Enhancing magnetic resonance imaging with CFD: in vitro validation and patient specific application

G. Annio[a], R. Torii[a]*, A. Ducci[a], V. Muthurangu[b], V. Tsang[b], G. Burriesci[a]†

[a] *UCL Mechanical Engineering, University College London, London , UK,*

[b] *Great Ormond Street Hospital for Children NHS Trust, London, UK,*

[c] *Ri.MED Foundation, Palermo, Italy*

Keywords MRI, CFD, PIV, cardiovascular, flow.

1. Introduction

Cardiovascular diseases (CVDs) are the main cause of death globally, taking the lives of 17.9 million people every year [1]. The study of blood flow in the great thoracic arteries plays a crucial role in the diagnosis and prevention of CVDs [2]. Flow-sensitive four-dimensional Magnetic Resonance Imaging (4D Flow CMR) has increasingly been utilised to characterise patients' blood flow in the clinical environment. Nevertheless, spatial and temporal resolutions are still limited to enable a detailed assessment of the haemodynamics quantities [3]. Computational fluid dynamics (CFD) is a powerful tool that has the potential to expand this information and, when integrated with experimentally-obtained velocity fields, enables to derive all the fluid dynamics descriptors of interest. However, the accuracy of the computed flow parameters is necessarily limited by the limited resolution of the 4D MRI, and highly influenced by the boundary conditions imposed. We propose a novel approach in which 4D Flow CMR and CFD-computed velocity fields are integrated synergistically in order to obtain an enhanced 4D Flow CMR imaging (EMRI) [4]. The approach was validated in-vitro against 2D particle image velocimetry (PIV) data on an idealised mock aortic arch, subject to pulsatile flow conditions, and tested on a patient specific aorta.

2. Methods

2.1 Computational framework

In this study, the Navier-Stokes equations (1) for incompressible flows were solved including an additional virtual external force $\bar{f}$ (1) which is proportional to the difference between the MRI measured velocity, v_{MRI}, and the computed velocity, v:

$$\rho\left(\frac{\partial \bar{v}}{\partial t} + \bar{v}\cdot\nabla\bar{v}\right) = -\nabla p + \mu\left(\nabla^2\bar{v}\right) + \bar{f} \qquad (1)$$

$$\nabla\cdot\bar{v} = 0 \qquad (2)$$

where p, ρ and μ are the pressure, the density and the viscosity of the fluid, respectively. K feedback gain coefficient, expressed as as [**?**]:

$$K = k\left(\frac{\rho U}{L}\right) \qquad (3)$$

where k is a dimensionless constant, and U and L are the characteristic velocity and length of the system studied (chosen at the inlet). K was kept constant across the domain and over the simulation.

2.2 In vitro validation

The method was validated on an idealised-simplified model of the human aortic arch, realised to be compatible with both PIV and MRI measurements. This was realised by casting a clear, solvent free, low viscosity silicone elastomer with a refractive index n = 1.4. A mixture of water and glycerol (60 % by weight of the solution) was adopted. A pulsatile flow (Figure 1 b) was generated by using a Pulsatile Blood Pump. The U bend was scanned with a cardiac gated 4D Flow CMRI on a 1.5 T MRI scanner, and a CFD analysis and EMRI were performed on the geometry. Subsequently, 2D PIV was performed using the TSI PIV 2D Measurement system, on the longitudinal cross section in the middle of the U bend (Figure 1 a), and compared with the flow field obtained with 4D CMR, CFD and EMRI.

2.3 Patient specific application

EMRI was applied to a patient specific aorta, which was obtained by scanning a healthy male volunteer with a cardiac gated 4D flow CMR sequence (QFlow SENSE) on a 1.5T MRI scanner. The experimentally obtained velocity field was compared with the one computed with CFD and EMRI.

3. Results and discussion

3.1 In vitro validation

Figure3.1 c shows the velocity maps at 4 selected instants, determined with 4D Flow CMR, computed with CFD and EMRI, and measured PIV. Overall there is a good qualitative agreement of the velocity distribution between all the different modalities. The agreement between 4D Flow CMR and PIV is better than between 4D Flow CMR and CFD. Taking PIV as the gold standard for in vitro full field flow measurements, MRI

*Corresponding author. Email: r.torii@ucl.ac.uk

†Corresponding author. Email: g.burriesci@ucl.ac.uk

generally gives lower velocities, especially in the outlet branch, and in the inner part of the arch. This can be attributed to the partial volume effect and temporal averaging. On the other hand, CFD shows much higher velocities in the whole domain. The limitations from MRI and CFD appear to be mitigated by the EMRI approach, which provides velocity map much closer to the PIV in terms of velocity magnitude and flow patterns. In fact, the velocity averaging occurring in MRI is compensated by enforcing the need to obey Navier-Stokes equations, leading to a physically acceptable velocity profile. Moreover, thanks to the non-slip condition and the presence of an high resolution mesh in the boundary layer, EMRI is able to correct the velocity in proximity of the wall, which in the 4D Flow CMR case are wrongly measured.

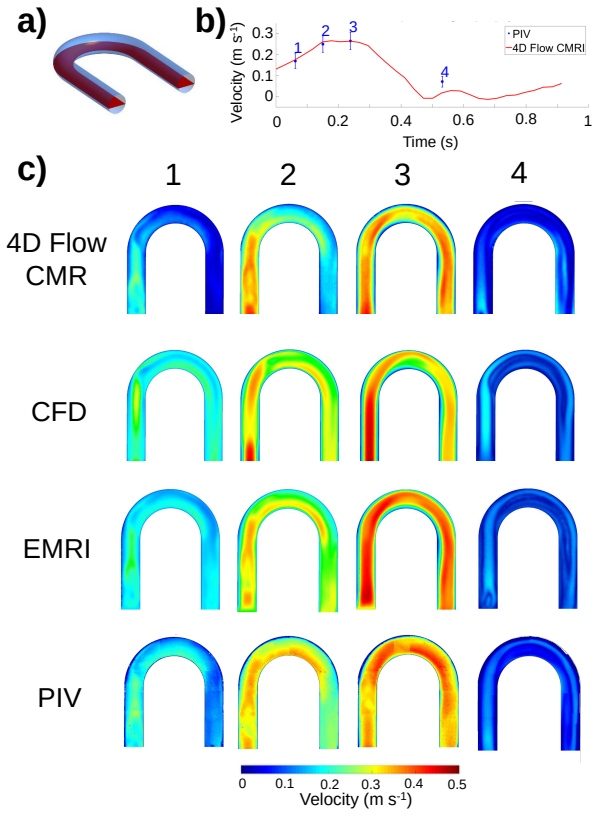

Figure 1: a) Plane selected for the comparison b) Average velocity at the inlet of the U bend during the pump cycle measured with 4D Flow CMRI and PIV c) velocity maps in the selected plane at the 4 instant measured with 4D Flow CMR and PIV and computed with CFD and EMRI

3.2 Patient specific application

The velocity maps of a sagittal and a longitudinal section of the aorta in late systole (t = 0.23 s from the start of the systole), obtained with 4D Flow CMR, CFD and EMRI are presented in Figure 2. The velocities obtained are in the same range (0–0.9 m/s) which is the physiological range of velocity in the aorta [5]. The 4D flow CMR velocity distribution presents local peaks of velocity, and a discontinuous velocity field. Conversely, in the standard CFD, the velocity is smoothly varying. The EMRI computed flow reflects the spatially heterogeneous pattern of the velocity observed in 4D flow CMR while maintaining smooth variation across the aorta. In particular the behaviour near the wall in the EMRI is ruled out by the non-slip condition, that allows for the correction of the non-zero wall velocities retrieved by 4D flow CMR.

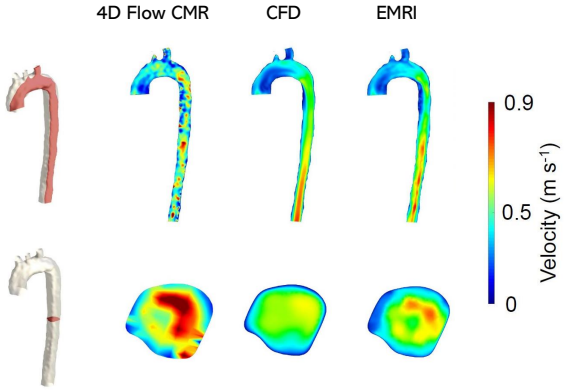

Figure 2: Velocity maps of a sagittal and coronal section of the human aorta at t=0.23 s from the start of the systole, obtained with 4D Flow CMR, CFD and EMRI.

4. Conclusion

The results presented show how the integration of 4D Flow CMR data and CFD results into a velocity distribution with enhanced spatial resolution, which, contrary to the raw clinical data, fulfils continuity and momentum balances. Moreover EMRI enables to correct the velocity field in area susceptible to errors such as the region in proximity to the wall. These feature could play a crucial role for the retrieval of flow patterns and flow derived parameters (e.g. WSS), both in clinical and research environment.

5. Acknowledgements

This research was supported by the UCL CDT in Medical Imaging (EPSRC).

6. References

[1] Mendis, S. et al. *WHO*, pp:2-14, 2011.
[2] Ku, D. N. *Annu rev fluid mech*, 29:399–434, 1997.
[3] Wood, N.B. et al. *JMR* 13:699–713, 2001.
[4] Annio, G. et al. *JESMDT* 22:1–11, 2019.
[5] Gardin, J. M. et al. *Am. Heart J.*, 107(2):310–319, 1984.