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A numerical model to investigate aorta coarctation

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Abstract

In the past few decades, significant strides in computer technology have empowered the examination of diverse phenomena previously beyond reach. This progress has particularly allowed for the intricate exploration of human physiology. Of notable interest to scientists is the numerical analysis of blood flow, which has emerged as a highly fruitful area of study. In recent years, computational fluid dynamics (CFD) has been applied in the clinical field to elucidate blood flow in physiological and pathological situations. In this study, velocity, flow and Wall Shear Stress parameters were evaluated in the case of an arterial vessel affected by coarctation. The simulations were carried out starting from a patient's specific geometry. The simulations done provide very precise values of the identified parameters. Other simulations can be carried out to verify what happens by reducing the percentage of stenosis. This could be useful to optimize the type of intervention.

Keywords: CFD; Aorta; Coarctation

1. Introduction

Coarctation of the aorta (CoA) accounts for 6%–8% of congenital heart defects [Roger et al. 2011, Jenkins et al. 1999]. This pathology increases afterload and reduces peripheral perfusion pressures. Particularly, pressure increases in upper extremities and head, aorta and aortic valve dilate. Otherwise, pressure decreases in lower extremities, so that perfusion to kidney decreases and it is possible to cause reversed flow in posterior intercostal arteries [Schneeweiss et al 1982]. There have been significant advances in the diagnosis and management of coarctation with the development of imaging and rapid progress in interventional techniques. The growth of coordinated care for patients with adult congenital heart disease in developed countries has also led to improvements in outcomes. There is rising evidence that CoA represents a generalized arterial disease, leading to increased cardiovascular risk throughout the patient's life and the need for lifelong follow-up with a specialist in adult congenital heart disease [Forbes et al. 2011]. Recent evidence indicates that CFD can offer additional hemodynamic parameters, which have the potential to forecast the progression of aortic lesions, the impact of surgical interventions, and patient prognosis [Song et al. 2023, Ong et al. 2019]. More specifically, a scientific contribution [Qin et al.2023] aimed to evaluate the morphology and arch development of aortic arches in CoA patients. The authors used computational fluid dynamics (CFD) to describe the kinetic significance of special aortic arch morphology in patients with CoA, thus providing more powerful clinical references. In a different study [Rafiei 2021], the innovative computational simulations were implemented incorporating fluid–solid interaction models, with the aim to advance non-invasive methods for quantifying global and local hemodynamics across varying severities of CoA. In order to increase knowledge on this specific pathological condition, the aim of our work is to develop a computational fluid dynamics model useful to study the blood hemodynamic behavior in the pathological vessel. In the paper, the geometric model and the mathematical model used are initially described. The calculated parameters and the results obtained are subsequently described.

2. Materials and Methods

A three-dimensional patient-specific model of the aorta of a patient affected by CoA with three epiaortic vessels was obtained from *in vivo* CT-scan slices, done for clinical reasons, using a commercial software. The derived faced surface was simplified for the CFD analysis by using the reverse engineering process (Figure 2 and Figure 3).

Based on the 3D model, a study was carried out by solving the model numerically **by following a CFD procedure (figure 1)** with the commercial finite element analyzer, solver, and simulation software package Comsol Multiphysics version 6.1 (Comsol Inc., Burlington, MA, USA). Ascending aorta flow waveform were considered as inlet of CFD models, and pressures were imposed at outlets [Raffa et al. 2020]. To eliminate non-linear start-up effects, three consecutive cardiac cycles were considered. For the analysis of the results only the last three cycles were taken into consideration.

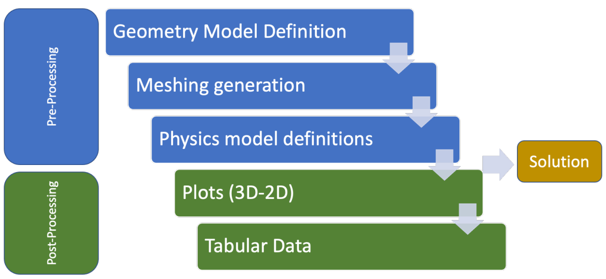

Figure 1. Workflow for the CFD process.

For the convergence of CFD simulations, a mesh quality check was performed using grid convergence index analysis. The blood flow was assumed laminar and Newtonian since aorta is a large vessel, with density of 1060 kg/m^3 and viscosity of 0.0035 Pa*s [Gramigna et al. 2015, 2023 Lee et al. 2008, Fragomeni 2023]. The meshes had boundary layers and both tetrahedral and triangular elements, according to the geometry. The meshes were optimized by analysing the error trend as a function of simulation time and consisted of about 1300000 elements.

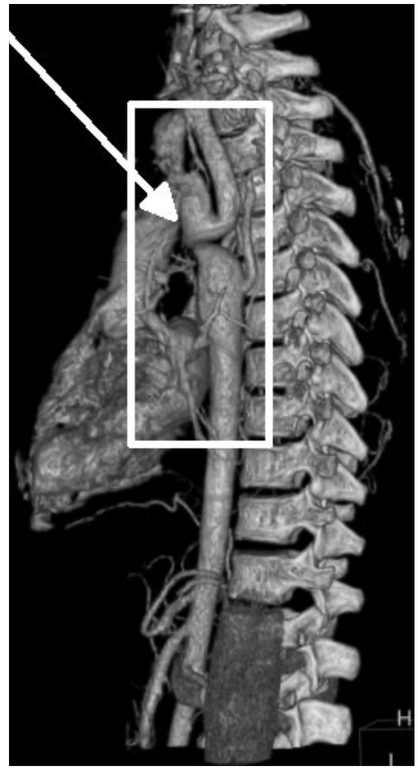

Figure 2. CT-scan image showing the aorta coarctation.

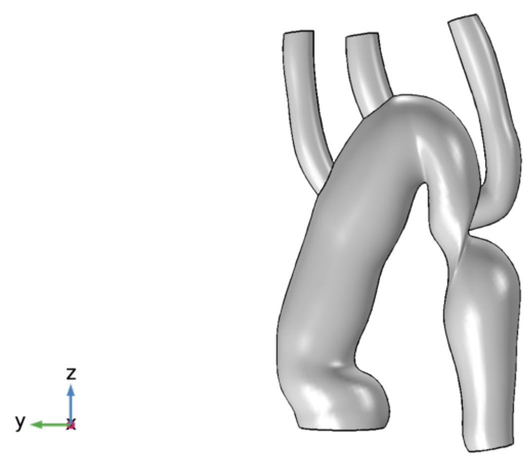

Figure 3. 3D model reconstruction.

3. Results and Discussion

Flow velocity, wall shear stress and related parameters (OSI, RRT and TAWSS) were calculated. These indices are responsible for the change of morphology and the orientation of the tissue of the artery [Caruso et al. 2015]:

Wall shear stress is calculated as:

$$WSS = \sqrt{(\tau_x)^2+(\tau_y)^2+(\tau_z)^2} \quad (1)$$

where τ is the viscous stress. Wall shear stress is calculated near the wall of the vessel [Caruso et al. 2015, Gaudio et al. 2017].

Time-averaged Wall Shear Stress (TAWSS) is calculated considering the expression:

$$\text{TAWSS} = \frac{1}{T}\int_0^T |\text{WSS}|\, dt \qquad (2)$$

defined by integrating each nodal wall shear stress value over the cardiac cycle [Caruso et al.2015].

The dimensionless Oscillatory Stress Index (OSI) is defined as:

$$\text{OSI} = \frac{1}{2}\left[1- \frac{\left|\int_0^T \text{WSS}\, dt\right|}{\int_0^T |\text{WSS}|\, dt}\right] \qquad (3)$$

and it is a parameter which calculates the wall shear stress when it is aligned with the TAWSS during the cardiac cycle [Caruso 2015].

TAWSS and OSI could be arranged in the relative residence time (RRT) as indicated:

$$\text{RRT} = [(1-2 \cdot \text{OSI}) \cdot \text{TAWSS}]{-}1 \qquad (4)$$

that represents the residence time of fluid particles near the vessel. Therefore, it can be viewed as a stagnation index [Lee et al. 2008].

The numerical results indicate that the flow is changed in the descending aorta due to the presence of the coarctation.

More specifically, all the calculated parameters increase in the stenosis area, as illustrated in Figure 4-8. This leads to a significant impact of the pathology itself on all hemodynamic parameters. These variations could be mitigated by using a method of hemodynamic correction (for example, the insertion of a stent) [Gaudio et al. 2017, Tradigo et al. 2022]. The value of the various parameters could be estimated before the intervention through other simulations to better plan the type of intervention to be carried out.

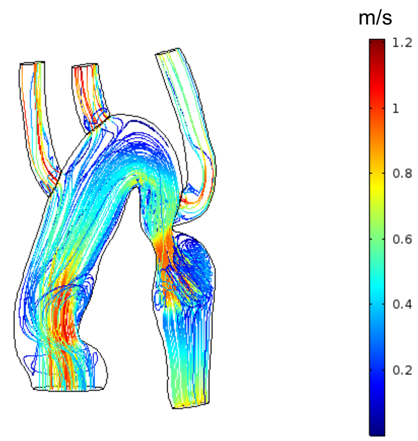

Figure 4. Flow velocity inside the pathological vessel represented though streamlines

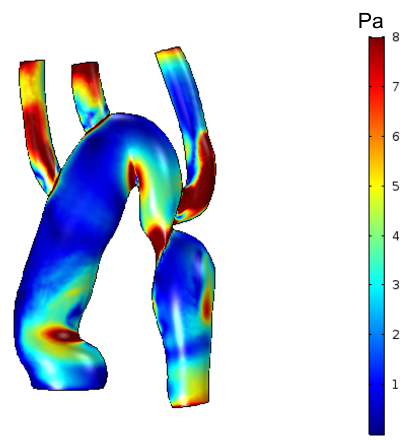

Figure 5. Wall Shear Stress.

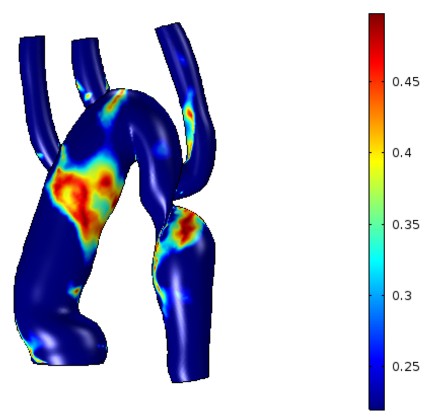

Figure 6. Oscillatory Stress Index.

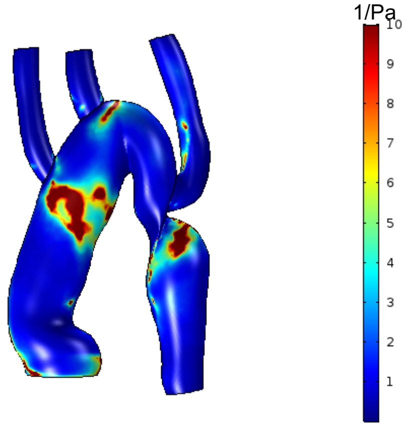

Figure 7. Relative residence time.

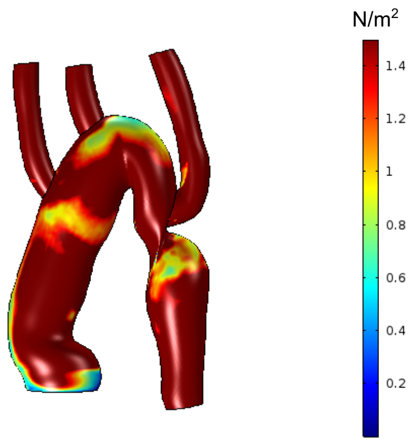

Figure 8. Time-averaged Wall Shear Stress

Although this study can be seen as a promising tool to improve the existing knowledge of pathologies effects on aortic hemodynamics, it presents several limitations that have to be underlined. The initial assumption is the hypothesis of rigid surfaces, neglecting wall compliance and enforcing the no-slip boundary conditions. This hypothesis was adopted to reduce the simulation time and is helpful for obtaining initial results. Indeed, CFD results can be considered before implementing fluid–structure interaction (FSI) models, which will be examined in the future phases of this preliminary computational study. Additionally, we assumed blood to be an incompressible fluid, which is a widely accepted assumption for vessels as large as the aorta. For future research directions, to estimate the transitional flow in the aorta and its major branches, we plan to use a low Reynolds number model (k-omega). Despite these simplifications, the CFD simulation remains a valid and innovative tool to aid clinicians in their decision-making.

4. Conclusions

The obtained results agree with literature and highlight that simulations based on CT anatomical data and adequate flow conditions can be used successfully to predict the hemodynamic changes in patients with coarctation. This could allow the type of surgery to be optimized, also reducing costs. Our study demonstrated that computational fluid dynamics method, as an amalgamation of medical and engineering disciplines, possesses the capability to compute intravascular hemodynamic parameters utilizing imaging data and can achieve notable advancements in the diagnosis, treatment, and monitoring of conditions such as intracranial aneurysms, aortic dissections, atherosclerosis, and other vascular diseases.

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