An integrated CFD and UQ approach to assess hemodynamic alteration in the Aortic Coarctation

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INTRODUCTION

Aortic coarctation (CoA) is a vessel narrowing (Fig. 1). Coarctation obstructs blood flowing from the heart to the lower part of the body. Blood pressure increases above the constriction. The blood pressure is higher than normal in the left pumping chamber (left ventricle), and the heart must work harder to pump blood through the constriction in the aorta. This can cause thickening (hypertrophy) and damage to the overworked heart muscle. The coarctation obstruction can be relieved using surgery or catheterization. Intervention is suggested when $\Delta P \geq 20$ mmHg [1].

CFD has been revealed as a feasible tool to asses the blood flow features in a non-invasive way. Currently, the setting of the correct or more suitable boundary condition remains challenging: the inlet BCs are derived from Phase Contrast (PC) MRI images; while for the outlets a 0-D system based on a 3-element Windkessel model is used, and the RCR repartition is based on the cross area of the outflow vessel, the total proximal and distal resistance, and on the total compliance. However, this approach is not able to cope with the blood flow correctly (Fig.2).

Fig. 1 – CoA example

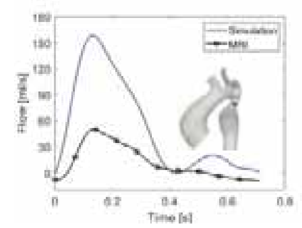

Fig. 2 – Example of state of art limitations

This study aims to present a novel non-invasive study of a CoA case before and after the intervention, integrating 3D MRI and uncertainty quantification techniques in CFD environments.

MATERIAL AND METHODS

The pipeline of the proposed approach consists of three main phases: image segmentations pre and post-intervention (1); flow extraction from PC-MRI images; CFD setup (3). For the 0-D outflow condition, the RCR splitting equation reported in literature has been modified according to Equation 1, introducing a partitioning α parameter:

$$\begin{cases} R_{p|i} = (1+\alpha)\dfrac{A_{tot}}{Ai}R_p & i=1..3 \\ R_{d|i} = (1+\alpha)\dfrac{A_{tot}}{Ai}R_d & i=1..3 \end{cases} \qquad \text{(Eq. 1)}$$

The α parameter was used as UNCERTAIN PARAMETER, ranging from -0.15 to -0.08; for this parameter an uniform PDF was assumed, and the generalized Polynomial Chaos (gPC) with third order polynomials was adopted [2].

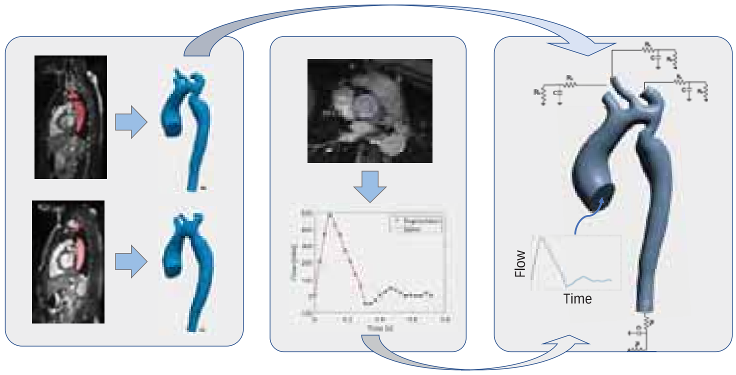

Fig. 3 – Example of our workflow

RESULTS & DISCUSSION

- In Fig. 4 the flowrate waveforms at the CoA site are reported: varying α there is a better agreement between the simulation results and the patient's flow (MRI).
- Fig. 5 depicts the pressure drop during a cardiac cycle in pre and post-intervention cases. No significant variations were observed connected with the α parameter. The physiological ΔP was correctly reproduced in the pathological state.
- In Fig. 6 the stochastic results in terms of mean (continuous line) and standard deviation (dashed lines) of the flow rate waveforms before and after the intervention are depicted:
  - the maximum impact of α is at the systolic peak (pre-operative case);
  - α has a slighter impact on post-intervention;
  - the largest variability is at the diastole of the post-intervention.

The Probability Distribution Function (PDF) confirmed what stated above (Fig. 6b-d), and (Fig. 7b-d).

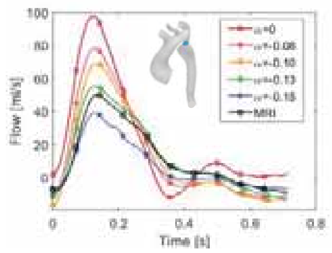

Fig. 4 – Flow rate curves at DA

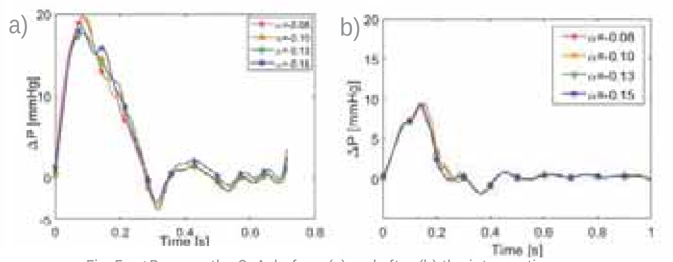

Fig. 5 – ΔP across the CoA, before (a) and after (b) the intervention

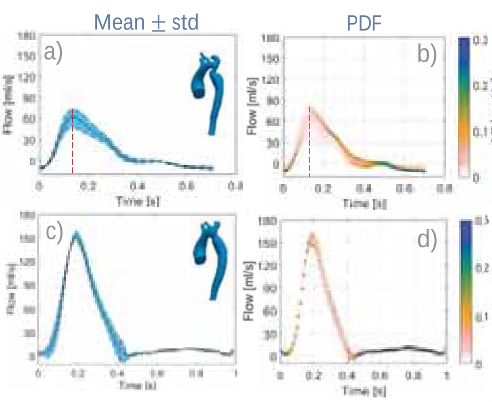

Fig. 6 – Flow rate stochastic mean ± std before (a) and after (c) intervention; PDF before (b) and after (d) the intervention

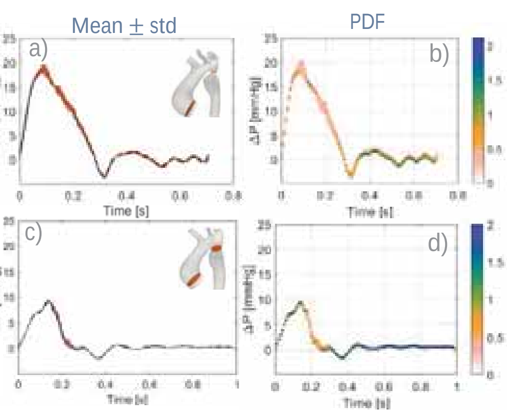

Fig. 7– ΔP stochastic mean ± std before (a) and after (c) the intervention; PDF before (b) and after (d) the intervention

CONCLUSION

Simulations of the patient specific hemodynamic with CoA and UQ were performed. A novel parameter α was introduced to cope with the flow partition in the branches. The stochastic analysis demonstrates that the additional parameter α: mostly affects the flow rate waveform and the WSS at the systolic peak of the pre-surgery; slightly affects all the quantities of interest in the other cases.

REFERENCES: [1] D. K. Arnett et al., *Circulation*, 2019 [2] A. Boccadifuoco et al., *Computer and Fluids*, 2018

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