3-D Super Resolution Imaging using a 62+62 Elements Row-Column Array

Jensen, Jørgen Arendt; Schou, Mikkel; Ommen, Martin Lind; Øygard, Sigrid Husebø; Sams, Thomas; Stuart, Matthias Bo; Thomsen, Erik Vilain; Larsen, Niels Bent; Beers, Christopher; Tomov, Borislav Gueorguiev

Published in:
Proceedings of 2019 IEEE International Ultrasonics Symposium

Publication date:
2019

Document Version
Peer reviewed version

Citation (APA):
Abstract—Current 2-D Super Resolution (SR) imaging is limited by the slice thickness determined by the elevation focus. The fixed, geometric elevation focus is often poor due to its high F-number. SR images are, thus, a summation of vessels across the elevation plane without the possibility to track scatterers in 3-D for full visualization. 3-D SR imaging has been obtained by translating the probe, but this does not remove the elevation summation. Full 3-D can be acquired using 2-D matrix probes, but the equipment is expensive, and the amount of data is excessive, when channel data are acquired over thousands of elements for minutes. This paper demonstrates that full volumetric SRI can be attained using a 62+62 channels Row-Column (RC) probe with \( \lambda \) minutes generating Gbytes of data. Currently, most SRI is conducted using 1-D array probes due to the large amount of data generated, and that few scanners are capable of full 3-D imaging.

Visualization of 3-D SR volumes has been performed by several groups using mechanically translated linear array probes [6, 8, 9], but such a setup does not make it possible to estimate the out-of-plane location. SR has also been made by several groups using mechanically translated linear array probes [6, 8, 9], but such a setup does not make it possible to estimate the out-of-plane location. The images are acquired over several seconds to minutes generating Gbytes of data. Currently, most SRI is conducted using 1-D array probes due to the large amount of data generated, and that few scanners are capable of full 3-D imaging.

Currently, the largest research scanners have 1024 channels [11, 12], and they generate around 20-50 Gbytes/s of data for 3 MHz probes, only making short acquisitions possible and precluding the use of high-frequency probes. They can handle 2-D arrays with \( 32 \times 32 = 1024 = N^2 \) elements, which have been fabricated with \( \lambda/2 \) pitch. This makes them suitable for phased array imaging, but severely limits their focusing ability due to their small size and hence high F-numbers.

The problem can be somewhat alleviated by using sparse arrays, and Harput et al. [13] recently used a 512 elements sparse 2-D array based on a spiral pattern to acquire full 3-D SR imaging. Two 256 channels research scanners [14] were used for scanning of 200 \( \mu \)m cellulose tubes with a final localization precision of 18 \( \mu \)m. The main drawback of this approach is the many transducer channels needed to avoid grating lobes and the corresponding large amounts of data generated per second. Further, the probe is quite small.
This paper describes a 3-D SR method based on a Row-Column (RC) array with only 62+62 elements. The approach is implemented using a prototype RC array, and the imaging is conducted using the SARUS research scanner [11]. Its precision is investigated using a 3-D printed micro-phantom and is estimated from the located bubbles in the phantom.

II. METHODS

A. Data acquisition and beamforming

A prototype 3 MHz PZT RC array with 62 rows and 62 columns was used for the data acquisition [15]. It contains amplifiers in the handle and was fabricated with edge apodization to reduce ghost echoes after the main point spread function (PSF) [16]. The probe has λ/2 pitch to avoid grating lobes. It was connected to the SARUS scanner [11], which acquired full RF data for all the receiving channels.

A synthetic aperture, pulse inversion sequence was used for imaging. Transmissions were conducted using the rows, and data were received on all 62 columns. The virtual line sources emitted cylindrical waves [17] in a sequence with 32 positive emissions and 32 negative emission to make pulse inversion imaging possible. The transmit F-number was -1 using 32 Hanning apodized active elements, with the virtual source placed behind the array.

B. 3-D micro-phantom

A flow micro-phantom is fabricated for validating the approach by 3-D printing of a PEGDA 700 g/mol hydrogel using stereo-lithography, as described in [18]. The phantom measures 21.1 × 8.16 × 11.9 mm³, and the voxel size of the printer is (Δx, Δy, Δz) = 10.8 × 10.8 × 20 μm³. The flow micro-phantom contains a single cylindrical 100 μm radius channel placed 3 mm from the top surface of the phantom. After a 5.8 mm long inlet, the channel bends 90° into a 7 mm long central region before bending 90° again into the 5.8 mm outlet. The flow channel is infused at 1.61 μL/s with SonoVue (Bracco, Milano, Italy) in a 1:10 dilution, giving a peak velocity of 102.4 mm/s.

C. Processing pipeline

The beamformed volumes are processed in Matlab using our 3-D SR processing pipeline consisting of three steps. The first is to beamform the stored RF data from the SARUS scanner using the beamforming strategy described by Rasmussen et al. [16, 17] implemented in Matlab and running on an Nvidia GeForce GTX 1050 Ti (Nvidia, Santa Clara, CA, USA) GPU [19]. For the flow micro-phantom the second harmonic signal is employed, and a filter matched to the second harmonic is employed on all the received signals. The GPU beamformer was used for making the focusing of the full volumes for all emissions with an F-number of 1.5 in transmit and 1 in receive with a dynamic Hanning apodization weighting the elements. The volumes with a size of ±15λ in both the x and y directions were beamformed with a line density of λ/2 covering the full depth of the phantom. The sampling density in the z direction is λ/16. All emissions are added to generate the high resolution volume (HRV), and the positive and negative emissions HRVs are added to enhance the bubble signals.

The second step is to subtract the stationary background signal. The mean value of twenty volumes is found and subtracted from all the 400 volumes acquired. The envelope of the HRV is then found using a Hilbert transform and log compressed to a 40 dB dynamic range in relation to the data in the volume for finding locations.

The bubble locations can either be found from calculation of the centroid of local maxima, or the peak locations can be interpolated to increase the location accuracy. Experimentation with the data showed that the interpolation scheme is the most stable and accurate method, and this is the one used in this paper.

The third stage finds bubble locations by interpolating the peak position by fitting a second order polynomial to the data and then finding its interpolated maximum position xi, as:

\[
ix = i - \frac{0.5(d(i+1,j,k)+d(i-1,j,k))}{d(i+1,j,k)-2d(i,j,k)+d(i-1,j,k)}
\]

where i,j,k are the indices of the maximum and d is the envelope data for the volume. This is conducted in all three coordinates xi,yi,zi with similar equations for an increased resolution in all three directions.

D. Statistical evaluation

The detected bubble locations are randomly distributed in the flow micro-phantom tube due to noise in the localization estimation, and some of them will appear to be located outside the phantom wall. The distribution of positions found can therefore yield an estimate of the localization precision. An estimate of the y–z and x–z precision can be obtained from the two straight segments of the 200μm channel phantom. In the straight segments a line is fitted to the data and considered an estimate of the center of the channel, and the distance from each bubble to the center is calculated. Assuming the measurement uncertainty in each dimension is normal distributed, the radial distribution of all bubbles in the segment will follow the distribution

\[
f(r) = \frac{2\pi r}{\lambda R^2} \frac{1}{2\pi\sigma^2} \exp\left(-\frac{|r-R|^2}{2\sigma^2}\right) d^2r,
\]

where r is radial position, R is the radius of the tube, and σ is the standard deviation of the uncertainty. The integral is a convolution of a constant density (1/(πR²)) with a two-dimensional Gaussian. The non-analytical integral (2) is estimated in a Monte-Carlo calculation and is a Rayleigh distribution convolved with a uniform disk distribution of radius R = 100 μm. The fraction of bubbles estimated to fall outside the tube can then be translated into an estimate for the standard deviation σ (localization precision).
initially the penetration depth for the scheme is measured. it

gives a penetration depth of 14 cm (0 db signal-to-noise ratio)
when using a tissue mimicking phantom with an attenuation of
0.5 db/[MHz cm]. the SA imaging sequence and array were
also simulated in Field II [20, 21] and yielded a PSF with a
size of $(1.17\lambda \times 2.12\lambda \times 0.63\lambda)$ at 15 mm.

the resulting 3-D SR image is shown in Fig. 1, where
each blue dot indicates the identification of a bubble. the full
gometry of the phantom can be seen with the inlet and outlet
and the detected bubbles seem confined to the tube.

the localization in the $y - z$ has been investigated by
selecting the bubble only moving in the $x$ direction as is shown
in the top graph in Fig. 2, where blue crosses are the selected
bubbles and red dots indicates all localized bubbles. Lines have
then been fitted to the center of all the locations as shown in
Fig. 3, so the distance from the tube center to the bubble
locations can be found. the radial positions are then found
and shown in Fig. 4. Bubbles inside the tube are marked by
a cross and bubbles outside are marked by a red circle with a
blue cross.

the fraction of bubbles outside the tube, as shown in
Fig. 5, is then an indication of the precision of the bubble
localization as described in Section II-D. the fraction is in
this case 13.0%, which translates to a precision of 16.5 $\mu m$.
the fraction is 18.2% in the $x - z$ plane translating to a
precision of 23.0 $\mu m$. the simulated point spread function
of the imaging setup at this depth is $0.58 \times 1.05 \times 0.31 \text{ mm}^3
(x, y, z)$, which corresponds to an interrogated volume of 0.189
$\text{ mm}^3$. assuming the precision in all three coordinates is 23.0
$\mu m$ gives a volume of 12,167 $\mu m^3$, which is 15,700 times
smaller than for the PSF limited system.

IV. DISCUSSION AND CONCLUSION

A 3-D SR measurement scheme and processing pipeline
have been presented. the approach uses a 62+62 elements RC
probe, where only rows are used for emission and columns
for reception. the scheme employs two times 32 emissions
for pulse inversion imaging attaining a volume rate of 240
Hz down to 5 cm or 85 Hz down to 14 cm, which is the
penetration depth of the imaging scheme.

the major advantage is that the volume is focused in all
three directions including the elevation direction, which yields
a resolution of $(1.17\lambda \times 2.12\lambda \times 0.63\lambda)$ at a depth of 15
mm. this was attained for a modest 62 elements, which
both reduces the amount of data from the probe by a factor
of 8 compared to previous 3-D SRI [13] as well as the
beamforming time for a probe with 4 times the area of a 1024
elements 2-D matrix probe.
The processing pipeline yield a precision of 16.5 $\mu$m in the $y-z$ plane and 23.0 $\mu$m in the $x-z$ plane, which is 15,700 times smaller in volume than for the PSF limited plane. Blue crosses marks the locations of all bubbles and red circles mark bubbles outside the vessel boundary. The beamforming can be attained in near real-time, when $A$ is 15,700 times smaller in volume than for the PSF limited plane. Blue crosses marks the locations of all bubbles and red circles mark bubbles outside the vessel boundary. Fig. 5. Histogram for the bubble radius. The red line indicates the 100 $\mu$m radius of the tube and the fraction of bubbles outside is 13.0%.

Acknowledgement

This work was financially supported by grant 7050-00004B from Innovation Fund Denmark, and from BK Medical, Herlev, Denmark.

References


