The Rheology of Blood Flow in a Branched Arterial System

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Abstract:
Blood flow rheology is a complex phenomenon. Presently there is no universally agreed upon model to represent the viscous property of blood. However, under the general classification of non-Newtonian models that simulate blood behavior to different degrees of accuracy, there are many variants. The power law, Casson and Carreau models are popular non-Newtonian models and affect hemodynamics quantities under many conditions. In this study, the finite volume method is used to investigate hemodynamics predictions of each of the models. To implement the finite volume method, the computational fluid dynamics software Fluent 6.1 is used. In this numerical study the different hemorheological models are found to predict different results of hemodynamics variables which are known to impact the genesis of atherosclerosis and formation of thrombosis. The axial velocity magnitude percentage difference of up to 2 % and radial velocity difference up to 90 % is found at different sections of the T-junction geometry. The size of flow recirculation zones and their associated separation and reattachment point's locations differ for each model. The wall shear stress also experiences up to 12 % shift in the main tube. A velocity magnitude distribution of the grid cells shows that the Newtonian model is close dynamically to the Casson model while the power law model resembles the Carreau model.

Zusammenfassung:
Die Rheologie von Blutströmungen ist ein komplexes Phänomen. Gegenwärtig existiert kein allgemein akzeptiertes Modell, um die viskosen Eigenschaften von Blut wiederzugeben. Jedoch gibt es mehrere Varianten unter der allgemeinen Klassifikation von nicht-Newtonschen Modellen, die das Verhalten von Blut mit unterschiedlicher Genauigkeit simulieren. Die Potenzgesetz-, Casson und Carreau-Modelle sind beliebte nicht-Newtonsche Modelle und beeinflussen die hämodynamischen Eigenschaften in vielen Situationen. In dieser Studie wurde die finite Volumenmethode angewandt, um die hämodynamischen Vorhersagen dieser Modelle zu untersuchen. Um die finite Volumenmethode zu implementieren, wurde die Fluiddynamiksoftware Fluent 6.1 verwendet. In dieser numerischen Studie wurde gefunden, dass die unterschiedlichen hämorheologischen Modelle unterschiedliche Resultate für die hämodynamischen Größen vorhersagen, von denen bekannt ist, dass sie die Entstehung von Arteriosklerose und die Bildung von Thrombose beeinflussen. Es wurde gefunden, dass die relative Differenz der axialen Geschwindigkeit bis zu 2% und die der radialen Geschwindigkeit bis zu 90% in unterschiedlichen Abschnitten der T-Verbindung beträgt. Die Größe der Strömungszirkulationszonen und ihrer dazugehörigen Trennungs- und Vereinigungspunkte differieren für jedes Modell. Die Scherspannung an der Wand erfährt ebenfalls eine Verschiebung im Hauptrohr von bis zu 12%. Der Verlauf der Geschwindigkeit auf den Gitterzellen zeigt, dass das Newtonsche Modell mit Bezug auf die Dynamik dem Casson-Modell nahe ist, während das Potenzgesetzmodell dem Carreau-Modell ähnlich ist.

Résumé:
La rhéologie de l'écoulement sanguin est un phénomène complexe. Présentement, il n'y a pas de consensus universel sur le modèle qui représente la propriété visqueuse du sang. Cependant, parmi la classification générale des modèles non-Newtoniens qui simulent le comportement du sang avec différents degrés de précision, il y a plusieurs différences. Les lois de puissance, les modèles de Casson et Carreau sont des modèles non-Newtoniens populaires et ont un effet sur les quantités hémodynamiques sous plusieurs conditions. Dans cette étude, la méthode de volume fini est utilisée pour explorer les prédictions hémodynamiques de chacun de ces modèles. Pour implémenter la méthode de volume fini, le logiciel de calcul de dynamique des fluides Fluent 6.1 a été utilisé. Dans cette étude numérique, les différents modèles hémorhéologiques tendent à prédire des résultats différents pour les variables hémodynamiques qui sont reconnues comme ayant un impact sur la genèse de l'artériosclérose et de la thrombose. Une différence jusqu'à 2% dans l'amplitude de la vélocité axiale et une différence jusqu'à 90% dans la vélocité radiale sont découverts dans différentes sections d'une géométrie de type jonction en T. La taille des zones de re-circulation d'écoulement et les localisations des points de séparation et de rattachement qui leur sont associées, diffèrent pour chacun des modèles. La contrainte de cisaillement aux parois présente également un déplacement de 12% dans le tube principal. La distribution de l'amplitude de vitesse dans les cellules du maillage montre que le modèle Newtonien est dynamiquement proche du modèle de Casson tandis que le modèle en loi de puissance ressemble au modèle de Carreau.

Key words: hemorheology, Newtonian model, non-Newtonian models, wall shear stress, atherosclerosis, thrombosis, wall shear stress, recirculation zone

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osclerosis [30]. Previous studies seldom consider the effect of non-Newtonian rheology on radial velocity and the comparisons that we can draw.

Previous numerical studies of arterial blood flow and low-density lipoprotein (LDL) transport in T-junction geometry shows the recirculation zone size increases with increase of Reynolds number [32]. The same study also shows that the peak of the mass transfer distribution of LDL from the lumen to the wall is the largest at lower Reynolds number and the peaks are observed at reattachment points. This shows that the observed variation in vortex size of flow recirculation zones indicated in Figure 7 between Newtonian and non-Newtonian models is resulted from variation in shear rate dependence of the models and can affect hemodynamics description of atherotherombogenesis.

The WSS, the other important hemodynamics physical quantity, also depends on constitutive equations (Fig. 8). The WSS variation on blood flow rheology models has different patterns at different wall sections of the T-junction model. The WSS at the upper wall of the main tube shows the largest contrast showing a maximum percentage difference of 12 % (Fig. 8A). The side branch walls however show the minimal contrast (Figs. 8C and D). Previous numerical study on the effect of non-Newtonian viscosity of blood on flows in a human coronary artery casting shows that the non-Newtonian model yields a larger WSS than a Newtonian model [7]. Another flow simulation study in a forty five degree end-to-side anastomoses model and study at aortic and carotid artery bifurcation reveals that non-Newtonian blood rheology has a significant effect on steady and unsteady flow WSS [16 – 18]. Numerical study on non-Newtonina blood rheology in different coronary artery shows that different models render varying prediction of WSS magnitude. However the patterns of WSS are similar [26].

5 CONCLUSIONS

Blood rheology is a complex property and there is no agreeable single model for its representation. These diverse models affect hemodynamics descriptions to different degrees. The axial velocity change of about 2 % is observed both in the main and branch tubes. The radial velocity profile which controls the convective flux of atherogenic cellular and plasma components to the artery wall experience the largest contrast that ranges up to 90 %. The size of the recirculation zone and the location of separation reattachment point's prediction vary for each model. The Newtonian model predicts the largest vortex length and the Carreau model predict the least which half in size. The variation in vortex strength can affect local mass transfer of atherogenic plasma protein and cellular blood components which regulate atherotherombogenesis. The wall shear stress which is known to modulate the behavior of the artery wall permeability also shows significant variation which ranges up to 12 %. Both the convective flux and WSS play roles in initiating arterial diseases. Therefore, the observed discrepancies can influence hemodynamics description of atherotherombogenesis and this signifies that for future and more profound hemodynamics studies of cardiovascular diseases a more universal and profound hemorheological model is essential.

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