Vortex ring phantom for investigation of ultrasound Vector Flow Imaging

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***Abstract*— High frame rate ultrasound allows accurate quantification of the velocity flows, which could improve the current measurements that assist clinicians in diagnosis. The validation of novel approaches is essential before considering their translation to clinical ultrasound. To achieve this, we propose to use a vortex ring phantom, which presents two advantages. First, it offers complex three-dimensional flow patterns that closely reproduces intracardiac flow jets. Second, it is supposed to be controllable, reproducible and transportable, which is of key importance when validating new techniques. In this context, our objective was to evaluate if such a vortex phantom is a good candidate for validating and optimizing high-frame-rate velocity estimation methods. The 2D vortex kinematics was successfully recovered using speckle tracking and Doppler estimates. A good correlation (r^2 = 0.95) was found between the rotational and the translational velocity components for 315 estimations. Our preliminary 3-D results showed that Doppler velocities can be estimated in both sagittal and axial planes at thousands of volumes per second. In conclusion, the vortex phantom can be considered as a good candidate for testing novel high-frame-rate velocity estimation approaches.**

Keywords—high-frame-rate imaging, vortex ring, vector flow, speckle tracking, Doppler

I. INTRODUCTION

The emergence of high-frame-rate ultrasound imaging has enabled significant progress in blood flow quantification, as it makes it possible to acquire wide field of views at fine temporal steps. Before considering bench-to-bedside translation, there is a need in evaluating the multi-component time-resolved velocity fields provided by the new imaging methods. *In vitro* test objects can be used to perform such an evaluation, since they provide realistic experimental conditions.

Several test devices have been proposed over time. A simple example is given by the flow tubular phantoms through which a blood mimicking fluid is usually pumped [1], [2]. Although the first attempts used c-flex rubber for constructing the walls of the vessels, this material caused a distortion of the ultrasound waves [3], which motivated the use of the vessel mimicking materials [4], [5]. Even if these phantoms provide a suitable experimental model, having acoustic properties similar to those of soft tissues, they do not take into account the major anatomical features, such as arterial branching. In order to cope with this limitation, carotid bifurcation test objects have been proposed, which increases the complexity in terms of both anatomy and blood perfusion [6], [7]. Aneurysm aorta phantoms have also been proposed to reproduce realistic physiological conditions [8]. Other authors focused on developing rotating disk phantoms [9] enabling a wide range of velocity amplitudes and directions, as encountered in an *in vivo* flow. Additionally, assessing three-dimensional flows has become possible thanks to the *in vitro* spiral-flow model proposed by [10].

Although significant progress has been made for increasing the complexity of test objects and providing realistic physiological flows, the above mentioned phantoms are still insufficient to characterize a distinguishing feature of the intraventricular flow: the formation of vortices. The vortex dynamics has been shown to reveal physiological conditions that could allow early identification of cardiac abnormalities [11]. A realistic test object that simulates the left heart circulation and the vortex formation has been proposed in [12]. Although this phantom was successfully used to test vector flow mapping with conventional ultrasound [13], this *in vitro* model has the disadvantage of not being easily controllable and transportable. The vortex ring phantom proposed in [14] overcomes these limitations by offering a stable, reproducible and controllable model. Moreover, it makes it possible to generate vortices at different sizes and velocities. Thus, it provides a number of features that are of high relevance for the validation of high-frame-rate vector flow imaging by ultrasound [15].

In this context, the objective of this preliminary study was to evaluate if the vortex ring phantom is a good candidate for quantifying complex flows using high-frame-rate ultrasound methods. To achieve this purpose, we carried out 2-D and 3-D experiments.

II. METHODS

A. Vortex Ring

A vortex ring is a toroidal volume of fluid moving along the axis perpendicular to the torus plane (x-axis). The velocity along this axis (V_{trans}), represented in red in Fig. 1, is called “translational” in this manuscript. The toroidal vortex ring moves together with a flattened ellipsoidal volume which embraces it, called vortex atmosphere. Inside the vortex atmosphere, the fluid circulates along the closed streamlines surrounding the toroidal core [16]. The toroidal core is constituted by concentric circles rotating at the angular velocity ω. The angular velocity together with the radius of the concentric circles give the rotational velocity, V_{rot}, as represented in green in Fig. 1.

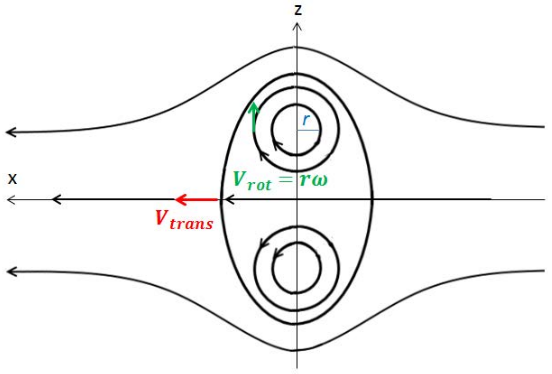

Fig. 1. Streamline pattern of the vortex ring

A vortex ring can be generated by using a cylinder-piston mechanism that ejects the fluid through a circular orifice. Such a system was proposed in [14]. The phantom used in this study was a recent prototype developed by the same authors.

B. 2D Acquisition set-up

Ultrasound 2-D images were acquired using a Vantage 256 research scanner (Verasonics Inc., Redmond, WA) controlling a 5-MHz linear transducer (ATL L7-4, 128 elements). We located the probe at approximatively 10 cm downstream of the orifice, as shown in Fig. 2 A. Series of unsteered plane waves were transmitted through the seeded fluid and sets of vortex images were acquired through the plane illustrated in Fig. 2 B.

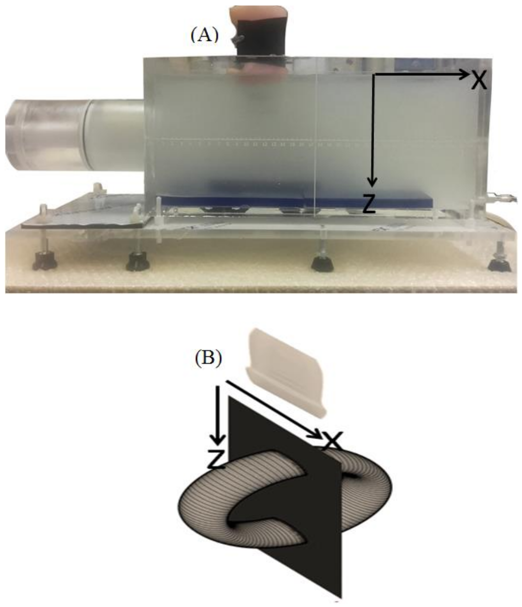

Fig. 2. The probe was located at approximatively 10 cm downstream from the orifice (A), which allowed imaging vortex planes, as showed in (B)

C. 3D Acquisition set-up

Ultrasound volumes were acquired using four Vantage 256 scanners (Verasonics, Kirkland, WA, USA), synchronized to control a 3-MHz matrix-array transducer (Vermon, Tours, France). For more details about the 3D system, the reader can refer to [17].

D. Flow velocity estimation

Regarding 2D acquisitions, we estimated the vortex velocity fields using 1) echo-PIV by tracking the real-envelope speckle patterns using phase correlation [18]; and 2) a classical Doppler estimator based on a 2D autocorrelator applied on the I/Q data.

Since we did not have a reference at the time of the acquisitions, we acquired multiple sets of acquisitions to investigate the theoretical relationship between the vortical rotational and translational velocities. The maximum rotational component was retrieved from the Doppler velocity estimates. A series of successive Doppler maps were used to retrieve the translational component through a phase correlation method. Several diameters and velocities (2 and 2.5 cm, 1-7 cm/s) of the vortex phantom were used for this analysis. We acquired a total of 21 datasets consisting of 49 frames each. For each dataset, we estimated 15 pairs of rotational-translational velocity components.

Finally, regarding 3D acquisitions, we estimated Doppler velocity fields using a 2D autocorrelator, as for the 2D experiments.

III. RESULTS

A. 2D results

The velocity maps are shown in Fig. 3 for both Echo-PIV (A) and Doppler (B).

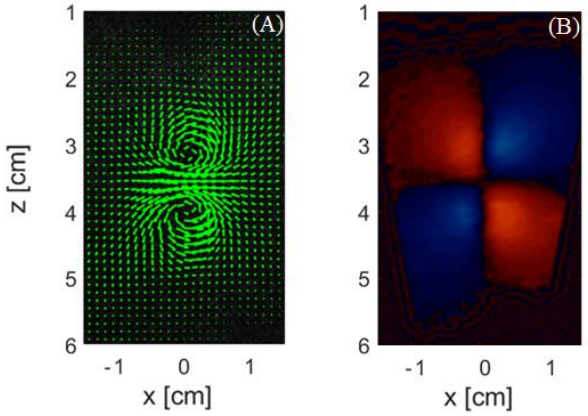

Fig. 3. Velocity estimation using Echo-PIV (A) and Doppler (B) for a translational velocity of 4 cm/s

The link between the rotational and translational velocity is shown in Fig. 4, where each set of points corresponds to a different set of acquisitions, acquired for a different translational velocity (between 1-7 cm/s) and for one of the two diameters: 2.5 cm (blue) and 2 cm (black). For each set of acquisitions, we show the median over 15 estimates and their deviation from the median (calculated as the absolute difference between median and the min/max estimated value over the 15 pairs). The regression curve between the two velocity components is shown in red.

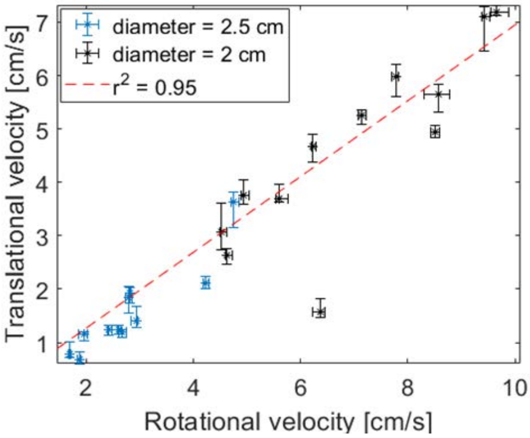

Fig. 4. Linear relationship between the rotational and the translational velocities for 2 orifice diameters (2.5 cm and 2 cm)

B. 3D preliminary results

Fig. 5 shows the Doppler maps obtained from a volumetric insonification of the vortex ring. Both *x-z* and *y-z* velocity maps are provided.

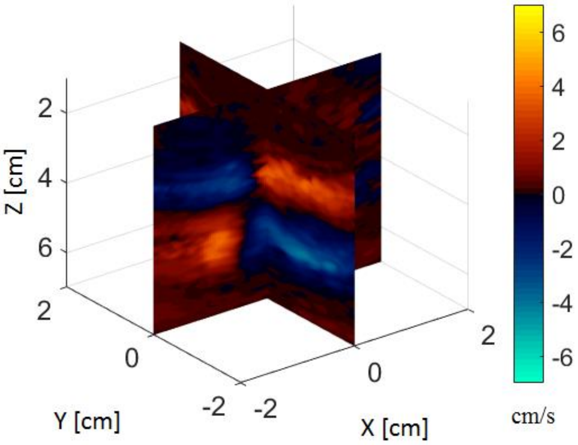

Fig. 5. 1D Doppler velocity components for the *x-z* and *y-z* planes

IV. Discussion

Our preliminary results showed consistent observations with regards to the geometry and kinematics of the toroidal vortices, which tends to confirm that high-speed echo-PIV and Doppler by ultrafast ultrasound can be successfully used to evaluate the dynamics of cardiac-type vortices (Fig. 3). When the link between the rotational and translational speeds was investigated, the two velocity components were highly correlated (r^2 = 0.95, Fig. 4), in accordance with theory [19]. Although this shows a stable phantom behavior at a given position of the vortex propagation, a limitation of this study is that we did not compare our results with a reference. When developing new imaging-based diagnostic tools, the evaluation of their accuracy and reproducibility is of paramount importance. Indeed, this can have a significant impact on clinical decision. This is the reason why the knowledge of the ground-truth velocities is necessary; Therefore, an important perspective of this study will be the comparison of the ultrasound results against velocities yielded by an analytical model or computational fluid dynamics. Ground-truth velocities can also be given directly by optical particle image velocimetry [20]. We also plan to design an MRI-compatible prototype to allow comparison against an alternative imaging modality, as done for vorticity in [21].

In spite of the current difficulty in providing a quantitative measure of accuracy, our promising 2D results in revealing the vortex kinematics, motivated us to extend our study to 3D. As observed in Fig. 5, in addition to the axial Doppler velocity components available when using a linear array (Fig. 3 B), the acquisitions with the 2D array allowed us to compute the sagittal Doppler components. Extending further the Doppler and the echo PIV approaches to 3D could offer a complete three-dimensional three-component vector field.

Although the 2D and 3D results presented in this study are preliminary, we illustrated the compatibility of the vortex ring generator with the ultrasound system.

V. Conclusion

High-frame-rate ultrasound can be used successfully to estimate complex vector flows such as the ones characterizing the ring vortices. 2D echo PIV and the Doppler estimator appear to be able to recover the vortex velocity maps. Preliminary 3D Doppler results showed that the Doppler velocities on both *x-z* and *y-z* planes can be recovered from series of volumetric insonifications.

Overall, this study showed that the vortex ring phantom is a good candidate for optimization and validation of ultrasound flow imaging methods in controllable, non-stationary, three-dimensional complex flows.

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