On the potential of 4D Flow in guiding CFD analyses: a case study of aortic coartaction

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***Abstract*—In the context of congenital diseases of the aorta, affecting either the valve apparatus or the thoracic portions, new biomarkers derived from fluid dynamics has been investigated as possible means to gain further insight in patients' diagnosis and risk stratification. To this aim, in the present work we exploited the potential of *in vivo* data based on magnetic resonance imaging to guide and verify the reliability of numerical simulations in a case of aortic coarctation.**

***Keywords*—4D Flow, magnetic resonance, CFD analysis, aortic coartaction.**

I. Introduction

CONGENITAL abnormalities of the aorta may affect the valve apparatus (e.g. bicuspid aortic valve), or the ascending and arch portions (e.g. coarctation). In the clinical scenario, morphological analyses are commonly used to grade the progression of the pathology [1]. In the last decade, derangements of the fluid dynamics within the region of interest have been investigate as possible diagnostic and prognostic markers of the pathology. In this context, novel *in vivo* flow-encoding magnetic resonance (MR) imaging techniques and *in silico* computational fluid dynamics (CFD) have been exploited to gain insights in the redistribution of flows and pressures [2,3]. Nonetheless, MR-derived measurements suffer from low spatial-temporal resolution and uncertainties in data processing, while the realism of CFD-based models is yet of great challenge.

In the present work, we proposed a combination of in vivo and in silico methods to highlight the potential of MR-derived data in guiding the realism of CFD models, focusing on a specific case of a 26 years old female with aortic coarctation.

II. Materials and Methods

A. MR sequences

MR acquisitions were performed on a 1.5 T scanner (Magnetom Aera, Siemens Healthcare, Erlangen, Germany). Two MR sequences were acquired: gadolinium-enhanced MR angiography (MRA), and 3D time-resolved phase-contrast cardiac magnetic resonance, with prototype pulse sequences for three-directional velocity-encoding (4D Flow). The MRA volume was acquired prescribing a voxel size resolution of 1.09×1.09x1.10 mm^3 (echo time = 0.95 ms, repetition time = 2.67 ms, flip angle = 25°). The 4D Flow volume of acquisition was oriented along a sagittal plane encompassing the ascending aorta, the aortic arch and the thoracic aorta. An almost isotropic voxel resolution of 1.77×1.77x2.00 mm^3 was prescribed [4]. The remaining parameters were: echo time = 2.44 ms, repetition time = 38.72 ms, flip angle = 8°, temporal resolution = 45.27 ms. Data were acquired with prospective ECG-gating during free-breathing, using a respiratory navigator. The velocity-encoding range (VENC) was properly set to 200 cm/s after scouting on cross-sections positioned in the ascending aorta and downstream of the coarctation. Exploiting *ad hoc* in-house MATLAB software MATLAB (The MathWorks Inc., Natick, MA, United States), 4D Flow data were analyzed yielding the time-dependent 3D velocity field within a user-defined region of interest (ROI) [5].

B. CFD model

The patient-specific inner-wall of the aorta was extracted from the MRA volume through a level sets algorithm available in VMTKLab (Orobix Srl, Bergamo, Italy) for semi-automated segmentation. The aortic inner-wall surface was clipped proximally, at the sino-tubular junction, to define the inlet surface (S_{in}) and distally to create the outlet surfaces for the three sovra-aortic branches $S_{out,i}$ (i=1,2,3) the descending aorta $S_{out,4}$.

A volumetric mesh was then computed in ANSYS Icem CFD (ANSYS, Inc., Canonsburg, USA), resulting in approximately 800,000 tetrahedrons with an average mesh size of 1.1 mm and boundary layers to improve near-wall gradients computations. The CFD boundary conditions were defined according to the 3D velocity field extracted from the 4D Flow volume. Specifically, the inlet and outlet surfaces of the CFD model were registered in the 4D Flow volume applying a rigid transformation computed according to the relative orientation of MRA and 4D Flow scans. The discrete velocity field was sampled within the ROI on the cross-sections identified by S_{in}, $S_{out,1\text{-}2\text{-}3}$, following the methods proposed in [6]. The extracted points were used to define: i) the full 3D velocity profile at S_{in}, ii) the net flow rate at $S_{out,1\text{-}2\text{-}3}$. At $S_{out,4}$ a zero-pressure boundary condition was applied. Blood was modeled as a Newtonian fluid (ρ=1060 kg·m^{-3} and μ=0.0035cP). A no-slip condition was assumed at the aortic wall and. Three cardiac cycles were simulated to minimize the influences of initial-conditions.

III. Results and Discussion

Simulated systolic fluid dynamics well compared with ground-truth 4D Flow data, reporting a qualitatively similar

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pattern of blood velocity field. Computed streamlines highlighted the persistence of a high-velocity jet passing across the coartaction region from mid to late systole (Fig. 1). Consistently with 4D Flow data, recirculation zones were observed proximal to the coartaction jet as well as in the concavity of the ascending aorta.

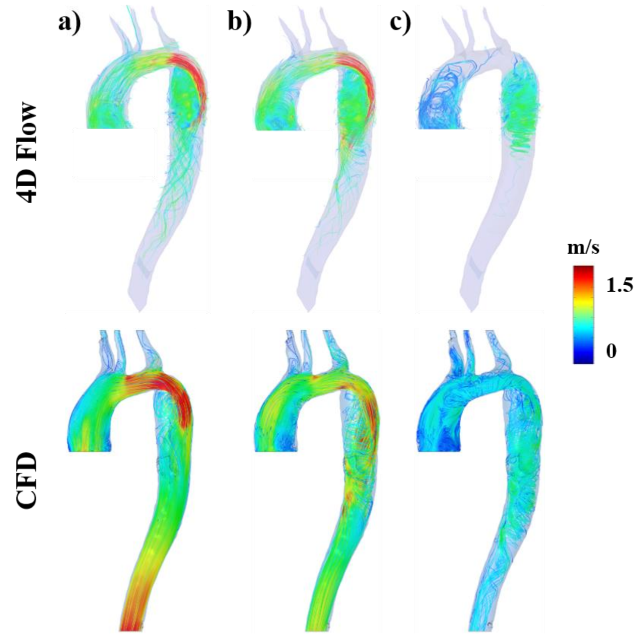

Fig. 1. Streamlines computed at the time-frames corresponding to peak (a), mid- (b) and late (c) systole.

At peak systole, we quantitatively compared CFD results and 4D Flow data on three different aortic sections: i) in the proximal ascending aorta close to pulmonary trunk, ii) downstream of the aortic arch and iii) in the distal descending aorta (Table 1).

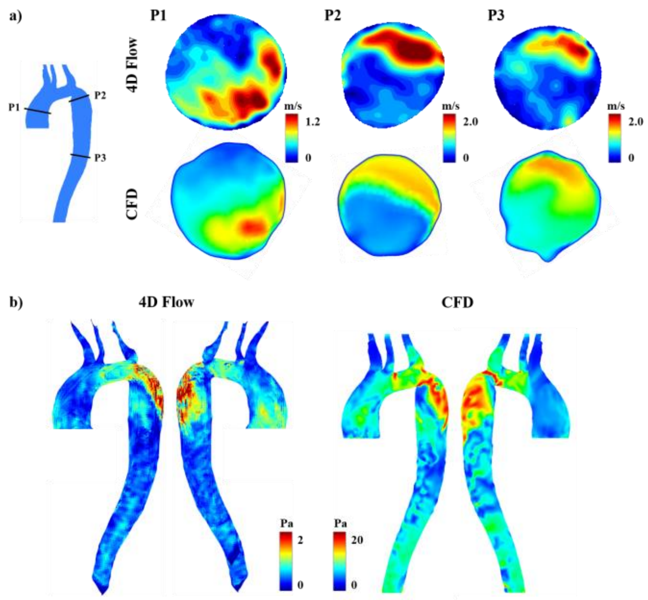

Fig. 2. a) velocity magnitude contours on selected cross-sections and b) wall shear stress distributions, computed at peak systole.

On all the selected cross-sections, the CFD analysis captured the patterns of the velocity field reported by the 4D Flow processing (Fig. 2). However, CFD underestimated peak velocity values ($|v|_{max}$) by 2% and 24% in the ascending and descending aorta, respectively (Table 1). The length of the blood jet passing across the coartaction was comparable and equal to about 53 mm. When focusing on the wall shear stress (WSS) field, the CFD model well-captured the high-WSS region downstream of the coartaction, as visible in the 4D Flow dataset, even if the computed WSS peak values were an order of magnitude higher than the ones estimated with 4D Flow data. Of note, this result is in accordance with previous evidences [5, 7], proving that the use of highly space- and time-resolved CFD analysis can provide more accurate estimations of aortic WSS.

TABLE I

	4D Flow	*CFD*
$|v|_{max,\ Tps}$ *(m/s)*		
Plane 1	1.34	1.32 (-1.5%)
Plane 2	2.23	1.70 (-23.8%)
Plane 3	2.01	1.81 (-9.9%)
L_{Jet} *(mm)*	52.9	53.3 (+0.7%)
$|WSS|_{max,\ Tps}$ *(Pa)*	2.3	22.9
L_{WSS} *(mm)*	58.6	60.1 (+2.6%)

Results of 4D Flow post-processing and of CFD simulation

IV. CONCLUSIONS

As suggested by our preliminary results, the realism and reliability of CFD simulations can be assessed by comparison with ground-truth *in vivo* 4D Flow data. Specifically, the potential of 4D Flow was exploited both considering the time-dependent characteristics of the velocity field, thus confirming the transient features captured by CFD, as well as location dependent velocity patterns and peak values. Also, comparisons between more refined variables, e.g. WSS, owing to their improved estimation from 4D Flow data [5], may contribute in evaluating the outcomes of CFD models, which would allow, if further optimized, to obtain more accurate computations of the considered variables.

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