Influence of the coronaries on the flow in the aortic root

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Abstract The blood flow ejected from the left ventricle of the heart enters the aorta artery and, through the cardiovascular network, it distributes nutrients (i.e., oxygen) to the whole body. The aorta initial tract, the aortic root, has a peculiar geometry: it is characterized by three sinuses (sinuses of Valsalva) where, from two of them, the coronary arteries originate. These small arteries have a great clinical relevance because they supply oxygenated blood to the myocardial muscle and their filling could affect in turn the fluid dynamics in the aorta. The in vitro analysis of the fluid dynamics inside the aortic root has widely performed: worldwide several Pulse Duplicators (PD) have been designed to simulate the heart/circulatory system behavior. However, to the authors’ knowledge the model used in this work is the first that includes the coronary arteries. The objective of this study is to analyze the influence of these small arteries on the flow field downstream a mechanical aortic valve inside an aortic root placed in an elastic and transparent anatomically accurate replica of a human aorta. The study was focused on the diastole phase, in which the coronary arteries filling occurs. Two-dimensional two-components instantaneous velocity fields were measured in a plane including the mid-plane of both the proximal left coronary artery and the aortic root. In the performed experiments a series of 100 cardiac cycles have been acquired and phase average of the velocity fields and of derived quantities have then computed.

1. Introduction

The major vessels of the coronary circulation are the left and right coronary arteries that originate at the base of the aorta from openings called the coronary ostia, located behind the aortic valve leaflets inside the Valsalva sinuses. These vessels and their branches lie on the surface of the heart and distribute blood flow to different regions of the heart muscle. The aortic valve replacement with a mechanical or biological prosthesis is nowadays a common surgical procedure: when the disease affects simultaneously the aortic valve, the aortic root and the ascending aorta, the standard surgical approach is the Bentall procedure (Bentall et al., 1968), performed by implanting a polyethylene terephthalate fiber (Dacron) tube including a mechanical or biological prosthesis. A very important step following the remodeling or re-implantation of the aortic root involves the coronary arteries, because of they must be connected to the sinuses of Valsalva, the geometry of which (following the insertion of the fiber tube) could change. There is little information available about whether or not this geometry can influence the dynamics of a prosthetic valve with two mechanical leaflets and consequently the coronary blood flow. Indeed, the nature of the coronary system is extremely complex, with branches that reach every part of the myocardium muscle forming a coronary network, variable among different individuals, that is one of the most compact and complex within the human body (Zamir, 2005), difficult to access in vivo, and thus not completely known. Moreover, due to the difficulty in finding precise relationships between pressure and flow rate under different conditions, most of the contributions found in literature are based on in vivo investigations.

Kleine et al. (2002) studied the influence of bi-leaflet and tilting disc valve orientation on coronary artery flow in pigs, finding that coronary blood flow was significantly influenced by the valve orientation and showing the optimum configuration for each valve model. De Paulis et al. (2004) carried out an in vivo investigation of coronary flow after aortic root replacement in humans and they did not find any influence of pseudo-sinuses of Valsalva on the coronary flow reserve. De Tullio et al. (2011) studied by means of numerical simulations the effect of aortic root geometry on the coronary entry-flow after a bileaflet...
mechanical heart valve implant; they found that the geometry of the aortic root affects only marginally the kinematic features of either the aortic and coronary flows.

Several *in vitro* study of the aortic flow have been performed to assess the performances of prosthetic valves (Brücker et al., 2002; Chandran et al., 1985; Gülan et al., 2012; Hutchison et al., 2011; Leo et al., 2012; Lim et al., 2001; Yoganathan et al., 1979; Querzoli et al., 2010). Nevertheless to the authors' knowledge, neither *in vitro* investigations of the coronary flow are present in literature nor *in vitro* study of the flow inside aortic root models equipped with the coronary arteries have been performed so far. The aim of present work is to analyze the differences induced by the presence of coronary arteries on the aortic flow. To do this, a PD already used for previous investigation in the intraventricular flow (Querzoli et al. 2010, Espa et al. 2012, Fortini et al. 2013, Vukicevic et al. 2012) has been used. The study was performed by using an aortic root model equipped with coronary arteries. In a first series of measurements, these small arteries were left open; then, the coronaries were crimped in order to do not allow their filling. In both cases the time evolution of velocity/vorticity fields during a cardiac cycle is investigated.

2. Materials and methods

Fig. 1 shows a sketch of the experimental apparatus.

![Fig. 1. Sketch of the experimental apparatus: M. Linear motor, P. Hydraulic piston, VC. Ventricular chamber, AC. Aortic chamber, R₁-R₂. Periferic resistances, RC. Compliance flow regulator, C. Compliance, S₁. Constant head tank, S₂. Atrial tank, CC Coronary arteries Chamber, P₁-P₂ Pressure Transducers.](image-url)
The flow inside the aortic root model equipped with the coronary arteries was investigated in a Pulse Duplicator (PD), i.e. a hydraulic loop simulating the human systemic circulation, in both flow rate and ventricular-aortic pressure waves. The anatomic district between the left ventricle outflow tract and the aortic root was accurately reproduced, and the impedance of vascular systemic net was mimicked according to a concentrated parameters approach. The piston pump (P) displacement, driven by the linear motor (M), moves accordingly to a given pulsatile time function governing the volume changes of the ventricle chamber (Fig. 2). The aortic chamber AC, which is the core of the apparatus, is made of plexiglass for the required optical access. The aortic root is placed inside the aortic chamber. It is made of silicon rubber, to both simulate the physiological blood vessel elasticity, and also to allow optical access. The branched vessels, that arise from the Valsalva sinuses, are connected to the tank S2 by means the Coronary arteries Chamber (CC), in order to be influenced also to the volume variation inside the Ventricular Chamber (VC), especially in the diastole phase. The prosthetic valve was the mechanical aortic valve, with nominal diameter of 27 mm and an internal diameter of 25 mm, housed inside the aortic root just upstream of the Valsalva sinuses.

Two piezoelectric sensors (P1 and P2, PCB Piezotronics® 1500 series) are located upstream and downstream of the valve, in order to measure, respectively, the aortic (pa) and ventricular pressure (pv), according to the Italian Department of Health prescriptions. Ventricular and aortic pressure tapes are located at 6.25D and 3.5D from the valve housing, respectively. A Flowmeter (F) recorded the flow rates during the cardiac cycles.

The cardiovascular peripheral resistance is reproduced by two in series shutter taps (R1 and R2). A third valve, R_C controls the flow entering or leaving the compliance chamber. The latter is an air tank and reproduces the compliance of large arteries by allowing storage and release of fluid during the simulated cardiac cycle. The aortic flow enters the right atrium tank S1 through a nozzle open to the atmosphere, thus closing the systemic circulation. Tank S2 mimics the left atrium, and feeds the left ventricle chamber following a pressure regime completely separated from the aortic one.

The aortic root geometric aspect-ratio was 1:1. For the dynamical similarity, equality of both the Reynolds and the Womersley numbers is required between the physiological flow and the experimental one, these parameters being defined as:

\[ Re = \frac{UD}{\nu}; Wo = \sqrt{\frac{D^2}{\nu T}} \]

where \( \nu \) is the kinematic viscosity of the blood analogue fluid, \( U \) is the peak velocity through aortic valve orifice at the systolic phase, and \( T \) is the period of cardiac cycle. The experiments were performed adopting a solution of sodium chloride in water (9g/l), with viscosity of approximately 1/3 blood viscosity. Hence, to respect the dynamic similarity, an experimental cardiac cycle period equal to 3 times the physiologic one was adopted, for a given physiological stroke volume SV (i.e., the volume ejected from the ventricle in one heart beat).
The tests were performed by changing the stroke volume (SV = 54ml, 64 ml and 80ml), whereas the period was T = 2.4s in all the tests. Each series consisted of 100 runs that have been used to compute the phased averages; the main experimental parameters are listed in Table 1. A vertical plane including the mid-plane of both the proximal left coronary artery and the aortic root were illuminated by a 12 W, infrared laser. The working fluid was seeded with neutrally buoyant particles with an average diameter of 50μm. Images were acquired by a high speed camera (480 frames/s) with a spatial resolution of 1280x1024 pixels. A Feature Tracking algorithm (Cenedese et al., 2005) was used to measure the instantaneous velocity field in a Lagrangian framework by recognizing particles trajectories. Interpolation of sparse data on a regular 50x51 grid gave the 2D Eulerian velocity field for each time instant. Spatio-temporal resolution (Δxmin= 0.07mm, Δtmin=1/480) was estimated high enough to allow for identifying vortex structures in the aortic root, and following their evolution during the cardiac cycle.

<table>
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<th>U [m/s]</th>
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Table 1 Main parameters describing the flow field experiments

The configuration with stroke volume SV 64ml and period T 2.4s is the reference configuration, reproducing in similarity the same physiological parameters of a subject at rest, as well as the FDA guidelines for valve testing (stoke volume 64ml, hearth rate 75 beats/min). For each test, the same model was used: in the first series the coronary arteries were left open and the case in presence of the coronaries was studied; then the coronary arteries were clamped in order to avoid their filling and to exclude them from the hydraulic circuit: this was the case without the small arteries.

3. Results

3.1 Pressure and flow rate

Aiming at fully respect the similarity theory, during the tests the pressures and flow rate behaviors have been reproduced to match with the physiological reference values. Two pressure transducers, located upstream and downstream of the aortic valve respectively, have allowed to record the time behavior of the ventricular and aortic pressure for all the experimental conditions, they have then been phase-averaged over all the 100 cardiac cycles. The aortic and ventricular pressure waves for the reference condition have been set by adjusting the compliance and the resistance shutter taps into the hydraulic loop. Ventricular and aortic pressures vs time for the reference condition and in presence of the coronary arteries are shown in Fig 3. The mean values recovered during the cardiac cycle, with and without coronary arteries are substantially the same. However, the measured maxima pressure at the systolic peak are greater in the case without coronaries.
Flow-Rate. The electromagnetic flowmeter, located upstream the aortic valve, allowed to measure the flow rate for all the experimental conditions, in Fig. 4 we plot the time evolution of the theoretical (obtained as derivative of the time ventricular volume change) and measured flow-rate in presence of coronary arteries for the reference condition. The maximum instantaneous flow rate has been obtained at the systolic peak; in such condition a backflow towards the valve immediately at the end of the systolic phase was observed.

### 3.2 Velocity field

In Fig. 5 we report five salient instants of the cardiac cycle for the reference case: both streamlines and vorticity fields are shown. The non-dimensional time is reported on the lower-left corner of each plot, by a red spot on the flow rate graph. The left column refers to the case in presence of the coronary, the right one to that without coronary, respectively.
The first row ($t/T=0.210$) refers to the instant immediately before the systolic peak: the leaflets of the valve are then open and the observed vortical structures are those typically associated with the prosthetic valve here used i.e. three jets in correspondence of the three lumen of the valve. The observed flow pattern with and without coronaries is similar, however vortices are smaller and less intense in the first case (see A vs A’). Also not negligible slight flow is present in the coronary artery. Almost similar structures are present at the systolic peak ($t/T=0.250$); they had time to develop and grow in both the cases but vorticity is higher when coronary are absent (see B’ vs B). In addition, in the coronary artery there is a residual flow, less intense than the previous instant, due to the fact that these small arteries, as a results of the effect of the ventricular chamber through the coronary artery chamber, during the systole phase undergo a volume decrease that in turn induces a pressure increase. Therefore, the fluid tends to flow upward along the aortic vessel towards of lower pressure regions.

At $t/T=0.434$, that represents the begin of the diastole when the valve closes and the coronary filling starts, it has been observed that the closure of the leaflets occurs faster in the case with the coronary arteries (plot C). This is probably due to the fact that vorticity accumulates in correspondence of the sinus of Valsalva (right-side of the color maps) forming a nearly steady vortex, larger and less intense when in presence of the coronary arteries. This fact reflect some in vivo evidences (Escobar et al., 2004): the vortices fills the available space behind the valve leaflets and persists until diastole, expanding and moving inward during the aortic valve closure. These results also highlight how the presence of the coronary arteries determines a flow field reorganization in a wider vortex.

At $t/T=0.520$ the D graph shows the coronary filling. Higher vorticity values are recovered when the coronary arteries are closed.

Finally At $t/T=0.700$, i.e. the end of the diastolic phase, higher vorticity values are present in the coronary arteries, whereas a steady vortex in proximity of the Valsalva sinus is observed in the E’ map.
4. Conclusions

An in-vitro analysis of the district including the aortic root with the Valsalva sinuses and the coronary arteries has been performed. In particular, the measurements were aimed to highlight the differences induced by the presence of the coronary arteries on the fluid-dynamic inside the aortic root.

The mean velocity and vorticity fields found in mean and maximum values of the flow rates. The mean velocity and vorticity fields have been described at the salient instants of the cardiac cycle. The results highlighted that, in both the cases, during the systole phase the vortical structures are almost similar, even if the values are higher in the case without coronary arteries. On the contrary, during the diastole phase, different structures were found in the Valsalva sinus: a vortex wider but less intense was found in the case with coronaries, whereas the flow, outgoing from the aortic root, filled the coronary. This fact affected the valve closure: the closure of the leaflets occurs in fact in a faster manner in presence of the coronary arteries.

References