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Effect of angulation and Reynolds number on recirculation at the abdominal aorta-renal artery junction

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Abstract We investigate the effect of renal artery angle variation and Reynolds number on the probability of formation of atherosclerosis-prone regions at the abdominal aorta-renal artery junction. The rheologically accurate shear-thinning Yeleswarapu model for blood is used to simulate flow in a 3-Dimensional T-junction whose dimensions are those of the human abdominal aorta-renal artery junction. The recirculation length and wall shear stresses are evaluated at the junction for steady, laminar flow using ANSYS FLUENT v14.5. The recirculation length and wall shear stresses are calculated for Reynolds number of 500–1500, and the angle of renal artery (with the horizontal axis) of -20° to $+20^\circ$. Computational fluid dynamics analysis for the flow conditions used in present study show that the flow recirculation and low wall shear stress regions overlap at the top surface of renal artery downstream of the entrance and at the curved surface of abdominal aorta downstream of the junction, making these regions susceptible to atherosclerosis. Further investigations show that positive angles of renal artery have larger area of recirculation and larger low wall shear stress regions. The recirculation length increases with Reynolds number, and it is maximum when $\theta = +20^\circ$, and minimum when $\theta = -20^\circ$.

Introduction

Blood is a bodily fluid which plays an important role in the functioning of the human body. Blood flows through complex formations like curvatures, bifurcations, and branches in the network of blood vessels, especially the coronary, abdominal, carotid and femoral vasculature.[1] At these formations the flow is non-axial, and the wall shear stress is low, leading, over time, to formation of atherosclerotic lesions due to deposition of fatty matter. Each formation has its own geometric peculiarities, and hence merit reporting of the flow features individually in a computational study. We select the abdominal aorta-renal artery junction for consideration in this study. This

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formation is very important since atherosclerotic disease, when it affects the renal arteries, can result in renovascular hypertension and ischemic nephropathy.[2] This is because the deposition of fatty matter (plaque) reduces the lumen area of the renal artery, and the kidney responds by activating the renin-angiotensin system to increase the blood pressure.[3]

Due to the recent increase in demand for the use of non-invasive tools and cutting edge technologies in biomedical engineering, Computational Fluid Dynamics (CFD) has been accepted as a tool to analyze fluid flow in human anatomy. The formation of atherosclerotic lesions,[4] thrombosis,[5] and calculation of Fractional Flow Reserve (FFR)[6] can each be predicted using CFD. In the context of atherosclerotic plaque, the combination of CFD and images from Computed Tomography (CT)/Magnetic Resonance Imaging (MRI) will give realistic, accurate hemodynamic values that will help in effective identification of plaque growth in complex formations. Blood flow has been simulated in bifurcations and junctions by assuming that it behaves as a Newtonian fluid.[7,8] Specifically, many recent articles, which have studied the flow of Newtonian fluid in abdominal aorta-renal artery junction, predict the growth of atherosclerotic plaque in both laminar and turbulent flows.[3,9,10] However, the Newtonian assumption is a simplification because blood is non-Newtonian: in specific, it exhibits shear-thinning,[11] viscoelastic[12] and thixotropic[13] behavior. There are several references [4,14–16] that show the importance of, and major differences between, using a non-Newtonian model over a Newtonian model for blood. In this study we use a non-Newtonian model for blood: in particular, we use a shear-thinning model as a first step.

Generalized Newtonian models that capture the shear thinning behavior of blood have been applied to understand the flow mechanics in bifurcations: these include the Casson,[17] the Power-law,[18] and the Carreau-Yasuda model.[19] The earliest 3-Dimensional (3-D) frame-invariant model for blood, which had a function specifically fitted to shear-thinning viscosity data of human blood over a range of 0.05 s^{-1} to 600 s^{-1}, was the model described in Yeleswarapu et al.[15] Henceforth, we refer to this model as the Yeleswarapu model. The shear-thinning Yeleswarapu model has been used in steady and pulsatile flow simulations in an axisymmetric cylindrical pipe,[20] axisymmetric stenosed pipe,[21] and stenosed 2-D channel.[14] However, the full potential of the model can be achieved only in CFD simulations of flow in 3D reconstructions of arterial branches in the human vasculature. In this work, we do this and then detail the hemodynamic insights gained from the flow analysis.

The present work deals with the CFD analysis of steady flow of blood, modeled using the shear thinning Yeleswarapu model, in a 3-D T-junction with the same dimensions as those of the human abdominal aorta-renal artery junction. The following range of conditions are used: Reynolds number (Re) = 500–1500 (this range is chosen as the flow in undiseased renal artery is laminar, and Re typically varies between 400 and 1100[22]), and variation of renal artery angle θ with respect to horizontal axis = $-20°$ to $+20°$.[23,24] The problem is formulated in Section Method: the flow geometry is described, the model is introduced, the balance equations that need to be solved are written, and the numerical scheme is also detailed. The validation for the UDF implemented in our numerical analysis is given in Section Validation of methods. The results and discussion are given in Section Results and Discussion, respectively. A brief summary and possible future extensions of this work are given in Section Conclusions.

Method

Geometry

A 3D symmetric T-junction geometry representing the intersection of the renal artery and the abdominal aorta is generated in ANSYS 14.5. The 2-Dimensional (2-D) cross-sectional view of the junction is given in Fig. 1, and this clearly indicates θ to be the angle between the renal artery and the horizontal x-axis. Here, the dimensions (diameters, but not lengths) and angles of the T-junction are those of the abdominal aorta-renal artery junction as taken from clinical references[23–25]. The lengths of the abdominal aorta section and renal artery sections are chosen such that their effect on the computed recirculation length is minimum.

A preliminary test is done to determine the length of the renal artery for which predictions of the reattachment length vary within acceptable limits. The length of renal artery branch is varied in multiples of the main branch diameter (D) as 5D, 10D, 15D and simulations are carried out at Re = 1000, which is a typical number for this geometry. The relative percentage difference of reattachment length was 0.64% for change in length from 10D to 15D, and hence 10D is chosen for further simulations.

Governing equations

We simulate the steady flow of blood, and model blood as a shear thinning fluid as a first step to assess the effect of non-Newtonian behavior on hemodynamic predictions in 3D geometries. The governing equations for steady, laminar,

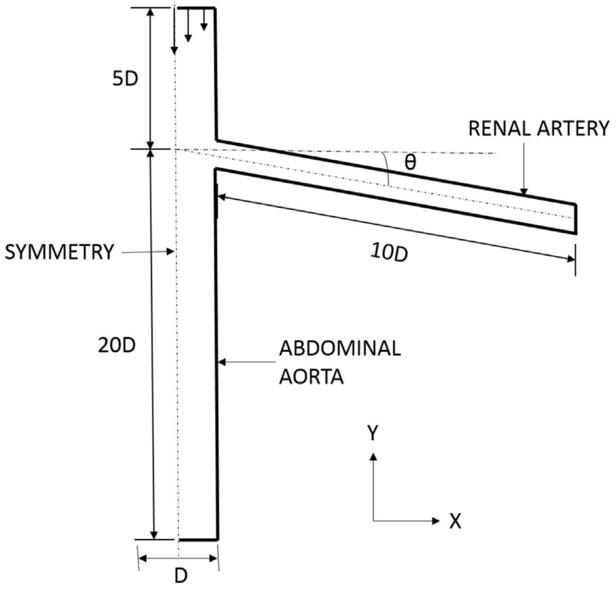

Figure 1 2D representation of abdominal aorta-renal artery junction.