mm giving a F-number of 5. The point scatterer was positioned 96 mm from the transducer surface. The transducer was translated in the elevation direction from -13 to +13 mm over the scatterer at steps of 0.375 mm. Each of the 70 planes is scanned using synthetic transmit aperture with 8 emissions. The beam-formed RF lines from the planes are passed through a second beamformer, in which the fixed focal points in the elevation plane are treated as virtual sources of spherical waves. Synthetic aperture focusing is applied on them. The -6 dB resolution in the elevation plane is increased from 7 mm to 2 mm. This gives a uniform point spread function, since the resolution in the azimuthal plane is also 2 mm.
Algorithms for estimating blood velocities using ultrasound

Ultrasound has been used intensively for the last 15 years for studying the hemodynamics of the human body. Systems for determining both the velocity distribution at one point of interest (spectral systems) and for displaying a map of velocity in real time have been constructed. A number of schemes have been developed for performing the estimation, and the various approaches are described. The current systems only display the velocity along the ultrasound beam direction and a velocity transverse to the beam is not detected. This is a major problem in these systems, since most blood vessels are parallel to the skin surface. Angling the transducer will often disturb the flow, and new techniques for finding transverse velocities are needed. The various approaches for determining transverse velocities will be explained. This includes techniques using two-dimensional correlation (speckle tracking), multiple beams, and the new transverse modulation technique. The different advantages and disadvantages of the approaches are explained.

A new approach for estimation of the axial velocity using ultrasound

The most used estimation method for calculating the blood velocity in commercial scanners is the autocorrelation approach. The calculation of the mean velocity used in this method depends on the center frequency of the interacting ultrasound pulse which downshifts as a function of depth, introducing a bias. A new velocity estimator for the mean axial velocity is presented. The estimation principle is based on the 2D Fourier transform and the Radon transform. The input data are a sequence of RF data forming a 2D data input, one column for each pulse emission. A 2D segment is selected for a specific depth. This data segment is first transformed by a 2D Fourier transform, and the result is then transformed by a Radon transform. The center of gravity for the angles of the lines intersecting the origin of the R-theta coordinate system in the Radon domain gives the mean axial velocity for the data segment. The benefit of this method is an estimate of the mean axial velocity which is independent of the center frequency of the propagating ultrasound pulse. The estimate will only depend on f<sub>s</sub> and f<sub>prf</sub>. Results of the estimation method is presented based on both simple generated RF harmonic data for different signal/noise ratios and simulated acoustic RF responses from a 3D measurement situation with an array transducer and a tube with plug flow. The new method shows improvement with a factor of 1.5–4 on the standard deviation on the estimated mean velocity for the simulated case.
Application of different spatial sampling patterns for sparse-array transducer design

In the last years the efforts of many researchers have been focused on developing 3D real-time scanners. The use of 2D phased-array transducers makes it possible to steer the ultrasonic beam in all directions in the scanned volume. An unacceptably large amount of transducer channels (more than $4000$) must be used, if the conventional phased array transducers are extrapolated to the two-dimensional case. To decrease the number of channels, sparse arrays with different aperture apodization functions in transmit and receive have to be designed. The design is usually carried out in 1D, and then transferred to a 2D rectangular grid. In this paper 5 different 2D array transducers have been considered and their performance was compared with respect to spatial and contrast resolution. An optimization of the element placement along the diagonals using vernier arrays is suggested. The simulation results of the ultrasound fields show a decrease of the grating-lobe level of 10 dB for the diagonally optimized 2D array transducers compared to the previously designed 2D arrays which didn't consider the diagonals.

Clinical use and evaluation of coded excitation in B-mode images

Use of long encoded waveforms can be advantageous in ultrasound imaging, as long as the pulse compression mechanism ensures low range sidelobes and preserves both axial resolution and contrast. A coded excitation/compression scheme was previously presented by our group, which is based on a predistorted FM excitation and a mismatched compression filter designed for medical ultrasonic applications. The attenuation effect, analyzed in this paper using the ambiguity function and simulations, dictated the choice of the coded waveform. In this study clinical images, images of wire phantoms, and digital video demonstrate the applicability, clinical relevance, and improvement attained with the proposed scheme. A commercial scanner (B-K Medical 3535) was modified and interfaced to a software configurable transmitter board and to a sampling system with a 2 GB memory storage. The experimental system was programmed to allow alternating excitation on every second frame. That offers the possibility of direct comparison of the same set of image pairs; one with pulsed and one with encoded excitation. Abdominal clinical images from healthy volunteers were acquired and statistically analyzed by means of the auto-covariance matrix of the image data. The resolution laterally is retained, axially is improved, while there is a clear increase in penetration. Phantom images using the proposed FM-based scheme as well as complementary Golay codes were also acquired, in order to quantitatively...
evaluate the characteristics of the compressed output and its stability to attenuation. Images of a wire phantom in water show that the range sidelobes resulting from pulse compression are below the acoustic noise, which was at 50 dB for the pulsed images. For images acquired from an attenuation phantom, the proposed compression scheme was robust to frequency shifts resulting from attenuation. The range resolution is improved 12% by the coded scheme compared to a 2-cycle pulse excitation. For the maximum acquisition depth of 15 cm, where the coded excitations are primarily intended, the improvement in SNR was more than 10 dB, while the resolution was retained.

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Estimation of vector velocity
Using a pulsed ultrasound field, the two-dimensional velocity vector can be determined with the invention. The method uses a transversally modulated ultrasound field for probing the moving medium under investigation. A modified autocorrelation approach is used in the velocity estimation. The new estimator automatically compensates for the axial velocity, when determining the transverse velocity by using fourth order moments rather than second order moments. The estimation is optimized by using a lag different from one in the estimation process, and noise artifacts are reduced by using averaging of RF samples. Further, compensation for the axial velocity can be introduced, and the velocity estimation is done at a fixed depth in tissue to reduce spatial velocity dispersion.

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**Fast simulation of ultrasound images**

Realistic B-mode and flow images can be simulated with scattering maps based on optical, CT, or MR images or parametric flow models. The image simulation often includes using 200,000 to 1 million point scatterers. One image line typically takes 1800 seconds to compute on a state-of-the-art PC, and a whole image can take a full day. Simulating 3D images and 3D flow takes even more time. A 3D image of 64 by 64 lines can take 21 days, which is not practical for iterative work. This paper presents a new fast simulation method based on the Field II program. In imaging the same spatial impulse response is calculated for each of the image lines, and making 100 lines, thus, gives 100 calculations of the same impulse response delayed differently for the different lines. Doing the focusing after this point in the simulation can make the calculation faster. This corresponds to full synthetic aperture imaging. The received response from each element is calculated, when emitting with each of the elements in the aperture, and then the responses are subsequently focused. This is the approach taken in this paper using a modified version of the Field II program. A 64 element array, thus, gives 4096 responses. For a 7 MHz 64 element linear array the simulation time for one image line is 471 seconds for 200,000 scatterers on a 800 MHz AMD Athlon PC, corresponding to 17 hours for one image with 128 lines. Using the new approach, the computation time is 10,963 seconds, and the beamforming time is 9 seconds, which makes the approach 5.5 times faster. For 3D images with 64 by 64 lines, the total conventional simulation time for one volume is 517 hours, whereas the new approach makes the simulation in 6,810 seconds. The time for beamforming is 288 seconds, and the new approach is, thus, 262 times faster. The simulation can also be split among a number of PCs for speeding up the simulation. A full 3D one second volume simulation then takes 7,500 seconds on a 32 CPU 600 MHz Pentium III PC cluster.

**Improved accuracy in the estimation of blood velocity vectors using matched filtering**

The blood velocity can be estimated by finding the shift in position of the blood scatterers between subsequent ultrasonic pulse emissions through cross-correlation of the received RF signals. Usually only the velocity component along the beam direction is found. It was shown in a previous paper that the complete velocity vector can be found, if the received signals are focused along lines parallel to the direction of the blood flow. A fairly broad beam is emitted in the approach, and this gives rise to a widening in the profiles of the estimated velocity. To reduce this effect, a focused ultrasound emission is used in this study to decrease the size of the beam. The transverse beam lines are then constructed by using filters matched to the response of the individual channels. The filters matched to the points on the focusing lines are obtained by considering the field response of the employed array transducer. The effect of the processing is studied through simulations with the Field II program. A 64-elements linear array with a center frequency of 3 MHz, pitch of 0.3 mm, and element height of 5 mm is used in the simulations. A parabolic velocity profile is considered for different angles between the flow and the ultrasound beam (30, 45, 60, and 90 degrees). The parabolic flow has a peak velocity of 0.5 m/s and the pulse repetition frequency is 3.5 kHz. Simulating twenty emissions and calculating the cross-correlation using four pulse-echo lines for each estimate, the parabolic flow profile is found with a standard deviation of 0.014 m/s at 45 degrees.
(corresponding to an accuracy of 2.8%) and 0.022 m/s (corresponding to an accuracy of 4.4%) at 90 degrees, which is transverse to the ultrasound beam.

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**Improved beamforming performance using pulsed plane wave decomposition**
A tool for calculating the beamformer setup associated with a specified pulsed acoustic field is presented. The method is named Pulsed Plane Wave Decomposition (PPWD) and is based on the decomposition of a pulsed acoustic field into a set of PPWs at a given depth. Each PPW can be propagated to the location of the elements of an array transducer by a time delay. The contribution of each propagated PPW is summed to form one time function for each array element (the BMF matrix). This approach gives the beamformer setup needed to obtain a close approximation to the desired bounded pulsed acoustic field without involving any optimization scheme. The approximation arises due to the limited size of the acoustic aperture and the spatial sampling property of the array transducer. Thus, the acoustical field can be designed according to the imaging needs. The method is demonstrated by examples in the 2D space by analytical equations, simulation, and experimental results.

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Potential of coded excitation in medical ultrasound imaging

Improvement in SNR and/or penetration depth can be achieved in medical ultrasound by using long coded waveforms, in a similar manner as in radars or sonars. However, the time-bandwidth product (TB) improvement, and thereby SNR improvement is considerably lower in medical ultrasound, due to the lower available bandwidth. There is still space for about 20 dB improvement in the SNR that will yield a penetration depth up to 20 cm at 5 MHz (O'Donnell, 1992). The limited TB additionally yields unacceptably high range sidelobes. However, the frequency weighting from the ultrasonic transducer's bandwidth, although suboptimal can be beneficial in sidelobe reduction. The purpose of this study is an experimental evaluation of the above considerations, using artificial tissue phantoms. Specifically as a first step, the effect of the transducer's impulse response has been identified. Attenuation has also been taken into consideration and its effect on the degradation of the compressed signal characteristics after both matched and mismatched filtering has been measured. Various codes that have been used successfully in radarsystems, such as chirps, m-sequences and polyphase codes have been examined. Since most of these binary codes have a larger bandwidth than the transducer in a typical medical ultrasound system can drive, a more careful code design has been proven essential. Simulation results are also presented for comparison. This paper presents an improved non-linear FM signal appropriate for ultrasonic applications. The new coded waveform exhibits distinctive features, that make it very attractive in the implementation of coded ultrasound systems. The range resolution that can be achieved is comparable to that of a conventional system, depending on the transducer's bandwidth and can even be better for broad-band transducers. The range sidelobes, at the same time, are well beyond the typical dynamic range of an ultrasound image. The energy of the sidelobe region is also reduced by lowering the distant sidelobes caused by the ripples of the spectrum's amplitude. The compressed signal-to-noise ratio loss is only ... dB. The effect of frequency shift on the matched filter due to attenuation has shown good stability of the new code. The new code is compared with the conventional approach of a linear chirp that is frequency weighted with a Chebyshev window for sidelobe reduction. Additionally, pulse compression on the receiver does not require any additional weighting or filtering and can be performed by a simple correlator.
Pre- and post-processing filters for improvement of blood velocity estimation

The standard deviation on the blood velocity estimates are influenced by measurement noise, velocity spread, and signal alteration introduced by de-noising and clutter filters. A noisy and non-smooth appearance of the velocity distribution is obtained, which is not consistent with the actual velocity in the vessels. Post-processing is beneficial to obtain an image that minimizes the variation, and present the important information to the clinicians. Applying the theory of fluid mechanics introduces restrictions on the variations possible in a flow field. Neighboring estimates in time and space should be highly correlated, since transitions should occur smoothly. This idea is the basis of the algorithm developed in this study. From Bayesian image processing theory an a posteriori probability distribution for the velocity field is computed based on constraints on smoothness. An estimate of the velocity in a given point is computed by maximization of the probability, given prior knowledge of the original estimate in that position, and the estimates in the neighboring positions in time and space. The method has been tested on simulated 2D RF-data resembling signals from the carotid artery with different signal-to-noise ratios (SNR). The exact extent of the vessel and the true velocities are thereby known. Velocity estimates were obtained by employing Kasai's autocorrelator on the data. The post-processing filter was used on the computed 2D velocity map. An improvement of the RMS error in the range of 15-53% was observed. For low SNRs the highest improvement was obtained. Visual inspection of the images show a high qualitative improvement. A more smooth profile has been obtained, which more closely resembles the true smooth profile. The same conclusion can be drawn after application of the filter to in-vivo data acquired with a dedicated sampling system.

Recursive ultrasound imaging

A method and an apparatus for recursive ultrasound imaging is presented. The method uses a Synthetic Transmit Aperture, but unlike previous approaches a new frame is created at every pulse emission. In receive, parallel beam forming is implemented. The beam formed RF data is added to the previously created RF lines. To keep the level of the signal, the RF data obtained previously, when emitting with the same element is subtracted from the RF lines. Up to 5000 frames/sec can be achieved for a tissue depth of 15 cm with a speed of sound of c = 1540 m/s. The high frame rate makes continuous imaging data possible, which can significantly enhance flow imaging. A point spread function 2° wide at -6 dB and grating lobes of $m(\theta) -50 dB$ is obtained with a 64 elements phased array with a central frequency $f_0 = 3$ MHz using a sparse transmit aperture using only 10 elements ($N_{x\times m\times t} = 10$) during pulse emission. The corresponding images have the quality of a dynamically focused image in transmit and receive. The dynamic focusing gives a small sampling volume and the capability to view small blood vessels and obtain the velocity profiles within the vessels with lower variance than with normal imaging.
Vector velocity estimation using directional beam forming and cross-correlation

The two-dimensional velocity vector using a pulsed ultrasound field can be determined with the invention. The method uses a focused ultrasound field along the velocity direction for probing the moving medium under investigation. Several pulses are emitted and the focused received fields along the velocity direction are cross-correlated. The time shift between received signals is found from the peak in the cross-correlation function and the velocity is thereby determined.

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Velocity estimation using recursive ultrasound imaging and spatially encoded signals

Previously we have presented a recursive beamforming algorithm for synthetic transmit aperture focusing. At every emission a beamformed low-resolution image is added to an existing high-resolution one, and the low-resolution image from the previous emission with the current active element is subtracted yielding a new frame at every pulse emission. In this paper the method is extended to blood velocity estimation, where a new color flow mapping (CFM) image is created after every pulse emission. The underlying assumption is that the velocity is constant between two pulse emissions and the current estimates can therefore be used for compensation of the motion artifacts in the data acquired in the next emission. Two different transmit strategies are investigated in this paper: (a) using a single defocused active aperture in transmit, and (b) emitting with all active transmit sub-apertures at the same time using orthogonal spatial encoding signals. The method was applied on data recorded by an experimental system. The estimates of the blood velocity for both methods had a bias less than 3% and a standard deviation around 2% making them a feasible approach for blood velocity estimations.
An effective coded excitation scheme based on a predistorted FM signal and an optimized digital filter

This paper presents a coded excitation imaging system based on a predistorted FM excitation and a digital compression filter designed for medical ultrasonic applications, in order to preserve both axial resolution and contrast. In radars, optimal Chebyshev windows efficiently weight a nearly rectangular spectrum. For the small time-bandwidth (TB) products available in ultrasound, the rectangular spectrum approximation is not valid, which reduces the effectiveness of weighting. Additionally, the distant range sidelobes are associated with the ripples of the spectrum amplitude and, thus, cannot be removed by weighting. We show that by using a predistorted chirp with amplitude or phase shaping for amplitude ripple reduction and a correlation filter that accounts for the transducer's natural frequency weighting and, output sidelobe levels of -35 to -40 dB are directly obtained. When an optimized filter is applied on receive, contrast or resolution can be traded in for range sidelobe levels down to -86 dB. The digital filter is designed to efficiently use the available bandwidth and at the same time to be insensitive to the transducer's impulse response. For evaluation of the method, simulations were performed with the program Field II.

A commercial scanner (B-K Medical 3535) was modified and interfaced to an arbitrary function generator along with an RF power amplifier (Ritec). Hydrophone measurements in water were done to establish excitation voltage and corresponding intensity levels (I-sptp and I-spta) well below the safety limits. In vivo images of the liver from two healthy volunteers show apparent increased depth of penetration of about 4 cm at 4 MHz, for codes of length 25 μs. Images taken from a non-attenuating wire phantom show that the -20 dB axial resolution for the coded scheme is as good as with pulse excitation (about 1.5 λ), depending on the filter design criteria. The axial sidelobes are below -40 dB, which is the noise level of the measuring imaging system. The proposed excitation/compression scheme shows good overall performance and stability to the frequency shift due to attenuation. It increases the penetration depth, and still yields a high resolution and low adjustable sidelobes.
A new Calculation Procedure for Spatial Impulse Responses in Ultrasound

A new procedure for the calculation of spatial impulse responses for linear sound fields is introduced. This calculation procedure uses the well known technique of calculating the spatial impulse response from the intersection of a circle emanating from the projected spherical wave with the boundary of the emitting aperture. This general result holds for all aperture boundaries for a flat transducer surface, and this is used in the procedure to yield the response for all types of flat transducers. An arbitrary apodization function over the aperture can be incorporated through a simple one-dimensional integration. The case of a soft baffle mounting of the aperture is also included. Specific solutions for transducer boundaries made from lines are given, so that any polygon transducer can be handled. Specific solutions for circles are also given. Finally, a solution for a general boundary is stated, and all these boundary elements can be combined to, e.g., handle annular arrays or semi-circle transducers. Results from an implementation of the approach are given and compared to previously developed solutions for a simple aperture, a complex aperture, and a Gaussian apodized circular transducer.

An improved estimation and focusing scheme for vector velocity estimation

The full blood velocity vector must be estimated in medical ultrasound to give a correct depiction of the blood flow. This can be done by introducing a transversely oscillating pulse-echo ultrasound field, which makes the received signal influenced by a transverse motion. Such an approach was suggested in [1]. Here the conventional autocorrelation approach was used for estimating the transverse velocity and a compensation for the axial motion was necessary in the estimation procedure.

This paper introduces a new estimator for determining the two-dimensional velocity vector and a new dynamic beamforming method. A modified autocorrelation approach employing fourth order moments of the input data is used for velocity estimation. The new estimator calculates the axial and lateral velocity component independently of each other. The estimation is optimized for differences in axial and lateral modulation periods in the ultrasound field by using a lag different from one in the estimation process, and noise artifacts are reduced by using averaging of RF samples. Furthermore, compensation for the axial velocity can be introduced, and the velocity estimation is done at a fixed depth in tissue to reduce spatial velocity dispersion. Examples of different velocity vector conditions are shown using the Field II simulation program. A relative accuracy of 10.1 % is obtained for the lateral velocity estimates for a parabolic velocity profile for a flow perpendicular to the ultrasound beam and a signal-to-noise ratio of 20 dB using 20 pulse-echo lines per
Estimation of blood velocity vectors using transverse ultrasound beam focusing and cross-correlation

Modern ultrasound scanners estimate the blood velocity by tracking the movement of the blood scatterers along the ultrasound beam. This is done by emitting pulsed ultrasound fields and finding the shift in position from pulse to pulse by correlating the received signals. Only the velocity component along the beam direction is found, and this is a serious limitation in the current scanners, since most blood vessels are parallel to the skin surface. A method to find the velocity across the vessel has been suggested by Bonnefous (1988). Here a number of parallel receive beams are measured and used in a correlation estimator to find the velocity across the beam. This approach is extended in this paper by making beamforming along the direction of the flow. A fairly broad beam is emitted and the received signal is then focused along a selected direction. This direction can be along the ultrasound beam or across it or in any direction to the beam. The focused lines, thus, follow the flow and a cross-correlation of lines from different pulses can find the movement of the blood particles between pulse emissions and, thus, the blood velocity. The new approach is investigated using the Field II simulation program. Simulations are shown for a parabolic velocity profile for flow-to-beam angles of 30, 45, 60, and 90 degrees using a 64 elements linear array with a center frequency of 3 MHz, a pitch of 0.3 mm, and an element height of 5 mm. The peak velocity in the parabolic flow was 0.5 m/s, and the pulse repetition frequency was 3.5 kHz. Using four pulse-echo lines, the parabolic flow profile was found with a standard deviation of 0.028 m/s at 60 degrees and 0.092 m/s at 90 degrees (transverse to the ultrasound beam), corresponding to accuracies of 5.6% and 18.4%. Using ten lines gave standard deviations of 0.021 m/s and 0.089 m/s, respectively, corresponding to accuracies of 4.2% and 17.8%.
Experimental ultrasound system for real-time synthetic imaging

Digital signal processing is being employed more and more in modern ultrasound scanners. This has made it possible to do dynamic receive focusing for each sample and implement other advanced imaging methods. The processing, however, has to be very fast and cost-effective at the same time. Dedicated chips are used in order to do real-time processing. This often makes it difficult to implement radically different imaging strategies on one platform and makes the scanners less accessible for research purposes. Here flexibility is the prime concern, and the storage of data from all transducer elements over 5 to 10 seconds is needed to perform clinical evaluation of synthetic and 3D imaging. This paper describes a real-time system specifically designed for research purposes.

The purpose of the system is to make it possible to acquire multi-channel data in real-time from clinical multi-element ultrasound transducers, and to enable real-time or near real-time processing of the acquired data. The system will be capable of performing the processing for the currently available imaging methods, and will make it possible to perform initial trials in a clinical environment with new imaging modalities for synthetic aperture imaging, 2D and 3D B-mode and velocity imaging.

The system can be used with 128 element transducers and can excite 128 channels and receive and sample data from 64 channels simultaneously at 40 MHz with 12 bits precision. Data can be processed in real time using the system's 80 signal processing units or it can be stored directly in RAM. The system has 24 GBytes RAM and can thus store 8 seconds of multi-channel data. It is fully software programmable and its signal processing units can also be reconfigured under software control. The control of the system is done over an Ethernet using C and Matlab. Programs for doing e.g. B-mode imaging can directly be written in Matlab and executed on the system over the net from any workstation running Matlab. The overall system concept is presented and an example of a 20 lines script for doing phased array B-mode imaging is presented.

Recursive Ultrasound Imaging

This paper presents a new imaging method, applicable for both 2D and 3D imaging. It is based on Synthetic Transmit Aperture Focusing, but unlike previous approaches a new frame is created after every pulse emission. The elements from a linear transducer array emit pulses one after another. The same transducer element is used after N-xmt emissions. For each emission the signals from the individual elements are beam-formed in parallel for all directions in the image. A new frame is created by adding the new RF lines to the RF lines from the previous frame. The RF data recorded at the previous emission with the same element are subtracted. This yields a new image after each pulse emission and can give a frame rate of e.g. 5000 images/sec.
The paper gives a derivation of the recursive imaging technique and compares simulations for fast B-mode imaging with measurements.

A low value of N-xmt is necessary to decrease the motion artifacts and to make flow estimation possible. The simulations show that for N-xmt = 13 the level of grating lobes is less than -50 dB from the peak, which is sufficient for B-mode imaging and flow estimation.

The measurements made with an off-line experimental system having 64 transmitting channels and 1 receiving channel, confirmed the simulation results. A linear array with a pitch of 208.5 μm, central frequency f(0tr) = 7.5 MHz and bandwidth BW = 70% was used. The signals from 64 elements were recorded, beam-formed and displayed as a sequence of B-mode frames, using the recursive algorithm. An excitation with a central frequency f(0) = 5 MHz (λ = 297 μm in water) was used to obtain the point spread function of the system. The -6 dB width of the PSF is 1.056 mm at axial distance of 39 mm. For a sparse synthetic transmit array with N-xmt = 22 the expected grating lobes from the simulations are -53 dB down from the peak value at, positioned at +/-28 degrees. The measured level was -51 dB at +/-27 degrees from the peak.

Images obtained with the experimental system are compared to the simulation results for different sparse arrays. The application of the method for 3D real-time imaging and blood-velocity estimations is discussed.

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**A New Method for Estimation of Velocity Vectors**
The paper describes a new method for determining the velocity vector of a remotely sensed object using either sound or electromagnetic radiation. The movement of the object is determined from a field with spatial oscillations in both the axial direction of the transducer and in one or two directions transverse to the axial direction. By using a number of pulse emissions, the inter-pulse movement can be estimated and the velocity found from the estimated movement and the time between pulses. The method is based on the principle of using transverse spatial modulation for making the received signal influenced by transverse motion. Such a transverse modulation can be generated by using apodization on individual transducer array elements together with a special focusing scheme. A method for making such a field is presented along with a suitable two-dimensional velocity estimator. An implementation usable in medical ultrasound is described, and simulated results are presented. Simulation results for a flow of 1 m/s in a tube rotated in the image plane at specific angles (0, 15, 35, 55, 75, and 90 degrees) are made and characterized by the estimated mean value, estimated angle, and the standard deviation in the lateral and longitudinal direction. The average performance of the estimates for all angles is: mean velocity 0.99 m/s, longitudinal S.D. 0.015 m/s, and lateral S.D. 0.196 m/s. For flow parallel to the transducer the results are: mean velocity 0.95 m/s, angle 0.10, longitudinal S.D. 0.020 m/s, and lateral S.D. 0.172 m/s.

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**Apparatus and method for determining movements and velocities of moving objects**

With an apparatus according to the invention it is possible to detect an object's velocity transverse to the direction of propagation of an interacting field. Such transverse movement is detected by applying a field that oscillates spatially in the transverse direction. The method used in the apparatus is applicable where wave energy is used to sense or detect an object by its scattering properties when using either sound waves or electro-magnetic waves. The movement can be detected according to the field properties. The field represented by the sampling pulse must feature a spatial oscillation in the directions, where the velocity components are of interest. Such a transversely oscillating field is e.g. generated by using apodization on individual transducer elements and a special focusing scheme. The apparatus uses waves of either sound or electro-magnetic radiation. The temporal characteristics are determined by the setup of the emitter (1). The spatial characteristics are determined by the transmitter array configuration (3) and the receiver array configuration (5) and the respective beam formers (2) and (6a, 6b, 6c). The transmit array consists of $i(N)$ elements and the receive array consists of $i(M)$ elements. The transmit beam former and the receive beam former are configured to obtain the spatially oscillating field. The signal received from the interacting objects (4) is processed by the velocity estimator processor (7) for calculation of the velocity vector components by estimating the shift in position as a function of time and the velocity is derived herefrom.

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Biomedical Engineering at the Technical University of Denmark

The paper gives a brief overview of the biomedical engineering research and education at the Technical University of Denmark. An account of the research activities since the 1950s is given, and examples of major efforts within ultrasound, biomagnetism, and neuroimaging are described. The evolution of the teaching activities since the late 1960s along with an account of the recent initiatives to make a biomedical engineering profile at the university is described.

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Performance of a vector velocity estimator

It is a well-known limitation of all commercially available scanners that only the velocity component along the propagation direction of the emitted pulse is measured, when evaluating blood velocities with ultrasound. Proposals for solving this limitation using several transducers or speckle tracking can be found in the literature, but no method with a satisfactory performance has been found that can be used in a commercial implementation. A method for estimation of the velocity vector is presented. Here an oscillation transverse to the ultrasound beam is generated, so that a transverse motion yields a change in the received signals. The method uses two ultrasound beams for sampling the in-phase and quadrature component of the lateral field, and a set of samples (in-phase and quadrature in both time and space) are taken for each pulse-echo line. These four samples are then used in an autocorrelation approach that yields both the axial and the lateral velocity, and thus the velocity vector. The method has the advantage that a standard array transducer and a modified digital beamformer, like those used in modern ultrasound scanners, is sufficient to obtain the information needed. The signal processing preceding the beamforming can be implemented using standard signal processors, and it is robust since the autocorrelation method is used.

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Determination of blood velocities for color flow mapping systems involves both stationary echo cancelling and velocity estimation. Often the stationary echo cancelling filter is the limiting factor in color flow mapping and the optimization and further development of this filter is crucial to the improvement of color flow imaging. Optimization based on in-vivo data is difficult since the blood and tissue signals cannot be accurately distinguished and the correct extend of the vessel under investigation is often unknown. This study introduces a model for the simulation of blood velocity data in which tissue motion is included. Tissue motion from breathing, heart beat, and vessel pulsation were determined based on in-vivo RF-data obtained from 10 healthy volunteers. The measurements were taken at the carotid artery at one condition and in the liver at three conditions. Each measurement was repeated 10 times to cover the whole cardiac cycle and a total of 400 independent RF measurements of 950 pulse echo lines were recorded. The motion of the tissue surrounding the hepatic vein from superficial breathing had a peak velocity of 6.2±3.4 mm/s over the cardiac cycle, when averaged over the 10 volunteers. The motion due to the heart, when the volunteer was asked to hold his breath, gave a peak velocity of 4.2±1.7 mm/s. The movement of the carotid artery wall due to changing blood pressure had a peak velocity of 8.9±3.7 mm/s over the cardiac cycle. The variations are due to differences in heart rhythm, breathing, and anatomy. All three of these motions are handled independently by the simulation program, which also includes a parametric model for the pulsatile velocity in the elastic vessel. The model can be used for optimizing both color flow mapping and spectral display systems.
plane of the emitting aperture. Summing the angles of the arcs within the aperture readily yields the spatial impulse
response for a point in space. The approach makes it possible to make very general calculation routines for arbitrary, flat
apertures in which the outline of the aperture is either analytically or numerically defined. The exact field can then be found
without evaluating any integrals by merely finding the zeros of the either the analytic or numerically defined functions. This
makes it possible to describe the transducer surface using an arbitrary number of lines for the boundary. The approach
can also be used for finding analytic solutions to the spatial impulse response for new geometries of, for example,
ellipsoidal shape. The approach also makes it easy to incorporate any apodization function and the effect from different
transducers baffle mountings. Examples of spatial impulse responses for a shape made from lines bounding the aperture
is shown along with solutions for Gaussian apodized round transducer.

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Research › peer-review

Computer phantoms for simulating ultrasound B-mode and CFM images
Programs capable of simulating ultrasound images have recently been developed. This opens the possibility of evaluating
transducers and focusing schemes not only from their point spread function, but also from an imaging point of view. The
calculation of the ultrasound field is based on linear acoustics using the Tupholme-Stepanishen method for calculating the
spatial impulse response. Any transducer can be simulated by splitting the aperture into rectangular or triangular sub-
apertures, and the calculation can include any transducer excitation and apodization. The acoustic settings can be
controlled in the entire image through dynamic apodization and focusing. The transmit and receive apertures can be
defined independently of each other. Frequency dependent attenuation can also be included in the simulation. The B-mode
images are generated by specifying a number of independent scatterers in a file that defines their position and amplitude.
Adjusting the number of scatterers and their relative amplitude yields the proper image. Five different computer phantoms
are described. The first one consists of a number of point targets. It is used for studying the point spread function as a
function of spatial position, and can give an indication of side-lobe levels and focusing abilities. The second phantom
contains a number of cysts and point targets along with a homogeneous speckle pattern. This is used for investigating
image contrast, and the system's ability to detect low-contrast objects. The third phantom is for realistic clinical imaging. It
contains the image of a 12 week old fetus, where the placenta and the upper body of the fetus is visible. This phantom
gives an indication of the whole system's capability for real imaging. The current fetus phantom is only two-dimensional,
as it is constant in reflection amplitude in the elevation direction. The program, however, can handle the full three-
dimensional simulation, and the whole body could in principle be simulated. An example for a simulated kidney is also
shown. The last phantom is used for color flow mapping and is a combination of static and moving scatterers. A model with
stepwise movement of the scatterers in an artery with a parabolic flow profile surrounded by tissue is used. The signal
from the scatterers is recorded between each movement and then they are propagated for the next image acquisition. The
phantom can be used to study both spectral estimation techniques and color flow mapping estimators. The scatte
description is three-dimensional and so is the acoustic field calculation. This approach allows the evaluation of an imaging
system design to be performed very fast and early in the development process. Typically a single phantom simulation
takes less than 12 hours of simulation time. Transducer designs can be optimized and the practical implementation
reduced to only one trial. Also different signal processing approaches can be evaluated realistically.

General information
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Field: A Program for Simulating Ultrasound Systems

A program for the simulation of ultrasound systems is presented. It is based on the Tupholme-Stephanishen method, and is fast because of the use of a far-field approximation. Any kind of transducer geometry and excitation can be simulated, and both pulse-echo and continuous wave fields can be calculated for both transmit and pulse-echo. Dynamic apodization and focusing are handled through time lines, and different focusing schemes can be simulated. The versatility of the program is ensured by interfacing it to Matlab. All routines are called directly from Matlab, and all Matlab features can be used. This makes it possible to simulate all types of ultrasound imaging systems.

Multi-processor system for real-time flow estimation in medical ultrasound imaging

Real-Time Blood Flow Estimation Using a Recursive Least-Squares Lattice Filter

Ultrasonic flow estimation involves Fourier-transforming data from successive pulses. The standard periodogram spectral estimate does not reflect the true velocity distribution in the blood and assumes quasi-stationarity in the data. Last year (see J.A. Jensen et al., IEEE Ultrasonics Symposium Proceedings, p. 1221-4, 1996), the authors demonstrated that a recursive lattice filter can yield results much closer to the correct velocity distribution. They have now implemented it in real time on a system with sixteen ADSP-21060 processors, interfaced to a commercial scanner. The system can perform real-time processing for both the periodogram and lattice-filter approaches and displays both results on a PC for
comparison. Results are shown for phantom data and for demodulated data from the aorta and hepatic vein of a healthy subject. This demonstrates under clinical conditions that the lattice filter gives a more realistic velocity distribution and can track rapid changes in the flow.

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**Estimation of blood velocities using ultrasound: A Signal Processing Approach**
Ultrasound systems are especially useful in estimating blood velocities in the human body because they are noninvasive and can display an estimate in real time. This book offers a comprehensive treatment of this relatively new, important technology. The book begins with an introduction to ultrasound, flow physics, and the circulatory system. Next, the interaction of ultrasound with blood is discussed. The special contribution of the book lies in the remaining chapters, which offer a lucid, thorough description of continuous and pulsed wave systems, the latest systems for doing color flow imaging, and, finally, some of the more recent experimental techniques. The authors shows that the Doppler shift, usually considered the way velocity is detected, actually, plays a minor role in pulsed systems. Rather, it is the shift of position of signals between pulses that is used in velocity estimation.

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**Estimation of the blood velocity spectrum using a recursive lattice filter**
In medical ultrasound the blood velocity distribution in a vessel can be found by emitting a pulsed field into the patient. The field is then scattered by the tissues and the red blood cells, and a single complex sample set is acquired at the depth of interest for each pulse emitted. The signals acquired for showing the blood velocity distribution are inherently non-stationary, due to the pulsatility of the flow. All current signal processing schemes assume that the signal is stationary within the window of analysis, although this is an approximation. In this paper a recursive least-squares lattice filter is used for finding a parametric model for the velocity distribution. A new set of complex coefficients is calculated for each point in time, and it is thus possible to track the non-stationary properties of the stochastic velocity signal. The dynamic characteristics of the non-stationarity are incorporated through an exponential decay factor, that sets the exponential horizon of the filter. A factor close to 1 gives a long horizon with low variance estimates, but can not track a highly non-stationary flow. Setting the factor is therefore a compromise between estimate variance and the filter’s dynamic adaptation. Using a lattice filter gives a structure that is easy and robust, when implemented with fixed point arithmetic. The procedure has been tested on both simulated and in-vivo data, and gives spectral estimates quite different from the
normal FFT approach. Synthetic data were generated based on the measured time evolution of the spatial mean velocity in the femoral artery. The smooth theoretical velocity distribution is then known and can be compared to the estimated distribution. Using 8 parameters a very smooth estimate of the velocity distribution is seen, more in line with the actual distributions that always will be smooth. Setting the exponential decay factor to 0.99 gives satisfactory results for in-vivo data from the carotid artery. The filter can easily be implemented using a standard fixed-point signal processing chip for real-time processing.

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Multi-processor system for real-time deconvolution and flow estimation in medical ultrasound

More and more advanced algorithms are being introduced for performing signal and image processing on medical ultrasound signals. The algorithms often use the RF ultrasound signal and perform adaptive signal processing. Two examples are the cross-correlation estimator for blood velocity estimation and adaptive blind deconvolution. The first algorithm uses the RF signal from a number of pulse emissions and correlates segments within different pulse-echo lines to obtain a velocity estimate. Real-time processing makes it necessary to perform around 600 million multiplications and additions per second for this algorithm. This has until now only been possible by using the sign of the signals, and such an implementation does not give optimal performance. The second algorithm also uses the RF data, and first performs an estimation of the one-dimensional pulse in the tissue as a function of depth. Then a Kalman filter is used with a second time-reversed recursive estimation step. Here it is necessary to perform about 70 arithmetic operations per RF sample or about 1 billion operations per second for real-time deconvolution. Furthermore, these have to be floating point operations due to the adaptive nature of the algorithms. Many of the algorithms can only be properly evaluated in a clinical setting with real-time processing, which generally cannot be done with conventional equipment. This paper therefore presents a multi-processor system capable of performing 1.2 billion floating point operations per second on RF ultrasound signals. It consists of 16 ADSP 21060 processors each capable of 80 Mflops. Four processors are placed on one board with 24 MBytes external storage and an internal storage of 0.5 MBytes per processor. All processors can access all storage on its physical board, and are further connected through parallel interface channels. Each channel can transmit 40 MBytes a second without slowing the processor down, and each processor has 6 of these channels. Four of these are accessible through front panel connectors, so that an almost arbitrary network of the 16 processors can be made. The system has been interfaced to our previously-developed real-time sampling system that can acquire RF data at a rate of 20 MHz and simultaneously transmit the data at 20 MHz to the processing system via several parallel channels. These two systems can, thus, perform real-time processing of ultrasound data. The advantage of the system is its generous input/output bandwidth, that makes it easy to balance the computational load between the processors and prevents data starvation. Due to the use of floating point calculations it is possible to simulate all types of signal processing in modem ultrasound scanners, and this system is, thus, a complete software scanner. The system has been connected to a B and K Medical type 3535 ultrasound scanner. Data is received by the PC through an Analog Devices EZ-LAB card with a ADSP21062 processor.

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Simulating arbitrary-geometry ultrasound transducers using triangles

Calculation of ultrasound fields from medical transducers is often done by applying linear acoustics and using the Tupholme-Stepanishen method of calculation. Here the spatial impulse response is found and, together with the basic one-dimensional pulse, it is used to find both the emitted and pulse-echo field. The spatial impulse response has only been determined analytically for a few geometries and using apodization over the transducer surface generally makes it impossible to find the response analytically. A popular approach to find the general field is thus to split the aperture into small rectangles, and then sum the weighted response from each of these. The problem with rectangles is their poor fit to apertures which do not have straight edges, such as circular and oval shapes. The simulation thus introduces artifacts in the response, that necessitates the use of a large number of rectangles for a precise simulation. A triangle better fits these aperture shapes, and the field from a triangle has recently been derived. A new field simulation program has been made based on the triangular shape. It is written in C and interfaced to the Matlab environment through a set of M-files. A large number of transducers can be defined and their properties manipulated. The program can calculate all types of ultrasound fields, and can also be used for simulating B-mode and color flow images. Both the focusing and apodization can be set to be dynamic with respect to time, and it is thus possible to simulate images focused at different zones. The time-integrated spatial impulse response is used in the program to minimize the effect of the sharp edges of the spatial impulse response in a sampled signal. Since the integrated response from a triangular element cannot be analytically evaluated, a simple numerical integration is used. Using this program, the geometrical artifacts from fitting the aperture with a basic element are significantly reduced and is in most instances negligible. The time for running the program is, however, increased by a factor of 3.3 to 1000 compared to using the simple far-field response of a rectangle, as the triangle equations are far more complicated. This approach is therefore best suited for accurate modeling of fields, whereas the rectangle program is better suited to make fast simulated images, since contributions from many scatterers are summed here and the error is thereby reduced.
Ultrasound fields from triangular apertures

The pulsed field from a triangular aperture mounted in an infinite, rigid baffle is calculated. The approach of spatial impulse responses, as developed by Tupholme and Stepanishen, is used. By this both the emitted and received pulsed ultrasound field can be found for any transducer excitation and electro-mechanical impulse response. The continuous wavefield is also readily obtainable through a simple Fourier transform. The spatial impulse response is calculated without approximation, and the solution is valid in the half space in front of the aperture for a homogeneous, non-attenuating medium. The solution can be used in finite elements programs for calculating fields from arbitrary transducer geometries.

An Analysis of Pulsed Wave Ultrasound Systems for Blood Velocity Estimation

Pulsed wave ultrasound systems can be used for determining blood’s velocity non-invasively in the body. A region of interest is selected, and the received signal is range gated to measure data from the region. One complex sample value is acquired for each pulse emission after complex demodulation of the received signal. The time evolution and distribution of velocity can then be found by using samples from a number of pulse-echo lines. Making a short-time Fourier transform of the data reveals the velocity distribution in the range gate over time. Such systems are called Doppler ultrasound systems implying that they use the classical Doppler effect. The velocity is typically on the order of 0.5 to 1 m/s giving a relative shift of 2 to 4 kHz of the center frequency of the received spectrum for a 3 MHz transducer. Finding such a shift is impossible since the unknown frequency shift from attenuation in tissue can be tens of kilohertz. Some recent reviews and articles state that the Doppler effect is used, and contradictory and wrong results and erroneous system diagrams arise from this assumption. Research done in the last few years has revealed that it is the movement of the scatterers between pulse emissions, that is used for finding the velocity. This finding gives new insight into the role of the complex demodulation stage, and shows that this can be replaced by a matched filter and quadrature RF sampling. A derivation of this result is presented in this paper, and it reveals how the bandwidth of the pulse and the number of pulse emissions affect the result. The final equation for the received signal is quite complicated, and a simplified interpretation is therefore also given. This readily reveals the influence from transducer bandwidth, attenuation, non-linear effects, classical Doppler effect, and scattering.
Neural network for sonogram gap filling

In duplex imaging both an anatomical B-mode image and a sonogram are acquired, and the time for data acquisition is divided between the two images. This gives problems when rapid B-mode image display is needed, since there is not time for measuring the velocity data. Gaps then appear in the sonogram and in the audio signal, rendering the audio signal useless, thus making diagnosis difficult. The current goal for ultrasound scanners is to maintain a high refresh rate for the B-mode image and at the same time attain a high maximum velocity in the sonogram display. This precludes the intermixing of the B-mode and sonogram pulses, and time must be shared between the two. Gaps will appear frequently in the sonogram since, e.g., half the time is spent on B-mode acquisition. The information in the gaps can be filled from the available information through interpolation. One possibility is to use a neural network for predicting mean frequency of the velocity signal and its variance. The neural network then predicts the evolution of the mean and variance in the gaps, and the sonogram and audio signal are reconstructed from these. The technique is applied on in-vivo data from the carotid artery. The neural network is trained on part of the data and the network is pruned by the optimal brain damage procedure in order to reduce the number of parameters in the network, and thereby reduce the risk of overfitting. The neural predictor is compared to using a linear filter for the mean and variance time series, and is shown to yield better results, i.e., the variances of the predictions are lower. The ability of the neural predictor to reconstruct both the sonogram and the audio signal, when only 50% of the time is used for velocity data acquisition, is demonstrated for the in-vivo data.

Artifacts in blood velocity estimation using ultrasound and cross-correlation

Estimation of blood velocities using ultrasound and time-domain cross-correlation is investigated. The measurement principle is introduced, and the basic properties of the cross-correlation function are discussed. Expressions for the variance of the estimates of the peak location are given, showing the influence of integration time, transducer bandwidth and signal-to-noise ratio. It is also shown that the technique can be implemented using only the sign of the signals. A simple simulation program is used in order to study the exact influence from the different parameters. Using the program, it is shown that any velocity can result from the estimation with a certain probability regardless of the true velocity, when the signal-to-noise ratio is low. This is due to the non-linear estimation technique employed and shows that estimation variance yields little information for this estimator. Graphs are given for the probability of correct estimation, when the different parameters are varied.
Estimation of in-vivo pulses in medical ultrasound

An algorithm for the estimation of one-dimensional in-vivo ultrasound pulses is derived. The routine estimates a set of ARMA parameters describing the pulse and uses data from a number of adjacent rf lines. Using multiple lines results in a decrease in variance on the estimated parameters and significantly reduces the risk of terminating the algorithm at a local minimum. Examples from use on synthetic data confirms the reduction in variance and increased chance of successful minimization termination. Simulations are also reported indicating the relation between the one-dimensional pulse and the three-dimensional, attenuated ultrasound field for a concave transducer. Pulses are estimated from in-vivo liver data showing good resemblance to a pulse measured as the response from a planar reflector and then properly attenuated. The main application for the algorithm is to function as a preprocessing stage for deconvolution algorithms using parametric pulses.

Nonparametric estimation of ultrasound pulses

An algorithm for nonparametric estimation of 1D ultrasound pulses in echo sequences from human tissues is derived. The technique is a variation of the homomorphic filtering technique using the real cepstrum, and the underlying basis of the method is explained. The algorithm exploits a priori knowledge about the structure of RF line echo data and can employ a number of adjacent RF lines from an image. The prime application of the algorithm is to yield a pulse suitable for deconvolution algorithms. This will enable these algorithms to properly take into account the frequency dependence of the attenuation and its variation within a patient and among patients. It is also possible to use the estimated pulse for attenuation estimation, and the consistency of the assumptions underlying the proposed technique is demonstrated by its ability to recover low variance attenuation estimates in the normal liver from in vivo pulse-echo data. Estimates are given for 8 different patients.
Two-dimensional random arrays for real time volumetric imaging

Two-dimensional arrays are necessary for a variety of ultrasonic imaging techniques, including elevation focusing, 2-D phase aberration correction, and real time volumetric imaging. In order to reduce system cost and complexity, sparse 2-D arrays have been considered with element geometries selected ad hoc, by algorithm, or by random process. Two random sparse array geometries and a sparse array with a Mills cross receive pattern were simulated and compared to a fully sampled aperture with the same overall dimensions. The sparse arrays were designed to the constraints of the Duke University real time volumetric imaging system, which employs a wide transmit beam and receive mode parallel processing to increase image frame rate. Depth-of-field comparisons were made from simulated on-axis and off-axis beamplots at ranges from 30 to 160 mm for both coaxial and offset transmit and receive beams. A random array with Gaussian distribution of transmitters and uniform distribution of receivers was found to have better resolution and depth-of-field than both a Mills cross array and a random array with uniform distribution of both transmit and receive elements. The Gaussian random array was constructed and experimental system response measurements were made at several ranges. Comparisons of B-scan images of a tissue mimicking phantom show improvement in resolution and depth-of-field consistent with simulation results.

Deconvolution of In Vivo Ultrasound B-Mode Images

An algorithm for deconvolution of medical ultrasound images is presented. The procedure involves estimation of the basic one-dimensional ultrasound pulse, determining the ratio of the covariance of the noise to the covariance of the reflection signal, and finally deconvolution of the rf signal from the transducer. Using pulse and covariance estimators makes the
approach self-calibrating, as all parameters for the procedure are estimated from the patient under investigation. An example of use on a clinical, in-vivo image is given. A 2 x 2 cm region of the portal vein in a liver is deconvolved. An increase in axial resolution by a factor of 2.4 is obtained. The procedure can also be applied to whole images, when it is ensured that the rf signal is properly measured. A method for doing that is outlined.

**Implementation of ultrasound time-domain cross-correlation blood velocity estimators**

The implementation of real-time blood velocity estimators using time-domain cross-correlation is investigated. The basic algorithm for stationary echo canceling, cross-correlation estimation and subsequent velocity estimation is presented. Sampled data acquired at rates of approximately 20 MHz are used in the algorithm, imposing a heavy burden on the signal processing hardware. The algorithm is analyzed with regard to the high sampling frequency, and a method for performing real-time high-speed-movement and cross-correlation is suggested. Implementation schemes based on using the sign of the data as well as the full precision are proposed. From an analysis of the process it is concluded that the sign data implementation can attain real-time processing. This can also be obtained for the full precision data, but at the expense of using a number of dedicated signal processing chips. Both implementations suggested can handle the estimation of velocities for A-lines acquired from multiple directions.
Range/velocity limitations for time-domain blood velocity estimation

The traditional range/velocity limitation for blood velocity estimation systems using ultrasound is elucidated. It is stated that the equation is a property of the estimator used, not the actual physical measurement situation, as higher velocities can be estimated by the time domain cross-correlation approach. It is demonstrated that the time domain technique under certain measurement conditions will yield unsatisfactory results, when trying to estimate high velocities. Various methods to avoid these artifacts using temporal and spatial clustering techniques are suggested. The improvement in probability of correct detection is derived, and several examples of simulations are shown.

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Stationary echo canceling in velocity estimation by time-domain cross-correlation

The application of stationary echo canceling to ultrasonic estimation of blood velocities using time-domain cross-correlation is investigated. Expressions are derived that show the influence from the echo canceler on the signals that enter the cross-correlation estimator. It is demonstrated that the filtration results in a velocity-dependent degradation of the signal-to-noise ratio. An analytic expression is given for the degradation for a realistic pulse. The probability of correct detection at low signal-to-noise ratios is influenced by signal-to-noise ratio, transducer bandwidth, center frequency, number of samples in the range gate, and number of A-lines employed in the estimation. Quantitative results calculated by a simple simulation program are given for the variation in probability from these parameters. An index reflecting the reliability of the estimate at hand can be calculated from the actual cross-correlation estimate by a simple formula and used in rejecting poor estimates or in displaying the reliability of the velocity estimated.

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Ultrasound fields in an attenuating medium

Ultrasound fields propagating in tissue will undergo changes in shape not only due to diffraction, but also due to the frequency dependent attenuation. Linear fields can be fairly well predicted for a non-attenuating medium like water by using the Tupholme-Stepanishen method for calculating the spatial impulse response, whereas the field cannot readily be found for an attenuating medium. In this paper we present a simulation program capable of calculating the field in a homogeneous attenuating medium. The program splits the aperture into rectangles and uses a far-field approximation for each of the rectangles and sums all contributions to arrive at the spatial impulse response for the aperture and field point. This approach makes it possible to model all transducer apertures, and the program can readily calculate the emitted, pulse-echo and continuous wave field. Attenuation is included by splitting it into a frequency dependent part and frequency independent part. The latter results in an attenuation factor that is multiplied onto the responses from the individual elements, and the frequency dependent part is handled by attenuating the basic one-dimensional pulse. The influence on ultrasound fields from attenuation is demonstrated.

Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers

A method for simulation of pulsed pressure fields from arbitrarily shaped, apodized and excited ultrasound transducers is suggested. It relies on the Tupholme-Stepanishen method for calculating pulsed pressure fields, and can also handle the continuous wave and pulse-echo case. The field is calculated by dividing the surface into small rectangles and then summing their response. A fast calculation is obtained by using the far-field approximation. Examples of the accuracy of the approach and actual calculation times are given.
Deconvolution of ultrasound images

Based on physical models, it is indicated that the received pressure field in ultrasound B-mode images can be described by a convolution between a tissue reflection signal and the emitted pressure field. This result is used in a description of current image formation and in formulating a new processing scheme. The suggested estimator can take into account the dispersive attenuation, the temporal and spatial variation of the pulse, and the change in reflection strength and signal-to-noise ratio. Details of the algorithm and the estimation of parameters to be used are given. The performance is indicated by two examples. One is for a synthetic signal and the other is for data measured from a tissue mimicking phantom. The last example shows a finer speckle pattern, giving an increased resolution.

Two-dimensional deconvolution of ultrasound images

A model for the propagation and scattering of ultrasound in tissue

An inhomogeneous wave equation is derived describing propagation and scattering of ultrasound in an inhomogeneous medium. The scattering term is a function of density and propagation velocity perturbations. The integral solution to the wave equation is combined with a general description of the field from typical transducers used in clinical ultrasound to yield a model for the received pulse-echo pressure field. Analytic expressions are found in the literature for a number of transducers, and any transducer excitation can be incorporated into the model. An example is given for a concave, nonapodized transducer in which the predicted pressure field is compared to a measured field.
Detection probabilities for time-domain velocity estimation

Estimation of blood velocities by time-domain cross-correlation of successive high frequency sampled ultrasound signals is investigated. It is shown that any velocity can result from the estimator regardless of the true velocity due to the nonlinear technique employed. Using a simple simulation program, it is demonstrated that the probability of correct estimation depends on the signal-to-noise ratio, transducer bandwidth, number of A-lines and number of samples used in the correlation estimate. The influence of applying a stationary echo-canceler is explained. The echo canceling can be modeled as a filter with a transfer function depending on the actual velocity. This influences the detection probability, which gets lower at certain velocities. An index directly reflecting the probability of detection can easily be calculated from the cross-correlation estimated. This makes it possible to assess the reliability of the velocity estimate in real time.

Estimation of pulses in ultrasound B-scan images

It is shown, based on an expression for the received pressure field in pulsed medical ultrasound systems, that a common one-dimensional pulse can be estimated from individual A-lines. An autoregressive moving average (ARMA) model is suggested for the pulse, and an estimator based on the prediction error method is derived. The estimator is used on a
segment of an A-line, assuming that the pulse does not change significantly inside the segment. Several examples of the use of the estimator on synthetic data measured from a tissue phantom and in vitro data measured from a calf’s liver are given. They show that a pulse can be estimated even at moderate signal-to-noise ratios.

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**Phase-processing as a tool for speckle reduction in pulse-echo images**
Due to the coherent nature of conventional ultrasound medical imaging systems interference artefacts occur in pulse echo images. These artefacts are generically termed ‘speckle’. The phenomenon may severely limit low contrast resolution with clinically relevant information being obscured. Traditional speckle reduction procedures regard speckle correction as a stochastic process and trade image smoothing (resolution loss) for speckle reduction. Recently, a new phase acknowledging technique has been proposed that is unique in its ability to correct for speckle interference with no image resolution tradeoff. The technique is outlined and preliminary in-vivo results are presented.

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**Sampling system for in vivo ultrasound images**
Newly developed algorithms for processing medical ultrasound images use the high frequency sampled transducer signal. This paper describes demands imposed on a sampling system suitable for acquiring such data and gives details about a prototype constructed. It acquires full clinical images at a sampling frequency of 20 MHz with a resolution of 12 bits. The prototype can be used for real time image processing. An example of a clinical in vivo image is shown and various aspects of the data acquisition process are discussed.

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Deconvolution of in vivo ultrasound images

In an ultrasound image, the influence of the pulse and attenuation should be removed from the picture in order to display a more consistent and uniform image. The author describes an algorithm to remove the influence of the attenuated pulse on the image. The algorithm takes into account the varying pulse, noise in the acquired signal, and the changing reflectivity in the tissue. Both one- and two-dimensional processing can be implemented. The algorithm relies on prior knowledge of the pulse and of the covariance of the noise and the reflections. Algorithms to estimate these factors are given. Examples of 1-D deconvoluted pictures of phantom data and in vivo data are given. They show, especially for the phantom data, an increased contrast and resolution.

On output measurements via radiation pressure

It is shown, by simple physical argument, that measurements of intensity with a radiation pressure balance should not agree with those based on calorimetric techniques. The conclusion is ultimately a consequence of the circumstance that radiation pressure measurements relate to wave momentum, while calorimetric methods relate to wave energy. Measurements with some typical ultrasound fields are performed with a novel type of hydrophone, and these allow an estimate to be made of the magnitude of the discrepancy to be expected between the two types of output measurement in a typical case.
Medical Ultrasound Imaging: An Estimation Based Approach

A new principle for a high-efficiency power audio amplifier for use with a digital preamplifier
The use of class-B and class-D amplifiers for converting digital audio signals to analog signals is discussed. It is shown that the class-D amplifier is unsuitable due to distortion. Therefore a new principle involving a switch-mode power supply and a class-B amplifier is suggested. By regulating the supply voltage to the amplifier according to the amplitude of the audio signal, a higher efficiency than can be obtained by the usual principles is achieved. The regulation can be done very efficiently by generating the control signal to the power supply in advance of the audio signal, made possible by a preceding digital signal from the preamplifier. A prototype shows possibilities for further developments

A new principle for an all-digital preamplifier and equalizer
A new principle for an all-digital preamplifier and equalizer, to be used together with a Compact Disc player, is described. The principle makes it possible to obtain an arbitrary gain transfer function together with a linear phase. The gain can be varied 20 dB from point to point, when specified on a logarithmic frequency axis with 30 divisions from 20 Hz to 20 kHz. The deviation in the passband is a maximum of 0.3 dB. Taking advantage of the digital signal from the preamplifier, a high-efficiency power amplifier can be developed. A prototype of the preamplifier built with commercially obtainable components has shown promising results
A New Principle for a High Efficiency Power Audio Amplifier for Use with a Digital Preamplifier

The use of class-B and class-D amplifiers for converting digital audio signals to analog signals is discussed. It is shown that the class-D amplifier is unsuitable due to distortion. Therefore, a new principle involving a switch-mode power supply and a class-B amplifier is suggested. By regulating the supply voltage to the amplifier according to the amplitude of the audio signal, a higher efficiency than can be obtained by the current principles is achieved. The regulation can be done very efficiently by generating the control signal to the power supply in advance of the audio signal, made possible by the digital signal from the preamplifier. A prototype shows possibilities for further developments.

A New Principle for an All Digital Preamplifier and Equalizer

A new principle for an all digital preamplifier and equalizer, to be used together with a compact disc player, is described. The principle makes it possible to obtain an arbitrary gain transfer function together with a linear phase. The gain can be varied 20 dB from point to point, when specified on a logarithmic frequency axis with 30 divisions from 20 Hz to 20 kHz. The deviation in the passbands is max. 0.2 dB. Taking advantage of the digital signal from the preamplifier, a high-efficiency power amplifier can be developed. A prototype of the preamplifier built with commercially obtainable components has shown promising results.
Long-Term Cycling of the Magnesium Hydrogen System
Magnesium powder with a grain size of approximately 50 μm was hydrogenated for 30 min and dehydrogenated the same time at 390°C, 515 times. A moderate loss in hydrogen storage capacity was observed and was ascribed to a measured decrease in reaction kinetics as the cycle number increased. The time for maximum hydrogen absorption was found to depend significantly on cycle number while the time for maximum desorption was found to be virtually independent of cycle number.

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