EXPERIMENTAL INVESTIGATION OF 3D LEFT VENTRICULAR FLOW USING A NOVEL MULTIPLANE SCANNING STEREO PIV SETUP

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INTRODUCTION

The spatiotemporal characteristics of the intraventricular flow field are of (patho)physiological and clinical interest [1]. This is shown in several recent in vivo studies which describe and evaluate cardiac flow using modern medical imaging techniques (such as echocardiography, 4D-MRI and echocardiographic PIV [2, 3]). Intraventricular flow is also a topic of biofluid mechanic research, in silico as well as in vitro. This is exemplified by several particle image velocimetry (PIV) studies that have been performed in hydraulic bench models to investigate the flow field inside a left ventricle (LV) replica in a 2D plane [4], or to reconstruct the 3D flow structures numerically from 2D velocity data [5]. However, as the intraventricular flow has a complex 3D and unsteady structure, a dedicated PIV system allowing for dynamic 3D flow measurements in the LV is highly desired.

The aim of this project is to design and develop a novel system that allows to quantitatively study the flow in experimental in vitro PIV models, for instance vascular segments, heart valves and left ventricle replicas. In this study we present an application which permits 3D volume reconstruction of the flow field by means of phase-locked stereo-PIV in a transparent pulsatile LV membrane model.

METHODS

The setup (figure 1) was primarily designed and developed to facilitate consecutive stereoscopic measurements without repeating the complex and time consuming stereo calibration. The proposed system is partly based on a previous study of Yagi and co-workers [6], and is built around two hexagonal transparent tanks. The shape of the two tanks is chosen such that optical access can be established orthogonally through the walls. Both tanks were filled entirely with the same refractive-index matched (n = 1.49) liquid as a working fluid.

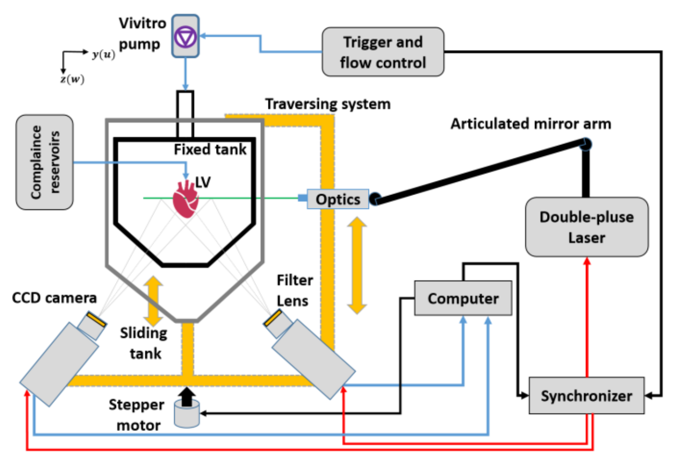

Figure 1: Schematic layout of the setup: two hexagonal tanks, CCD cameras, laser sheet, optical lenses, hydraulic components and the control system components.

To eliminate the need to perform the calibration in each measurement plane separately, the external tank, CCD cameras and the optical lenses have been rigidly connected to a traversing mechanism equipped with a stepper motor. Throughout the scanning sequence, the whole stereo-PIV apparatus translates simultaneously with the external tank, while the internal tank, which functions as the LV housing, remains fixed. This way, the relative optical positions between the cameras and the measurement plane are secured. The 45° stereo-PIV system consists of two CCD sensor cameras (PCO.2000, PCO, Germany) equipped with a long-pass filter at 550 nm, with a maximum resolution of 2048*2048 pixels and mounted on tilt adapters to achieve the Scheimpflug condition. A double-cavity pulsed NdYAG laser (Twins BSL 140, Quantel, USA delivering 140 mJ/pulse with a repetition rate of 15-30 Hz) and compound lenses were used to generate and shape a uniform laser light sheet (thickness 1.5-2 mm).

A commercially available cardiovascular simulator (Vivitro Systems, Inc., Victoria, Canada) was used to impose (and monitor) different physiological pressure and flow conditions. Compliance and resistance were carefully adjusted to achieve a physiological pressure wave form.

A pair of 25 mm mechanical bileaflet valves were mounted in the aortic and mitral positions. A three-component liquid consisting of sodium iodide, glycerol and distilled water (volume fraction 79:20:1) was used as a blood-mimicking liquid and seeded with fluorescent particles (ϕ10 μm) as tracers. Special attention has been paid to ensure the appropriate particle number and density in the interrogation window for reliable cross-correlation analysis of stereo PIV images. To avoid discoloration, a small amount (0.1% by weight) of sodium thiosulfate was added.

RESULTS AND DISCUSSION

Figure 2B shows a reconstruction of the 3D flow in the LV during early diastole, obtained after interpolating the velocity data from several parallel planes (distance 2 mm) measured in a phase-locked manner through 80 consecutive cycles. Stroke volume was set to 50 ml, for a heart rate of 70 beats/minute. The figure 2B displays an asymmetric transmitral jet flow passing through a bileaflet mechanical mitral valve (25mm), one jet toward the apical direction, whereas the second one drifted parallel to the LV wall. As a result of a relatively large LV model diameter (70mm) compared with an anatomical one, the velocity field map and the corresponding 3D flow reconstruction report low velocity values.

The CCD cameras and the double-cavity laser were triggered via the synchronizer (ILA GmbH). The onset of the measurement sequence was triggered by the cardiovascular simulator. For the stereo PIV calibration and image processing, a commercial PivView3c (PIVTEC GmbH) software was used. Tecplot was then used to visualize the resulting velocity data.

To the best of our knowledge, this is the first experimental stereoscopic PIV-setup that is capable of reconstructing the complex 3D left ventricle flow field at any given time instant in different controllable and repeatable physiologically relevant hydrodynamic conditions, in a time-efficient way. We believe that this experimental setup will serve as a reference and benchmark for future in vivo and numerical studies of left ventricle flow dynamics. In the near future, we plan to develop a more realistically shaped LV model, based on medical imaging.

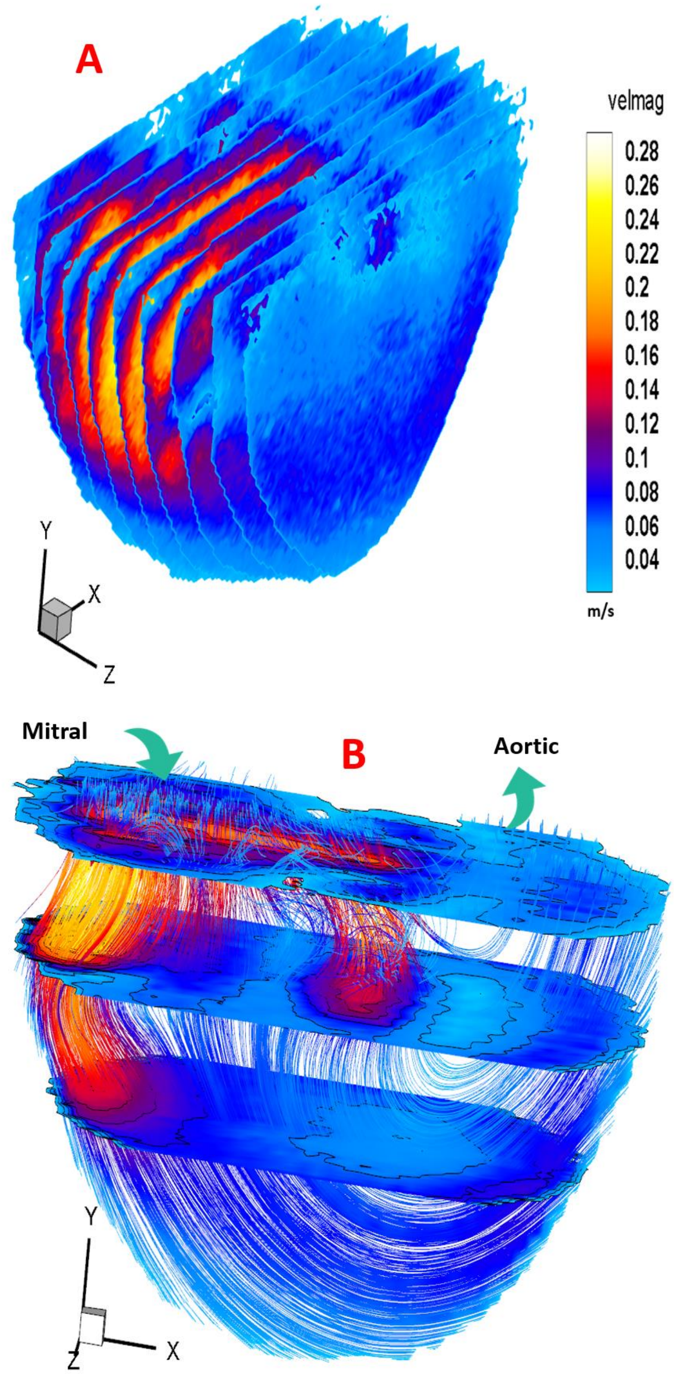

Figure 2: (A) Velocity field in several planes of intraventricular flow at early diastole (B) 3D streamlines of transmitral jet downstream a the mitral valve during diastole, reconstructed after interpolating the velocity data from several parallel planes along the z-axis. The streamlines are color coded based on velocity magnitude.

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