



Characterisation of spatiotemporal aortic flow and aortic wall biomechanics in coarctation

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The thoracic aorta performs sophisticated functions which depends largely on its almost unique structure¹. Coarctation of the aorta is a relatively common congenital anomaly, which causes a heavy burden of morbidity and mortality worldwide. As emphasized by Suradi and Hijazy in this issue of the journal, the long-term results can be very variable due to many factors. There is now a growing realization that the condition is associated with different forms of aortopathy, which are either a direct result of, or associated with, the narrowing²⁻⁴. These changes of the aorta can interfere with the long-term results of surgical correction of the anomaly and, therefore, need to be thoroughly defined and understood. Advances in modern imaging techniques, coupled with detailed computerized analysis, offer new opportunities to evaluate *in vivo* the mechano-biology of the arterial wall and the factors which could influence it, such as the spatiotemporal pattern of flow.

Computational fluid dynamics (CFD) offers an opportunity to study both the fluid dynamics as well as its potential impact on the (patho-) physiology of the aortic wall^{5,6}, (see [Figure 1](#) and [Figure 2](#)). It allows quantification of flow, vortex formation, pressure gradients, wall shear stress (WSS) and other relevant parameters starting from the aortic valve through the coarcted area downstream towards the distal descending aorta, based on patient-specific 3D anatomical models of the aorta and magnetic resonance imaging (MRI) flow acquisition. Briefly, CFD analysis of a patient-specific vasculature involves the following steps: (1) reconstruction of vascular anatomy from medical images such as CT and MRI, (2) setting inflow and outflow conditions as well as properties of the blood, (3) running computations, and (4) post-processing to visualise and/or quantify the variables of interest.

Goubergrits et al.⁷ developed a CFD model to calculate peak systolic pressure drops in coarctation patients pre- and post-treatment. This is particularly relevant due to the fact that pre-operative geometries vary considerably, ([Figure 3](#)). The model demonstrated a strong correlation with catheter-based measurements in the aorta as well as flow patterns captured using 4D velocity CMR imaging. Another interesting study on the use of CFD to calculate cardiac workload and hemodynamic behaviour in different types of aortic arch obstruction was presented by Coogan et al.⁸. The above examples demonstrate the potential of CFD as a functional imaging tool, by adding additional visualisation and quantification power to conventional diagnostic measurements such as CT and MRI.

More recently, *4D velocity CMR imaging (4D Flow)* has been used in looking at fluid dynamics over the cardiac cycle. Using 4D Flow acquisition sequence and post-processing software, the propagation of blood – velocity and flow – through an arterial segment can be calculated over the cardiac cycle ([Figure 4](#)).

4D velocity CMR imaging and quantification of cardiovascular hemodynamics are contributing to the understanding of cardiovascular pathologies: the combination of 3D spatial encoding, three-directional velocity encoding and cine acquisition provides data for the measurement and visualization of the temporal evolution of complex flow patterns throughout a 3D-volume⁹. Hope et al.¹⁰ showed that 4D velocity CMR imaging can help to evaluate collateral blood flow as a potential measure of hemodynamic significance in patients with aortic coarctation. Additionally, 4D Flow analysis showed

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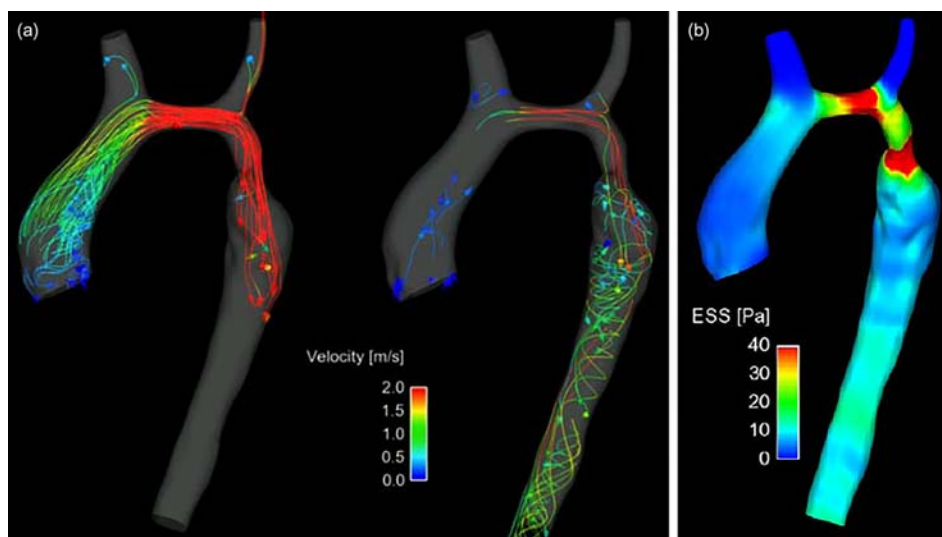


Figure 1. a) Flow patterns in a hypoplastic aortic arch ((left) systole, (right) diastole). The flow pathways are visualised by traces of virtual particles released in the aorta based on the CFD. High velocity flow through the hypoplastic arch leads to a hemodynamic jet in the post-coarctation area and markedly disturbed flow in the diastole. b) Quantification of Endothelial Shear Stress (ESS) and the impact of obstruction and flow in coarctation patients.

distorted flow patterns in the descending aorta after coarctation repair. Considerable helical and vortical flow in regions of post-stenotic dilation were identified. The utility of 4D Flow to analyse and understand vascular geometry and systolic flow characteristics in a patient with restenosis in aortic coarctation, after surgical repair, is presented by Markl et al.¹¹ (Figure 4). An early study by Kilner et al.¹² was published, describing helical and retrograde flows in normal aortic arch using three-directional cine velocity mapping (predecessor to 4D Flow). The development of flow through the two coronary cusp sinuses, the arch and the descending aorta was demonstrated at selected velocity mapping planes.

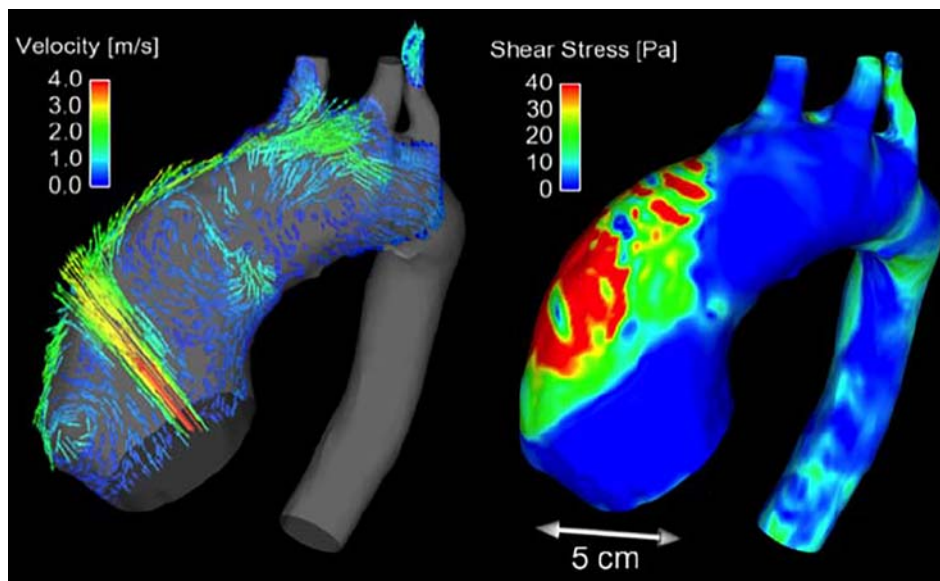


Figure 2. Flow patterns (left) and endothelial shear stress (right) of a patient with calcified bicuspid aortic valve (BAV) and thoracic aortic aneurysm. The impact of the hemodynamic jet coming out through the BAV elevates the shear stress level on the endothelium⁶. Excessive endothelial shear stress is associated with upregulated matrix metalloprotease and degradation of elastin structure in the wall¹.

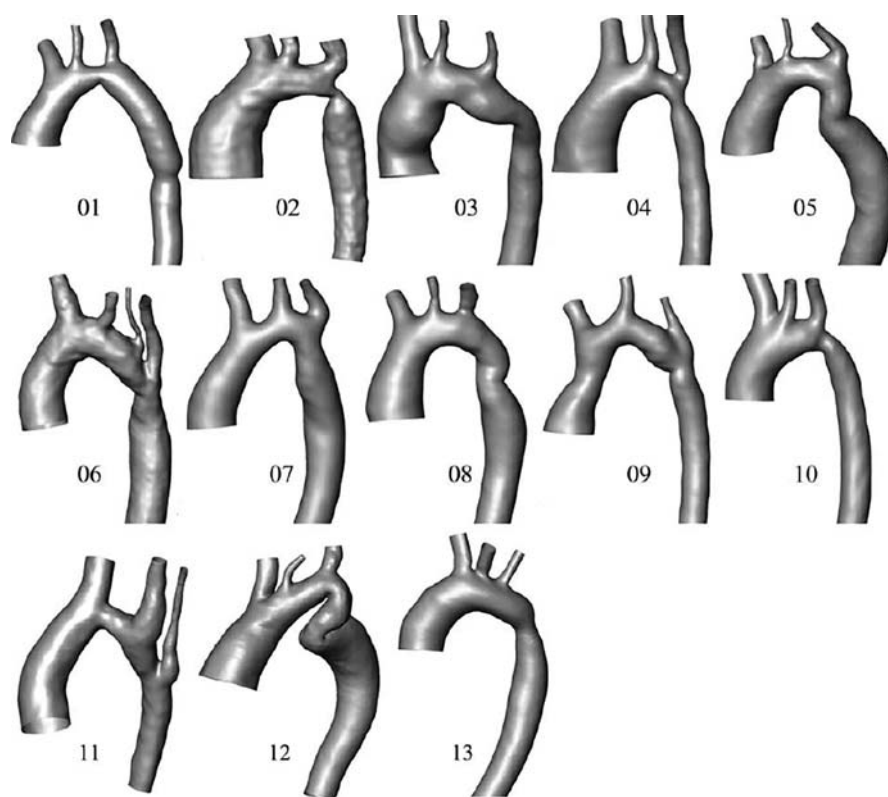


Figure 3. Anatomical models of different reconstructed cases representing aortic coarctation geometries⁷.

Image acquisition as well as post-processing of 4D flow datasets require time and multi-disciplinary skills. Efficient synchronization considering cardiac and respiratory movements has a significant impact on image quality¹³⁻¹⁴. 4D Flow is not yet a part of the clinical routine of CMR examination, but its use should increase in specialized centres in the near future.

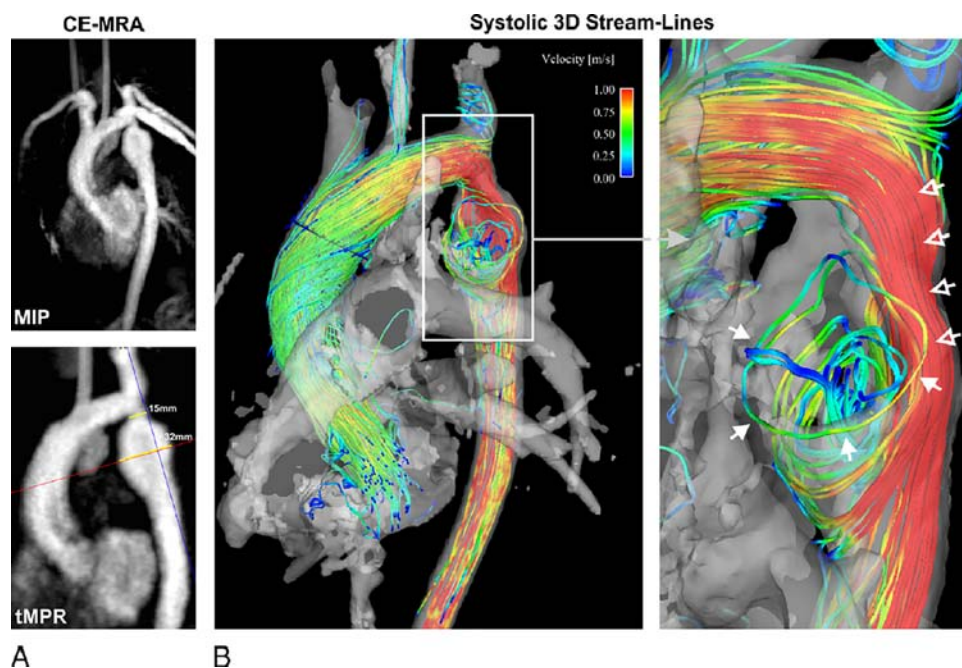


Figure 4. Post-processing results of 4D velocity CMR images in a patient with aortic coarctation and poststenotic dilatation. Systolic 3D streamlines in the entire thoracic aorta and a magnified region encompassing the pathological site¹⁴.

CONCLUSIONS AND FUTURE DIRECTIONS

In conclusion, *in vivo* assessment using advanced imaging techniques followed by computerized aortic flow and wall biomechanics modelling is extremely valuable for the management of arch coarctation patients in several ways: (1) the depiction and quantification of pre- and post-operative flow patterns and (2) predicting the new post-repair shape of the aorta provide deeper insight into main causes of post-operative complications, such as aortic aneurysm or recoarctation. Anatomical features of the coarctation, i.e. a narrowing followed by a sudden expansion, yields a turbulent haemodynamic jet into the post-coarctation opening. Such a jet is typically accompanied by large flow recirculation and vortices, where kinetic energy of the flow is lost. Moreover, low and oscillatory endothelial shear stress on the wall of the post-coarctation region is considered to be pathogenic stimulus to the arterial wall remodelling¹⁵. Because minimisation of energy loss from the flow through a narrowing and sudden expansion of a flow passage is a classic engineering problem, a collection of available knowledge to tackle it and can be transferred in the context of aortic coarctation. Hemodynamic factors can also influence endothelial function such as nitric oxide¹⁶, which can have implication on peripheral perfusion.

CFD and 4D Flow are complimentary techniques and therefore it is important to understand the advantages and limitations of each technique including their potential synergistic value. In short, CFD is a *modelling* of the reality and 4D Flow is a *measurement* of the reality. 4D velocity acquisition captures, with some measurement uncertainty and error, the real blood flow patterns but limited to the observation of the present state at the time of the measurement. CFD offers tools to design and predict different scenarios to help selecting personalized medical treatment but involves a number of assumptions, which need to be verified and justified depending on the type of application.

TOWARDS PERSONALISED MANAGEMENT

For optimal interventional planning in a personalised fashion, a patient-specific 3D model of the aorta can be reconstructed from CT or MRI, and modified using Computer Aided Design (CAD) tools according to the interventional options available, e.g. a surgical graft can be inserted to the anatomical model as a “virtual intervention”. CFD can then be used to model flow propagation and energy losses for the different post-interventional geometries¹⁷. The post-operative anatomy can be optimized in terms of geometrical and haemodynamic characteristics e.g. by quantifying the haemodynamic parameters for variable graft/patch length, characterising shape and diameter to avoid kinks or energy losses. For endovascular repair, a similar approach can be used to support pre-operative selection of stent material, design and size. Thus working towards achieving the holy grail of personalized medicine.

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