Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

3D+t Vector Flow Imaging with Transverse Oscillations and Doppler Estimator

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***Abstract*—Blood flow evaluation with ultrasound is an extremely usefull tool in the clinics in many different situations. The evaluation of the real 2D or 3D flow direction and amplitude remains an unsolved issue and a challenge to access to the full and correct flow characteristic. In this paper, an advanced 3D ultrasound system is used to estimate the 3D blood flow in an home made phantom with a laminar flow. After the acquisitions, the 3D processing of the beamformed volumes allow the creation of transverse oscillations and motion estimation in several direction to create a complex vector flow map in 3D. The obtained streamlines are coherent through the cycle and the qualitative evaluation of the flow is possible, even in direction perpendicular to the US beam axis. The proposed set-up and method must be evaluated more deeply in more complex geometries, but this work demonstrates the feasibility to use such advanced system in 3D+t flow evaluation.**

keywords: 3D ultrasound imaging, transverse oscillation, motion estimation, vector flow imaging

I. Introduction

Motivated by all the potential applications, imaging with ultrasound (US) the blood velocities in 3D in a wide volume of interest is one objective our community has been striving for since many years. Lately, the development of open 3D ultrasound systems has made it possible to perform 3D dynamic ultrasound volume acquisitions along time, at a high frame-rate [1]–[4]. This high performing system in terms of electronics and programming flexibility could control several hundreds of channels in both transmit and receive. Coupled with matrix arrays that are more and more available, such kind of imaging becomes now possible.

To evaluate the blood flow, several methods have been proposed in the literature, as classical phase-shift strategy [5]. However, such mathematical formulation project the velocity on the US beam direction, which lead to a biased estimation of the flow and no evaluation when the flow is perpendicular to the US beam. To overcome such limitations, several strategies have been proposed, mainly in 2D US imaging and are based on 2D speckle tracking [6], directional beamforming and classical Doppler estimator [7] or transverse oscillations [2].

Our objective was to develop and validate a full 3D+t US plane wave sequence for 3D blood flow imaging. Given the size of the footprint of 2D matrix array used in this study, the directional beamforming strategy appears to be strongly limited. Indeed, such beamforming depends of a small F-number which is adapted in function of the spatial pixel to beamform. For this reason, the transverse oscillations scheme will be evaluated experimentally for the proposed objective. The estimation of this pipeline was already proposed in simulation, but its experimental validation is still under investigation [8].

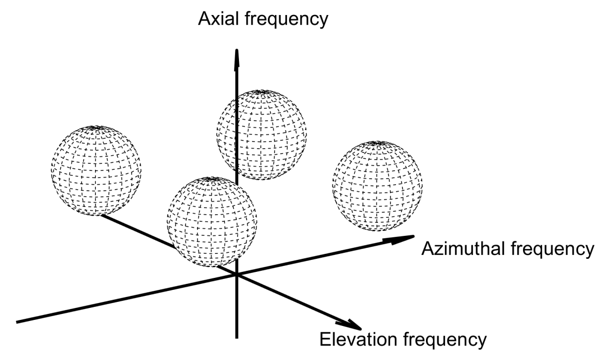


Fig. 1. Illustration for positive axial frequencies of the used masks to create the four volumes exhibiting lateral oscillations for the motion estimation.

In this paper, we propose a 3D blood flow evaluation on an advanced US system. A first section presents the used methods and materials for the acquisitions, then the results are drawn. A discussion concludes the paper.

II. Materials and Methods

A. Methods

The transverse oscillations strategy relies on a specific post-processing to create oscillations in the lateral direction of the beamformed images. Indeed, given an US wave, oscillations are naturally present along the US beam direction, but not in the lateral one. Two methods can be used to create the oscillations: specific beamforming of the raw signals [9] or filtering in the Fourier domain of the beamformed volumes [10], [11]. In this work, the filtering approach has been selected and oscillations have been created in both lateral and azimuth directions. For the axial oscillations, the beamforming was conducted in the RF domain to use this natural oscillations.

After beamforming, the axial velocity was estimated using conventional Doppler. Then, the volume is filtered four times

TABLE I
ACQUISITION PARAMETERS

Probe parameters	Value
Pitch	300 μm
Central frequency	3 MHz
Number of elements	32×32
Imaging parameters	**Value**
Sampling frequency	12 MHz
Number of cycles	8-cycle sinusoidal pulse
Transmission	one not-angled plane wave
PRF	3000 Hz
Maximal depth	40 mm
Post-processing parameters	**Value**
Packet size	32
Reconstructed volume dimension	$101 \times 101 \times 256$ voxels
Reconstructed volume dimension	$10 \times 10 \times 30$ mm
Lateral frequency	166 Hz
Standard deviation of oscillations	1000 Hz

with Gaussian windows to create the 4 IQ/RF volumes to create the lateral and azimuth oscillations. Filtering is made in either upper/bottom part of the spectrum and in the left/right part. An illustration of the mask applied in the Fourier domain is proposed in Figure 1. Then, conventional Doppler is one more time used in each IQ/RF volume to extract the phase shift in this four volumes. The phase shifts are combined to estimate the correct speed using the following equations:

$$\begin{cases} v_{elevation} & = (\phi_{UpperRight} - \phi_{LowerRight})/2 \\ v_{zeimuth} & = (\phi_{BottomRight} - \phi_{BottomRight})/2 \end{cases} \quad (1)$$

B. Material

To evaluate the proposed strategy, a home made blood flow phantom has been used. It is composed of a PVA tube in which the flow could circulate in a stable or pulsed configuration thanks to the multi-flow pump (GAMPT). The US acquisition is conducted by the synchronisation of 4 Vantage 256 systems (Verasonics Inc., USA) which allow to control in both transmit and receive 1024 elementary transducers. Then, a matrix probe of 32x32 elements probe was used. A quarter of the probe is connected to each system to image the phantom. In order to achieve the maximum possible frame rate, 3D plane wave excitation (no angle) with a 3000 Hz pulse repetition frequency (PRF) was used. 1600 volumes have been acquired, leading to 0.53 s of circulating flow in the PVA phantom. Then, 50 vector flow estimations are conducted using a packet size of 32 and non-overlapping estimation. The general parameters for the transmission and the reception are summarized in Table I.

III. RESULTS

After the transmission, the data are stored and reconstructed off-line. The reconstruction and the oscillations parameters are summarized in Table I. On the initial beamformed volume, the power Doppler is also evaluated. Moreover, the five Doppler variance volumes, computed on the initial volume and the four transverse oscillations ones, obtained during the Kasai Doppler phase shift calculation, are coupled to segment the reconstruct volume and keep the 3D vector flow only inside the tube.

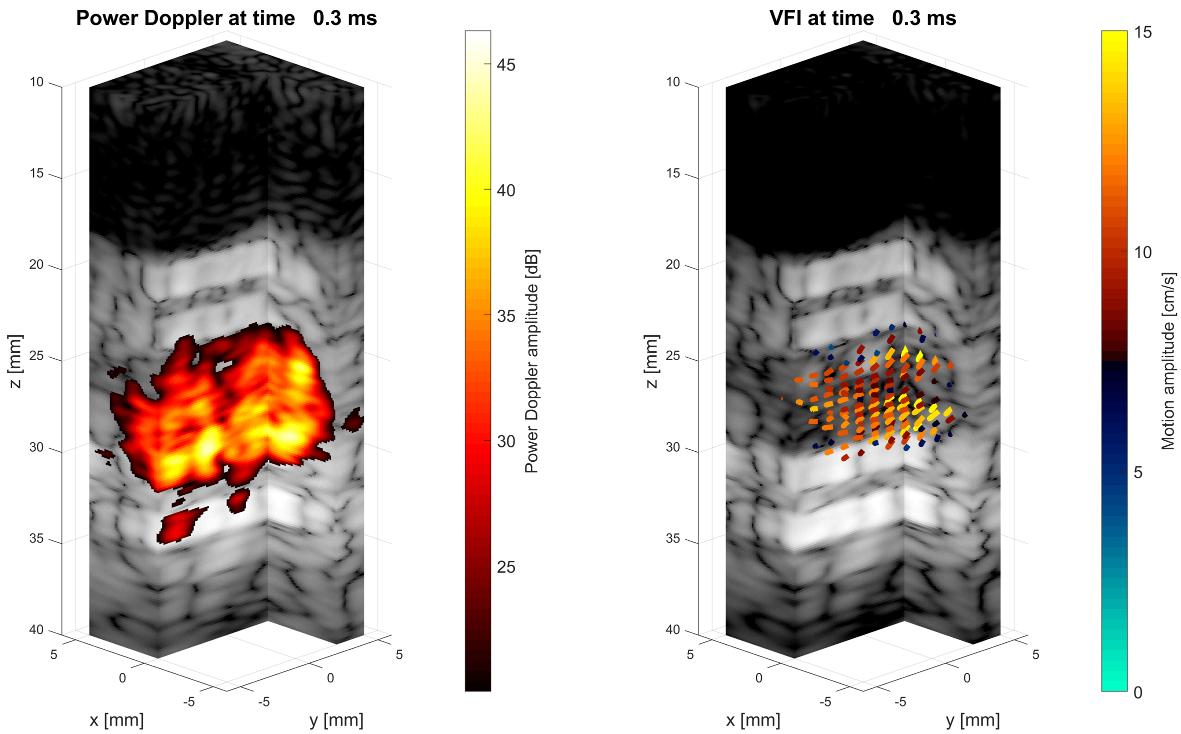
A first result of the processing pipeline is proposed in the Figure 2. In Figure 2.a, the obtained Power Doppler highlights the region where the vector flow will be extracted. In Figure 2.b, the arrows represent the 3D direction of the flow and the velocity amplitude is coded in colours. It can be noted that the flow is correctly evaluated in the horizontal direction of the tube. Moreover, the evaluation is correct even if the flow is in a direction which cannot be evaluated in classical Doppler techniques (flow perpendicular to the US beam axis). Another representation of the flow is proposed in Figure 3. The flow amplitude is coded in colours and the direction follows our proposed fibre representation [12]. The measured velocity direction is well in agreement with the experimental settings. The amplitude velocity, projected on the streamlines, highlights a maximum velocity in the central part of the tube. The measured velocity through the cycle is stable, as presented in three distinct instants. Similar conclusions and rendering are obtained when the local orientation is projected on the streamlines.

IV. DISCUSSION AND CONCLUSIONS

In this paper, we present a full post-processing strategy to compute the 3D vector flow maps using an experimental 3D system and a home made phantom. The transmission is restricted to one unique untitled plane wave in order to keep the frame rate as high as possible. The processing is based on a transverse oscillations mathematical background and classical Kasai Doppler estimator. The different estimations are coupled to extract the complete 3D flow orientation and amplitude. The proposed first results obtained in this work demonstrate the potential of this strategy and its qualitative interest thought the proposed renderings.

To compute the 3D orientation, the filtering in the Fourier domain is a sensitive step. Indeed, the central frequency and the standard deviation is very complex to select in order to create the correct oscillations and to ensure that enough signal is kept in the spectrum. Coupled with the fact that the transmitted/received energy in 3D US imaging is quite low, the reduction in the Fourier domain of the energy makes the whole very challenging. The lateral frequency, sued to create the oscillations, is assumed constant for the entire volume. Moreover, during the acquisition, the PRF is limited by the synchronisation of the 4 Vantage systems. Even with the low central frequency of the 3D probe (3 MHz), the maximum potential velocity that can be evaluated with the Kasai estimator is limited (38 cm.s^{-1}). In the flow pump, the velocity in unknown during the acquisition. The balance between the maximum velocity estimated though our strategy and the flow inside the tube must be carefully selected.

Future work will consist to run the same acquisition with a calibrated flow inside the tube in order to have access to the ground truth and to evaluate quantitatively the accuracy of our 3D vector flow evaluation. Last, the plane wave transmission limits the field-of-view that can be estimated. The increase of the field-of-view through diverging wave transmission has



(a) (b)

Fig. 2. Illustration of the 3D (a) Power Doppler and (b) vector doppler obtained at 0.3 ms. Even with horizontal flow, the 3D VFI allows to extract a flow inside the PVA tube.

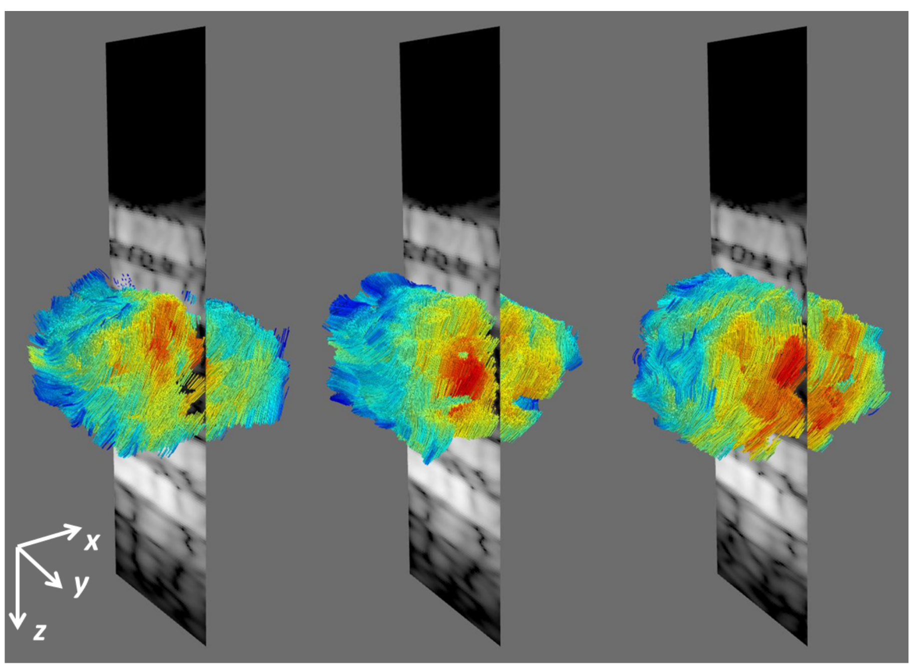


Fig. 3. 3D Vector flow imaging of the PVA phantom in three distinct instants. The colours on the fibre represent the local flow amplitude.

to be evaluated. However, the impact of this transmission modification in the methodology has also to be investigated.

ACKNOWLEDGMENT

This work was performed within the framework of the LABEX PRIMES (ANR-11-LABX-0063) of Université de Lyon, within the program "Investissements dAvenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR). The RF Verasonics generator was cofounded by the FEDER program, Saint-Etienne Metropole (SME) and Conseil General de la Loire (CG42) within the framework of the SonoCardio-Protection Project leaded by Pr Pierre Croisille. The authors would like to thank LabTAU for their contribution in the development of the 32x32 probe prototype compatible with a driving by 1 to 4 Verasonics Vantage 256 as well as for the provision of the probe and two Vantage 256 systems.

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