Imaging of complex blood flow with ultrasound: development of a novel simulation environment

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I. Introduction

Current ultrasound imaging techniques are insufficient to picture blood flow. In clinical practice, ultrasonic blood flow imaging consists of one-dimensional (1D) velocity estimation while complex 3D flow is often present in diseased arteries. In this work, a novel simulation environment is presented to validate and develop new ultrasonic flow imaging algorithms. The simulation tool integrates ultrasonic imaging simulations with computational fluid dynamics, which allows obtaining realistic images of complex flow.

Common vascular diseases are most often caused by atherosclerosis, a stiffening of the arterial wall, which appears to preferentially originate in disturbed flow fields. Efficient imaging of these disturbed flow fields may help in improving preliminary diagnosis of arterial disease, as well as contribute to the understanding of the origin and progression of cardiovascular disease.

The clinically used flow imaging techniques are based on estimating the time shift of the backscattered ultrasonic waves due to reflection on the moving red blood cells. Two common methods are pulsed wave Doppler and color flow imaging. The pulsed wave Doppler method is used to obtain velocity information at a specific location with high temporal resolution. Color flow imaging is applied if one desires high spatial resolution, with the velocities color coded to enhance interpretation. Both techniques have important limitations since they only image the velocity component in the scanning (=axial) direction and the measurable velocity range is limited by aliasing. Hence, 2D or 3D flow imaging methods which overcome these limitations are necessary and a simulation environment is desired to validate and develop new imaging algorithms.

II. Methods

The Field II software was used to compute ultrasonic fields [1,2], which allows modeling arbitrary probes and implementing realistic scanning sequences. The scattering centers (red blood cells) are modeled as randomly distributed point scatterers. The position of the scatterers can be updated for every emitted beam. Up until now, the scatterer movement has been analytically described and complex flow imaging could not be simulated. Realistic flow fields can be obtained with computational fluid dynamics (CFD), which solves the non-linear equations for conservation of mass and momentum in a discretized form. Hence, a coupling between computational fluid dynamics and ultrasonic simulations is necessary to simulate realistic flow images. In this work, we focused on the carotid artery since this is a location easily accessible with ultrasound and prone to atherosclerosis. A carotid geometry was reconstructed from MRI scans and as boundary conditions for the CFD simulations, we used a velocity profile measured in a healthy person and a 45-55% outflow division between the branches of the bifurcation.

Integration of CFD and ultrasound implies that the velocity on the CFD grid points has to be interpolated in 3D space and time. This because the scatterers are randomly distributed in space and because the time scale of ultrasonic imaging is much smaller than in CFD. A realistic ultrasonic probe and scanning sequence was implemented.

III. Results

The simulation environment was validated in a straight tube with a stationary parabolic velocity profile (V_{max} 50 cm/s). The velocity profile was estimated along a cross-section and the mean standard deviation and bias was 8.25% and 5% compared to V_{max}.

The clinically relevant setting of a stenosed carotid artery was investigated with both color flow images (CFI) and pulsed wave Doppler results of the complete cardiac cycle. The right column of fig.1 shows contourplots of the ultrasound (US) estimated velocities during 3 frames which are compared to CFD results in the left column. These dynamic CFD contourplots show the axial velocities at the same times and locations of the ultrasonic scanning. The contourplots reveal that the relatively long scanning time is an important limitation. This is clearly seen in frame 1 of figure 1: in the same image, low velocities are present in the main branch and high velocities can be noticed in the outlet branches.

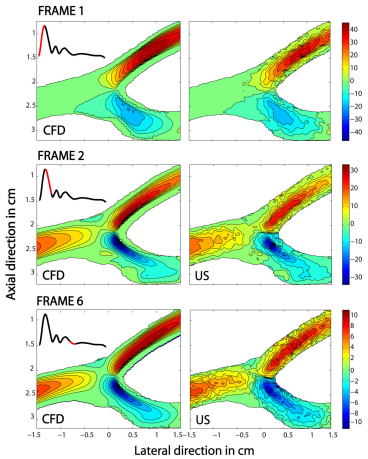

Figure 1. Contourplots for 3 frames of the cardiac cycle with the left column the CFD velocities and the right column the US velocities, displaying the flow field in the scanning direction.

Another limitation of the current flow imaging techniques is the 1D-nature of the measurements, as can be seen in figure 2. Conventional color flow image are displayed with the axial velocities color coded: red are velocities towards the probe and blue away from the probe. The lower panels show dynamic CFD vector plots with the velocity components in the imaging plane displayed at the same moments as in the CFI image. In the bifurcation, the CFD info reveals complex flow with vortices in frame 2 and 6, which however can not be univocally derived from the color flow image. The simulation environment was further validated with pulsed wave Doppler simulations showing good performance of the tool for high temporal resolution.

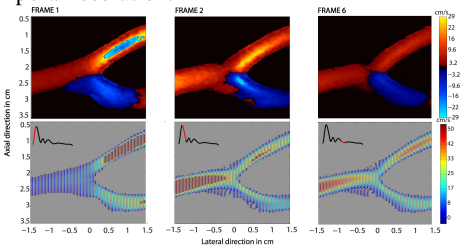

Figure 2. The upper panels show conventional CFI images which are compared to dynamic CFD vector plots in the lower panels during 3 frames of the cardiac cycle.

IV. Conclusion

A simulation environment to validate and develop ultrasonic flow imaging algorithms was presented. The limitations of current flow imaging methods were demonstrated in the clinically relevant setting of a stenosed carotid artery, with the scanning time and 1D nature of the measurements as main focus. Current and future works consist of using the simulation environment for testing and developing 2D and 3D flow estimators.

References

[1] J. A. Jensen, *Field:A program for simulating ultrasound systems*, Medical & Biological Engineering & Computing, vol. 34, pp. 351-353,

[2] J. A. Jensen, N. B. Svendsen, *Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers*, IEEE Trans. Ultrason., Ferroelec., Freq. Contr., vol. 39, pp. 262-267, 1992.