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In Vivo 3-D Vector Velocity Estimation with Continuous Data

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Abstract—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 healthy 27-year old female. Based on the out-of-plane velocity in vivo flow phantom and (TO) method was used to estimate 3-D vector flow in a carotid real-time continuous data in one plane. The transverse oscillation is presented. An emission sequence was designed to acquire velocities at very high frame rate using continuous data acquisition.

I. INTRODUCTION

The cardiovascular blood flow is very complex as it propagates in all three dimensions, where short lived vortices can arise and vanish within 100-200 ms [1]. So, to provide the true dynamics of the blood flow, 3-D vector velocities at a high frame rate is therefore necessary. However, current methods for velocity estimations are mainly restricted to 1-D or 2-D methods.

For estimating 2-D vector flow various methods have been proposed, e.g., speckle tracking [2], directional beamforming [3], plane wave emissions as suggested in [4] and transverse oscillation (TO) [5]. 2-D vector flow gives a more realistic picture of the actual flow, but does not provide information about the out-of-plane velocity component.

For realtime out-of-plane velocity estimation, a 2-D transducer is needed. A 2-D piezoelectric transducer was used in previous work, which showed that all three velocity components can be obtained for two crossing planes [6] using a 3-D implementation of the TO method [7] [8] and Provost et al with a similar transducer, estimated the axial velocities in a full volume using Doppler techniques [9].

One method to increase the frame rate significant, is by designing an emission sequence for continuous data acquisition. Continuous data acquisition offers several interesting options; for instance, the frame rates for velocity estimates can be increased to the kH range, which helps to capture complex flow patterns. Second, adaptive velocity estimation algorithms can be applied to create a more complex and dynamic echo cancelling or increase the detectable velocity range under the rapid changing conditions during a cardiac cycle.

This paper presents the results from 3-D vector velocity estimation using continuous data in both an experimental setup and for an in vivo measurement. The out-of-plane velocity components is in both cases used to derive the flow rates. With the applied emissions sequence, ultrafast frame rates up to 2.1 kHz was obtained. In combination with the TO method, both slow flow in the end-diastole and fast flow in the peak-systole could be detected.

II. MATERIALS & METHODS

This section describes the continuous 3-D method. It introduces the equipment, emission sequence, data processing, and theoretical properties of the TO velocity estimator. The basic principles of the TO method is described in [5][10].

A. Emission sequence

In Fig. 1 an illustration is seen of how the applied sequence was designed to yield continuous data. The idea is that the duration between emissions of two identical flow lines $F_i$ should be the same at all times. This could for instance be achieved by emitting the flow lines $F_i$-5 consecutively, followed by emitting the B-mode line $B_1$. Next, the flow lines $F_{i-5}$ would be emitted again, followed by the B-mode line $B_2$ etc. When the desired amount of B-mode lines $B_n$ has been reached, the sequence repeats itself from the beginning. The number of unique B-mode emission $B_N$ was set to 64 in all measurements. A schematic representation of an emission sequence is

$$F_1 \rightarrow F_2 \rightarrow F_3 \rightarrow F_4 \rightarrow F_5 \rightarrow B_1 \rightarrow$$
$$F_1 \rightarrow F_2 \rightarrow F_3 \rightarrow F_4 \rightarrow F_5 \rightarrow B_2 \rightarrow$$
$$\vdots \vdots \vdots \vdots \vdots \vdots$$
$$F_1 \rightarrow F_2 \rightarrow F_3 \rightarrow F_4 \rightarrow F_5 \rightarrow B_N \rightarrow$$

This would produce continuous flow data and one or multiple continuous B-modes images if desired.
limit were
of 16 elements between. From [10], the maximum transverse
directions two rect profiles spanning 8 elements with a spacing
between the two peaks in the receive apodization in the
depth of the beamformed RF-line and
where
beamformed along the lines separated spatially by their re-
were found by using the TO method [5] [10].

The two transverse velocity components
from F
followed by a B-mode line B
. This continues until
are only for illustrative purpose and not to scale.

B. Velocity estimators

The axial velocity estimates were based on the autocorrelation
approach [15], and the two transverse velocity components
were found by using the TO method [5] [10].

For each transverse velocity estimate two TO beams were
beamformed along the lines separated spatially by their re-
spective transverse wavelengths
/ 4 or
/ 4, thereby
generating two fields phase-shifted by 90°. The two transverse
wavelengths are theoretically given by

\[
\begin{align*}
\lambda_x(z) &= 2\lambda_z \frac{z}{d_x} \\
\lambda_y(z) &= 2\lambda_z \frac{z}{d_y},
\end{align*}
\]

(1)

where \( \lambda_z \) is the wavelength of the emitted pulse, \( z \) is the axial
depth of the beamformed RF-line and \( d_x, d_y \) are the distances
between the two peaks in the receive apodization in the \( x \)-
and \( y \)-direction. The apodization used in receive was in both
directions two rect profiles spanning 8 elements with a spacing
of 16 elements between. From [10], the maximum transverse
velocities that could be estimated without reaching the aliasing
limit were

\[
\begin{align*}
v_{x,\max} &= \frac{\lambda_z}{4k} f_{prf} \\
v_{y,\max} &= \frac{\lambda_y}{4k} f_{prf},
\end{align*}
\]

(2)

where \( k \) is the lag used in the autocorrelation and \( f_{prf} \), is
the effective pulse repetition frequency between two emissions
of the same flow line.

C. Measurement setup

The experimental ultrasound scanner SARUS [11] with
1024 channels in receive and transmit was used along with a
Vermon 3.5 MHz, 0.3 mm pitch, 0.278 mm height 32x32
element 2-D phased array transducer (Vermon S.A., Tours,
France) for data acquisition. See Table I for transducer specifi-
cations. The emitted frequency was 3.0 MHz, to avoid grating-
lobes and reduce transducer heating. Data was sampled from
all 1024 channels and stored for offline processing on a Linux
cluster.

The employed 2-D matrix probe contains, due to con-
struction issues, three inactive rows in the \( x \)-direction. The
dimensions of the actual transducer is therefore 35x32 with
the active aperture being 32x32.

D. Setup for flow pump measurements

For the phantom measurements a predefined pulsating
carotid flow profile was generated with a flow pump (Com-
puFlow 1000 System, Shelley Medical Imaging Technolo-
gies, Ontario, Canada) containing blood mimicking fluid with
backscattering coefficient equivalent to blood cells. With the
included software CompuFlow 1000 System, a carotid flow
profile was generated with a cycle time of 0.84 s and a flow
rate of 3.06 ml/s ± 0.09 ml/s. A blood mimicking fluid was
pumped through a carotid phantom (Danish Phantom Design,
Frederikssund, Denmark) with a diameter of 0.8 cm located
at a depth of 2.7 cm. Properties for the sequence used for
the experimental setup can be seen in Table I.

E. Clinical setup

Intensity measurements to ensure compliance with the FDA
limits, were performed for the \textit{in vivo} sequence. The derated
mechanical index (MI) was 1.29 and the pulse repetition
frequency \( f_{prf} \) was scaled to 12.6 kHz to obtain \( I_{spta,3} =
720 \text{ mW/cm}^2 \) in accordance with FDA limits. The \textit{in vivo}
measurement was performed on a healthy 27-year old female
who had been resting for 15 minutes before measurements
were conducted to ensure a steady flow. The scans were
performed by an experienced radiologist. Properties for the
\textit{in vivo} sequence are summarized in Table I as well.

III. DATA PROCESSING

The stored data was processed offline. The raw RF data
was match filtered and Hilbert transformed before the IQ data
was beamformed with the Beamformation Toolbox 3 [12]. In
this part, the three velocity components were decoupled, such
that one line was beamformed for the axial velocity estimation
and two dedicated lines were beamformed for each of the two
transverse velocity estimates. In total five unique beamformed
lines were used to estimate the 3-D velocity vector for each
flow line. Due to the asymmetric geometry of the transducer,
two different transverse wavelengths \( \lambda_x \) and \( \lambda_y \) used
for the velocity estimator. The applied transverse wavelengths
were \( \lambda_x = 3.42 \text{ mm} \) and \( \lambda_y = 3.90 \text{ mm} \) for the experimental
setup and \( \lambda_x = 1.98 \text{ mm} \) and \( \lambda_y = 2.18 \text{ mm} \) for the \textit{in vivo}
measurements at the depth of 2.7 cm and 1.5 cm respective.
For a more extensive description of the employed 3-D TO
method, see previous work [13],[7],[8]. Echo cancellation of
the beamformed data was subsequently performed with a low
frequency Doppler filter algorithm [14].
IV. RESULTS

In this section, results from the two conducted experiments are presented. First, results from the flow pump experiment are presented, and thereafter results from the in vivo experiment.

A. Flow pump measurements

From the experimental setup with the flow pump, four seconds of continuous data at 625 Hz was acquired corresponding to 4.8 cycles. Based on a B-mode image showing the cross-sectional view of the vessel, a mask was manually drawn to segment out an area used for velocity estimates. Out-of-plane velocities were calculated in the selected area and the flow rate through it was estimated. The calculated flow rates are seen in Fig. 2. From the known cycle time of 0.84 s, the data set was divided into four phase coherent cycles, and the mean and standard deviation (SD) were calculated. The average flow rate of the profile in Fig. 3 was 2.96 ± 0.35 ml/s compared with the theoretical average flow rate of 3.06 ml/s ± 0.09 ml/s.

B. In vivo measurements

From the 3.07 seconds of continuous data obtained at 2.1 kHz, three complete heart cycles could be identified. As expected the highest peak velocities were found for the center flow line, which propagated closest to the center of the vessel. Peak out-of-plane velocities in each cycle were 83 cm/s (t = 0.69 s), 87 cm/s and 90 cm/s (t = 2.55 s) based on an M-mode view. Based on the average time between these peak velocities, a heart cycle time of 0.93 s giving a heart rate of 64 beats/min was found. This heart cycle time was used in future calculations.

The discriminated velocity estimates for all three components were then scan converted and interpolated yielding a complete 3-D vector velocity map at each time instance. The data set was divided into three subsets each of length 0.93 s. The mean 3-D vector velocities during one cycle was then found by calculating the average velocity estimate for all three velocity components across the three sub-samples. In Fig. 4 3-D vector velocities averaged over three heart cycles at the identified end-diastole are presented. The magnitude of the velocity vector \(|\mathbf{v}| = \sqrt{v_x^2 + v_y^2 + v_z^2}\) was found to be 17.0 cm/s in the center of the vessel. The highest center velocity for \(|\mathbf{v}| = 81.6 \text{ cm/s}\) was identified as the peak-systole. Spatial variance in peak velocity between each heart cycle and a slightly variance in the heart cycle time results in an average \(|\mathbf{v}|\) during peak systole that is lower than the peak \(v_z\) velocities during each of the three heart cycles. The 3-D vector velocity map is seen in Fig. 4. Based on the cross-sectional area and the out-of-plane velocity component, the estimated mean average flow rate was 257 ml/min. In the literature the corresponding flow rate from the carotid artery found with spectral Doppler for a healthy person is 334 ml/min [16].

V. DISCUSSION & CONCLUSION

The presented results showed that 3-D vector velocities at very high frame could be obtained when acquiring continuous data. In combination with the TO method, both the slow and fast flow could be detected in pulsating flow setups. The TO method was applicable for estimating accurate flow rates in an experimental setup with a flow pump generating a carotid flow profile.
The presented method offers a unique possibility to study complex flow pattern in 3-D, even when slow and fast flow is present. Furthermore, accurate angle-independent flow rates and peak velocity estimates can be derived from the 3-D vector flow. However, further validation of the method against e.g. similar MRI estimates are needed to clarify the accuracy and potential for clinical use.

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REFERENCES


