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EDITORIAL

Computational fluid dynamics in complex aortic surgery: applications, prospects and challenges

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Abstract

A myriad of factors must be considered when evaluating the prognosis of complex aortic pathologies and complications after complex aortic surgery. It is a challenging task for clinicians to produce a prognosis and predict the efficacy of treatment options with utmost accuracy based solely on human judgement. Of late, computational fluid dynamics (CFD) has been the key to modelling and visualising complex haemodynamics by analysing fluid–fluid and fluid–surface interactions. This editorial discusses two promising applications of CFD in complex aortic pathology: (1) improving endovascular aneurysm repair (EVAR) treatment outcomes and (2) allowing clinicians to produce more accurate patient-specific diagnosis, prognosis and prediction when coupled with cardiovascular imaging. The prospective future application of CFD is in designing an integrated image-based CFD framework with a "digital patient" representation to allow clinicians to input patient-specific data and rapidly obtain a recommended treatment option, revolutionising the way in which doctors provide patient-centric care.

Keywords: *computational fluid dynamics; CFD; flow simulation; flow analysis; aortic surgery; aortic pathology*

Introduction

The number of applications using computational fluid dynamics (CFD) in complex aortic surgery has burgeoned significantly over the past few years as a result of its ability to model extremely complex haemodynamics with a high degree of accuracy. Utilisation of CFD is now ubiquitous in the development of new devices for vascular surgery, including flow-optimised stents, and is poised to add considerable value to routine clinical decision making.[1,2]

CFD has been proven advantageous in simulating haemodynamic changes because it (1) allows characterisation of intravascular pressure and flow fields requiring the numerical calculation of Navier–Stokes and continuity equations, which are far too complex to be solved analytically, (2) allows computation of metrics that cannot be measured, e.g. time-averaged wall shear stress (TAWSS), (3) allows modelling of the surrounding vasculature to a high degree of precision, especially if coupled with cardiovascular imaging technology, (4) allows collection and analysis of results in real time, and most importantly, (5) these objectives are achievable within clinically relevant time frames and at relatively low cost.[3,4]

CFD has been invaluable in improving endovascular aneurysm repair (EVAR) treatment outcomes. Numerous studies have invariably concluded that EVAR is recommended over open repair or conservative management in cases of aortic injury.[5,6] However, EVAR is associated with complications, especially stent thrombosis, endoleak and infolding.[5,7,8] CFD has enabled the evaluation and optimisation of haemodynamic and mechanical performance of stents in order to minimise the risk of post-procedure complications. Fluid structure interaction (FSI), which couples fluid and structural mechanics, is often used to evaluate the impact of haemodynamics on the structural integrity of surrounding vasculature.[9] FSI adds value to a conventional CFD study, providing a more comprehensive analysis of the wall mechanics. In this Editorial, we highlight two state-of-the-art applications of CFD and current research trends in complex aortic surgery. We then provide an overview of emerging challenges that need to be surmounted in order to realise the full potential of CFD approaches.

In order to utilise CFD in such an application, the first step is to create a geometric model of the stent and the surrounding vasculature using 3D computer-aided design software (e.g. AutoDesk/SolidWorks). After meshing, the model can be imported into specialised CFD software such as ANSYS FLUENT or COMSOL. The user then specifies several details required to run the simulation, including boundary conditions (e.g. pulsatile blood flow profile), characteristics of the stent and vasculature to simulate deformation in realistic conditions, and which parameters the algorithm should calculate, e.g. TAWSS, oscillatory shear index (OSI), relative residence times (RRT), etc.[10] The software runs a user-defined number of iterations to reach convergence, simulating haemodynamic flow and calculating numerical solutions to the parameters based on ab initio laws. These numerical solutions can be imported into visualisation software to allow the user to visualise the complete flow field of interest.

Studies that endeavour to optimise stent designs focus on minimising the impact of the stent on the haemodynamic environment of the vessel (reduced TAWSS, OSI, and RRT). By running simulations on a variety of different stents and juxtaposing their haemodynamic and mechanical performance, vascular surgeons gain deeper insight into the factors that have a strong influence on performance. For example, studies have singled out strut thickness as a primary factor.[11–14] Other studies have utilised CFD to analyse the complex parameters and mechanisms that lead to procedure complications, such as neointimal hyperplasia, malapposition and collapse.[15,16] CFD has even enabled simulation of the entire angioplasty procedure, which has revealed that the configuration of the angioplasty balloon has a strong impact on the short-term effectiveness of the stent and the mechanical environment of the vasculature.[17]

Another ground-breaking, albeit less-explored, application of CFD is in patient-specific diagnosis, prognosis and prediction. Vascular surgeons have essentially looked into the future by combining cardiovascular imaging and CFD to model how complex aortic pathologies develop under haemodynamic flow (prognosis) and to determine the best treatment option (prediction).[18–21] The value of such an application is immense, because the use of CFD or cardiovascular imaging in isolation will not provide reliable information of in vivo haemodynamic flow because of inherent limitations. Image-based CFD is apposite to such applications because it is conducted ex vivo, without any inherent threat to the patient if different treatment options are simulated.

The rapid advancements in imaging techniques such as computed tomographic angiography and magnetic resonance imaging (MRI) have enabled vascular surgeons to visualise vasculature with ever-improving accuracy and precision.[22] A virtual geometry of the vasculature can be reconstructed using medical image processing software packages such as Materialise Mimics and 3D Slicer. With an appropriate meshing algorithm, the patient-specific vasculature geometry can be imported into CFD software for simulation. In order to better characterise the haemodynamics and pulsatile blood flow pattern of the particular patient, 4D flow MRI or catheterisation should be performed to provide realistic boundary conditions.[23]

For example, studies regarding aneurysm rupture have been conducted extensively to determine whether certain parameters or vascular morphology could be indicative of an impending rupture.[24–27] Furthermore, studies on aortic dissection analysed the parameters and mechanisms that led to complications such as aneurysmal dilatation.[28,29] With such information at hand, vascular surgeons could run patient-specific CFD simulations to predict the possibility of complications based on the simulation results, which in turn could assist them in deciding whether intervention is necessary and which intervention is appropriate.

There is still much room for the application of CFD in patient-specific risk prediction and virtual treatment planning. The ultimate goal would be to design an integrated image-based CFD framework that would allow vascular surgeons to import a model of the patient's vasculature (based on cardiovascular imaging) together with other patient-specific data (e.g. gender, age, etc.), before running CFD simulations to first establish a prognosis, and subsequently a prediction of the outcome when different treatments are simulated. Based on the results, the surgeon would not only have a better understanding of the condition and how it would develop under haemodynamic flow but also which treatment option is optimal (e.g. conservative/EVAR/open repair).

This signifies a paradigm shift in model integration from registry-based, population-averaged data to digital patient representations.[4,30] Such virtual models add value to population-scale numerical models, and critically reduce the time, cost and risk associated with clinical trials. This approach can potentially aid in the development of individual-based models, as opposed to population-based models, which would otherwise require large patient numbers and clinical trials to develop. Taken further, the integrated image-based CFD framework could predict the possibility of complications based on case studies and data in the system, and include a Bayesian machine-learning component to continuously refine its predictions. However, there is much work to be done in this area because there are still insufficient data to construct a reliable, multivariant database from which the integrated framework can draw information and produce an accurate assessment.[21]

However, there are three inherent limitations in applying CFD in complex aortic surgery. First, CFD has limitations in modelling complicated biochemical processes, because it is traditionally used to model kinetics.[31] Since the development of aortic pathologies and post-treatment complications often involve biochemical interactions (e.g. coagulation cascade), CFD should not be used in isolation when evaluating a patient.

Second, there is a delicate balance between the degree of accuracy of the simulation and computational power and time. In some scenarios where structural mechanics has an insignificant impact on haemodynamic flow (e.g. computation of pressure gradients), the structural characteristics of the aorta will not affect the results to a large extent. Thus, simplifying the model will be advantageous because less computational power and time is required. However, in other scenarios, CFD should be used in harmony with FSI because the compliance and elastic recoil of the aorta will affect the conclusion of the study.[32] It is often difficult to decide the tilt of such a delicate balance.

Third, the accuracy of the model (in terms of pulsatile blood flow profile and structure of the vasculature) cannot be fully guaranteed. Patient-specific model parameterisation is challenging because it is not possible to model the constant fluctuations of physiological metrics, which differ according to lifestyle, culture and even genetic makeup (e.g. sudden changes in blood pressure as a result of movement). Further understanding of the relative importance of such patient-specific data is required to determine which are the most influential and which can be assumed or averaged.

The benefit that CFD can bring in the diagnosis, prediction and treatment of complex aortic pathologies is tremendous, especially in the areas of improving EVAR treatment outcomes (given its ubiquity) and using image-based CFD in clinical decision making. The prospective design of an integrated image-based CFD framework would be an invaluable tool to allow cardiovascular surgeons to simulate pre- and post-procedure complications of different treatment options in order to decide which procedure would be in the best interest of patients. The use of CFD in such applications will continue to revolutionise the way in which doctors provide patient-centric care.

Conflict of Interest

No conflicts of interest have been declared.

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