Non-invasive functional assessment in coronary artery using reduced order one dimensional CFD model.

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ABSTRACT

Time is a crucial factor for clinicians in taking clinical decisions. At present, 3D modelling of the entire arterial tree is not feasible. Due to a lack of detailed information about 3D geometry and material properties, the computational time needed to model such a massive network of branching arteries, including the fluid-structure relationship between blood and vessel walls, is massive. One-dimensional modeling is becoming an important method for better understanding blood flow in the arterial circulation and how it is affected by multiple interventions and diseases. Coronary heart disease (CHD) is one of the leading causes of mortality worldwide. For varying degrees of severity, the patient-specific Multislice CT scan is segmented into the CAD model and integrated into the one-dimensional numerical model. Using one-dimensional equations, a computational assessment of the whole arterial tree with a stenosed coronary artery is performed. An analytical equation is used as the basis for modelling the geometry of the stenosed portion. The forward and backward characteristic variables, which are solutions to the 1D characteristic system of equations, are used to determine unknown variables like area and velocity. A resistance model with a zero reflection coefficient is taken into account at the outflow with a realistic pressure waveform as the input. Numerical simulations are carried out for a single cardiac cycle, which consists of the systole and diastole. Fractional Flow Reserve (FFR) and instantaneous wave-free ratio are computed for patient-specific scenarios. With increasing stenosis severity, a decrease in FFR and iFR is observed.

Keywords—*Blood flow*; *CFD; FFR; iFR ;*

I. INTRODUCTION

A disease condition called coronary heart disease kills over 20 million individuals per year worldwide. The percentage of deaths brought on by this illness in India increased from 17% in 2001–2003 to 23% in 2010–2013 [1]. Thus, any fast and credible way to assess coronary artery diseases anywhere in the globe will improve succession planning. For really severe coronary occlusions, it is also simple to decide whether to execute an angioplasty or a more effective surgical repair treatment. Medicine has been used traditionally to treat moderate coronary heart disease. The majority of CHD patients, however, fall between a very mild and severe situation. For physicians to make the appropriate decision in this predicament, the aforementioned situation offers a complex scenario. Clinical parameters determined by invasive procedures are used to answer this conundrum. For the management of medically treated stenosis and the consequences of expenditure, these invasive approaches fall short [2]. iFR and fractional flow reserve are two approaches that are more frequently employed as a substitute for flow measurements when measuring coronary pressure. Cardiologists employ a combination of these procedures, the patient's medical history, current symptoms, and clinical risk factors to determine if a stenosis needs further treatment. To quantify clinical factors like the FFR value of the 3D arterial geometry, a computed tomography angiography (CTA) creates 3D reconstructions of the major blood arteries and heart of the patient. Due to the non-intrusive nature of this procedure, there is no risk of injury. Clinical parameter values that can be acquired by invasive procedures are estimated using 3D modelling. Due to the necessity for a realistic stenosis structure and the usage of closing blood arteries as a lumped model, which accounts for the overall cost of computing inside the 3D computational domain, a large amount of time is required for computation. A 3D numerical model was employed in several prior research to estimate FFR. However, 3D numerical investigations demand a significant investment in computer power, whereas 1D simulations take considerably less time and resources to do. A 1D model may be used to do the computational study of a whole arterial network with stenosis in one of the blood arteries with reasonable accuracy and little computational expense. Sherwin et al. [3] provided guiding equations that control blood flow via the blood arteries. The connections between the coronary flow system and the human systemic circulatory system were developed by Mynard and Nithiarasu [4]. This relationship between the two systems is taken into consideration in a comprehensive 1D computer model of the arterial network. This work used numerical simulation to create a cardiac model in the arterial circulation. A comparison of the haemodynamic parameters derived from 1D and 3D models in coronary arteries was described in several publications [5, 6]. Researchers at the outlet used a variety of boundary conditions to compute the hemodynamic parameters [7.8,9].

A reduced order CFD model that can predict numerous clinical parameters using CT scan is necessary rather than employing an intrusive diagnostic procedure. The 1D CFD model used in the study incorporates the patient-specific CT scan data. In the current study, the changes of several haemodynamic parameters, including Pressure drop, FFR and iFR, with severity are investigated.

II. METHODOLOGY

A. One dimensional governing equations

The blood vessel is depicted as having a form that resembles a cylindrical vessel with a surface that can move along the wall. The 1D equations for mass and momentum conservation are provided in work done by Sherwin et al [4] and are

$$\frac{\partial A}{\partial t} + \frac{\partial (Au)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{f}{\rho A} = 0 \tag{2}$$

Where the cross-sectional area is assumed to be A, the average space velocity across the flow area is u, the blood density (ρ) is 1060 kg/m3, p is assumed to represent the pressure inside the blood artery, and f is the force caused by friction. For the purpose of modelling the friction term, laminar flow conditions that correspond to Poiseuille flow are assumed [4, 5]. By adding additional restrictions that align the pressure with the vessel's cross-sectional area, the equation system is closed. Elasticity (wall behaviour), wall thickness, and Poisson's ratio all affect the scaling factor that determines how much pressure is applied to a given area. Formaggia et al. [10] and Olufsen et al. [11] provide the relationship between them.

$$p = p_{ext} + \beta\left(\sqrt{A} - \sqrt{A_0}\right) \tag{3}$$

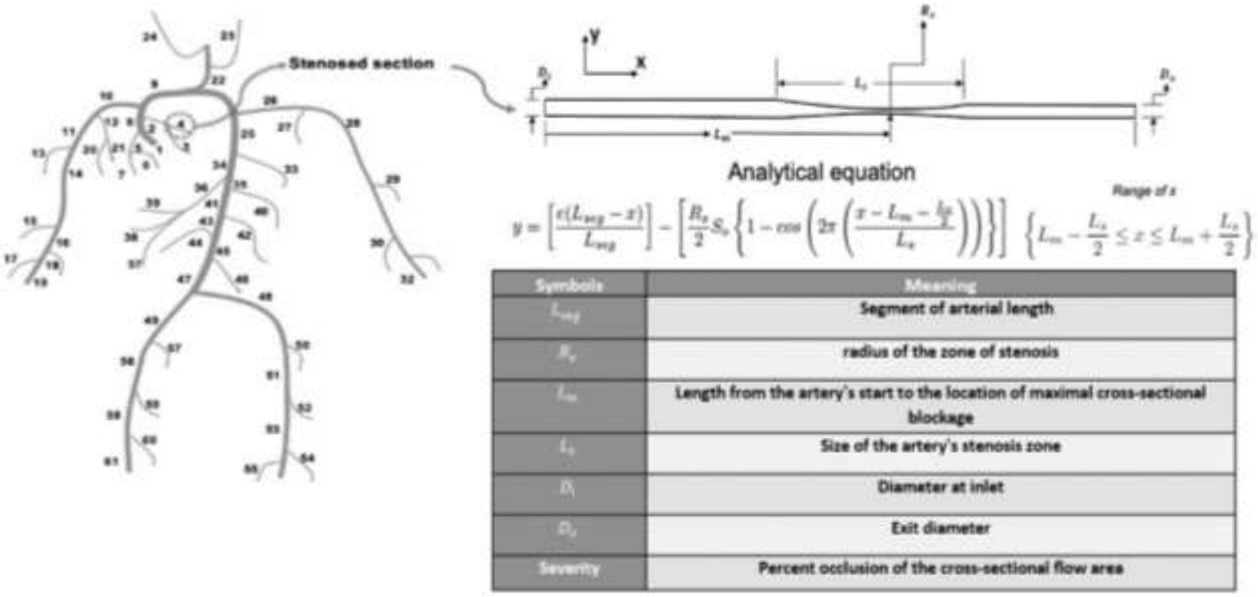
A_0 is the cross-section where it is assumed that the transmural pressure is zero (i.e., p = p_{ext}), p_{ext} is the transmural pressure, and are the physical characteristics of the blood vessel's material.

$$A = \frac{(W_1 - W_2)^2}{1024}\left(\frac{\rho}{\beta}\right)^2 \tag{4}$$

$$u = \frac{1}{2}(W_1 + W_2) \tag{5}$$

Equations 4 and 5 below compute the unknown parameters, such as velocity (u) and area (A), based on forward and backward travelling characteristics. The properties of the forward and backward travelling waves are denoted by W_1 and W_2 in equations 4 and 5. Locally Conservative Galerkin (LCG) is used in the computational simulation[4,12]. Each discretized element is treated as a separate sub-domain with its own computational constraints in this numerical approach.

B. **Computational domain of the study**



$$y=\left[\frac{\varepsilon(L_{seg}-x)}{L_{seg}}\right]-\left[\frac{R_s}{2}S_v\left\{1-\cos\left(2\pi\left(\frac{x-L_m-\frac{L_s}{2}}{L_s}\right)\right)\right\}\right]\quad\left\{L_m-\frac{L_s}{2}\leq x\leq L_m+\frac{L_s}{2}\right\}$$

Symbols	Meaning
L_{seg}	Segment of arterial length
R_s	radius of the zone of stenosis
L_m	Length from the artery's start to the location of maximal cross-sectional blockage
L_s	Size of the artery's stenosis zone
D_i	Diameter at inlet
D_o	Exit diameter
Severity	Percent occlusion of the cross-sectional flow area

Figure 1: Arterial tree with stenosed section modelled with analytical equation

The full arterial network is simulated and shown in Fig. 1 for both systemic and coronary circulation. The blood vessels and their modelling parameters were used in the current investigation and were obtained from the work of Mynard et al. [4]. The left endocardial artery is modelled as a stenotic artery, whereas all other segments of the arterial tree are modelled as regular. The analytical equation has been modified by include the blood vessel's tapering design as seen in Fig. 1, and the updated locus equation is also displayed there. The various severity cases are considered for different blockage percentage. Case A, Case B and Case C have percentage of area blockage of 70, 50 and 40 respectively. The CFD model incorporates the numerous patient-specific cases data that were collected from the hospital and the above three cases are utilized for the present study.

C. **One dimensional boundary condition**

The schematic design in Fig. 2 illustrates how boundary conditions were included in the 1D numerical model. At the arterial tree inlet, the pressure boundary condition that was produced using the sigmoid function is used. The outlet is assigned a reflection coefficient of zero. The literature [4] contains the specifics of the reference work on the boundary condition prescription employing characteristics variables.

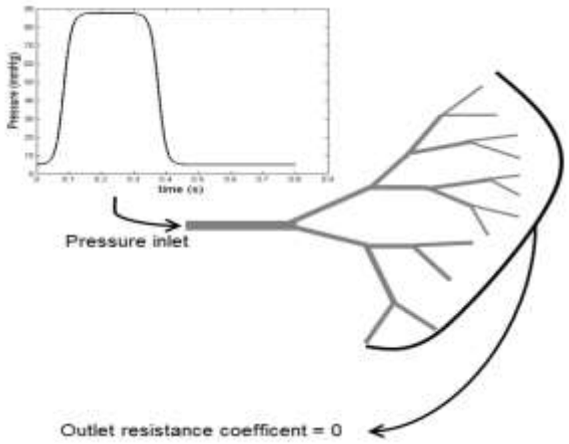


Figure 2: An arterial tree schematic showing a stenosed section

D. **Validation study**

The current simulated (present) findings are displayed in Figs. 3 and 4. These results are shown in contrast to the computational results displayed by Low et al. [13]. The validation research will focus on the right ascending aorta and right carotid artery. During typical conditions and cardiac function, it is discovered that the waveform trend of pressure and flow is in good accord. You may read about the reference work's specifics on prescribing boundary conditions utilising characteristics variables in the literature [4].

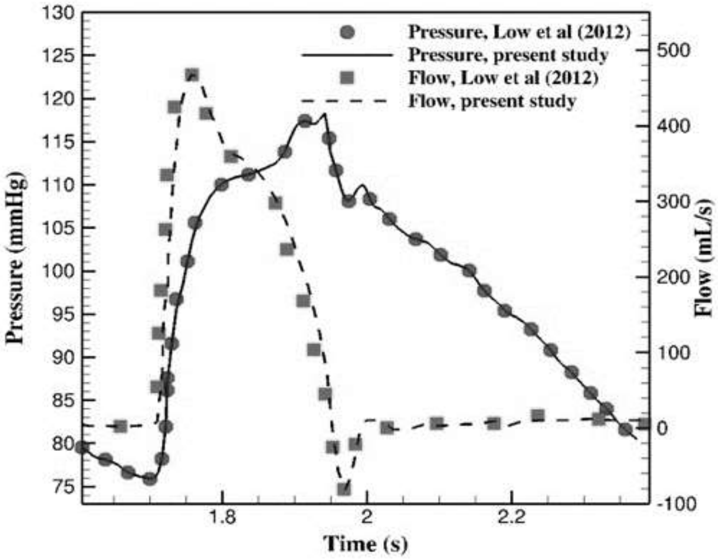


Figure 3: Ascending aorta waveforms were compared to the research reported by Low et al. [17]

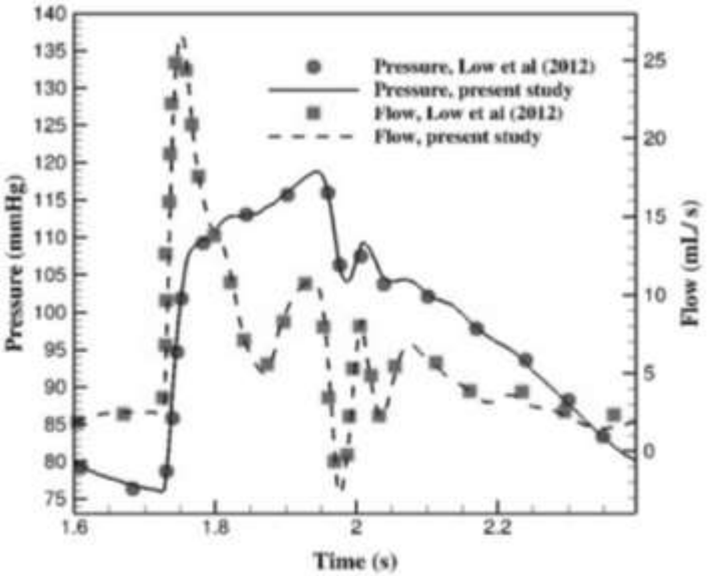


Figure 4: Right Carotid artery waveforms were compared with the research of Low et al. [13]

E. Grid independence study

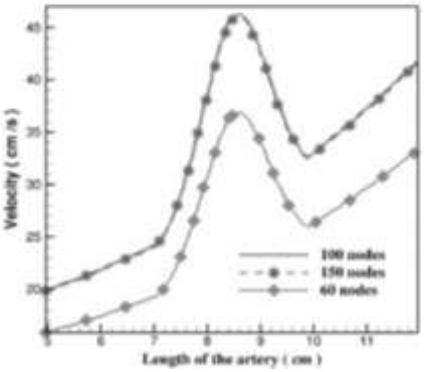


Figure 5: Axial velocity change with artery length for different grid sizes

Three mesh sizes of 50, 100, and 150 grid points are used in the numerical analysis for a certain severity condition. As shown in Fig. 5, the velocity magnitude along the artery's axial direction is calculated and contrasted with the three mesh sizes. It is discovered that the mesh sizes of 100 and 150 exhibit a similar pattern. 100 grid points are therefore taken into account for each artery segment in the numerical simulation.

III. Parameters to be investigated

A. Fractional flow reserve (FFR)

A diagnostic technique for determining severity is the pressure ratio in the stenosed coronary artery. The fractional flow reserve (FFR) ratio is referred to as such [2]. As seen in Fig. 6, Pd and Pp represent the pressures before and after the stenosed location, respectively.

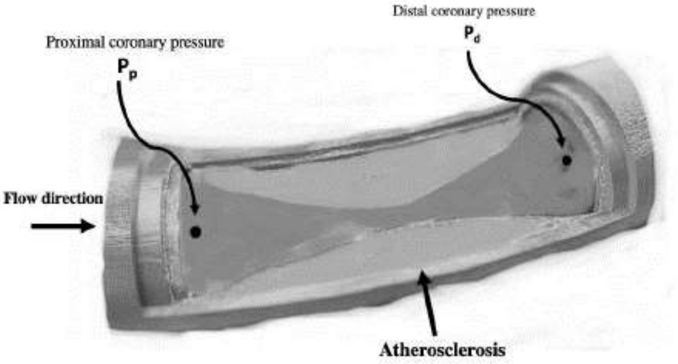


Figure 6: Location of the FFR measurement in the coronary artery in terms of location

$$FFR = \frac{P_d}{P_p} \qquad (7)$$

The patient's evaluation procedure to identify the severity of stenosis is invasive. The treatment entails inserting a wire probe into the coronary artery of the patient and moving it to the site of the stenosis for inspection. Equation 7 is an example of the FFR equation.

B. Instantaneous wave-free ratio (iFR)

A diagnostic technique for identifying if a stenosis is limiting blood flow in coronary arteries and resulting in ischemia is the instantaneous wave-free ratio (iFR) [14]. During the wave-free phase, when stenoses are flow limiting, Pd and Pp pressures diverge. Pd/Pa ratios typically range from 1.0 to 0.90, while iFR levels below 0.90 signify flow limitation. iFR is often measured with an average of five heartbeats, although it may alternatively be done with just one. The wave free period is depicted in Fig. 7.

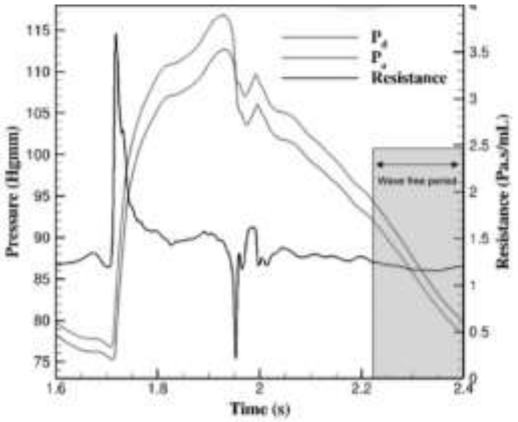


Figure 7: Pressure and resistance change with time at different arterial location

IV. Results and discussion

Fig. 8 depicts the real volume flow rate via diseased coronary arteries for various patient-specific circumstances. Systole and diastole are the two stages of the heart cycle. The pressure differential that drives the blood flow in a coronary artery during the cardiac cycle is significant. The flow is subsidiary if the pressure difference is less than the transmural pressure.

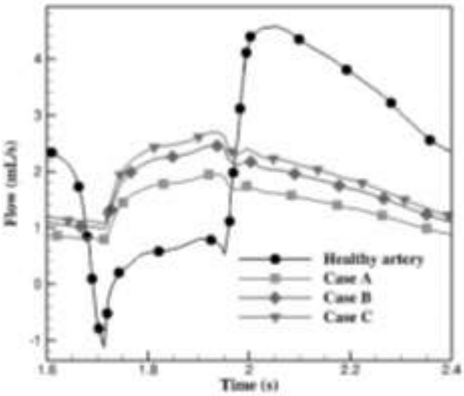


Figure 8: Flow rate for various severity cases

The diastolic phase of the cardiac cycle is when the main flow occurs because the pressure difference is greater than the transmural pressure. According to many publications, the flow increases in the sick condition compared to the normal artery during the systolic phase of the cardiac cycle [7,15]. Fig. 8 illustrates the increase in flow during the systolic portion of the heart cycle.

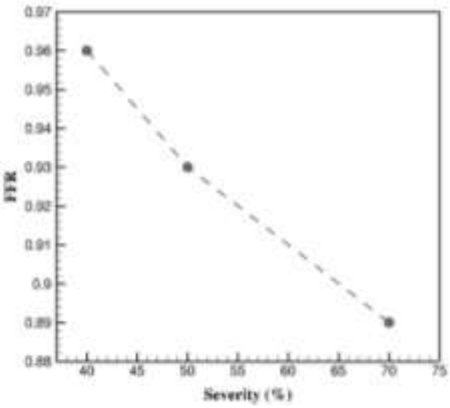


Figure 9: Variation of FFR with severity

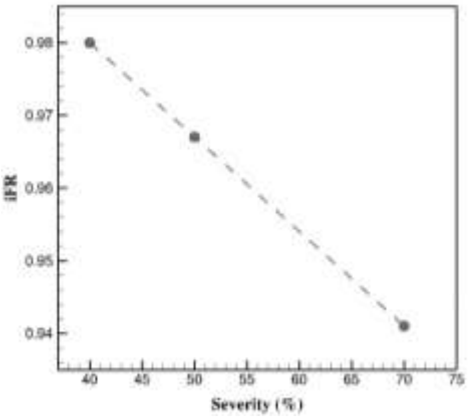


Figure 10: Variation of iFR with severity

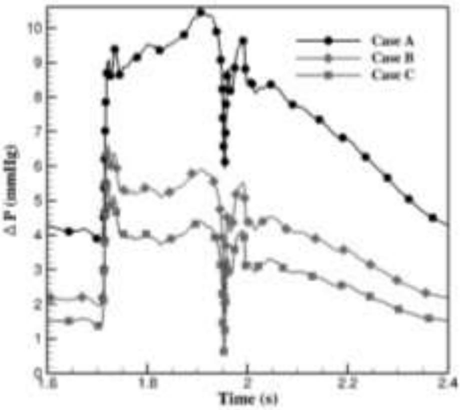


Figure 11: Temporal change of pressure drop at a certain arterial segment

According to numerous publications, the FFR is calculated for various patient-specific situations and is discovered to be declining with severity [5,14]. Fig. 9 depicts the FFR variation with severity. In a similar manner, iFR is calculated for various circumstances. According to numerous pieces of literature, the iFR was discovered to be decreasing with severity [14,16]. Figure 10 shows the iFR variation with severity. Different severity scenarios are estimated for pressure decrease (P). The pressure decrease is greatest for the most severe conditions and lowest for the least severe conditions. Figure 11 depicts the pressure drop fluctuation over time for various severity instances. According to research, pressure decrease was observed to be escalating with severity [17].

V. Conclusions

Due to the time required to compute haemodynamic parameters for clinical judgments, carrying a full-scale CFD model is not practically practicable. In this work, it is determined if a one-dimensional (1D) blood flow model can accurately predict clinically significant parameters from CT scan data. With the help of the locally conservative Galerkin technique, numerous clinical parameters are calculated using a reduced-order model for instances of varying severity (LCG). The severity was determined to be lowering FFR and iFR. In place of the model with resistance, the windkessel model may be used at the vessel terminal. It could be able to estimate clinical parameter values fairly and might improve the 1D model. It would likely increase model quality to include a non-Newtonian fluid as well, but doing so would be computationally challenging and time-consuming. A reduced-order model is used to aid doctors in reaching a clinical judgement as opposed to using an intrusive procedure.

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