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Blood flow of newtonian and non-newtonian fluid through blood vessels with flexible wall

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Abstract

The fluid-structure interaction between flexible wall and two types of fluid. Wall was considered as aorta and was described as hyperelastic material by 5-parameters Mooney-Rivlin model. Fluids and structure were set as incompressible. First fluid was Newtonian and has dynamic viscosity of the blood. Second was non-Newtonian and its viscosity was defined with Carreau rheology model. The aim of this investigation is to show a comparison between Newtonian and non-Newtonian blood fluid flow in pliable vessel.

Keywords: blood flow, newtonian, non-newtonian, flexible wall

Introduction

The cardiovascular diseases are one of lifestyle diseases and therefore cardiovascular system has to be explored. A general description of blood flow through blood vessels is not simple. Blood is heterogeneous fluid and material of blood vessels shows high elastic deformations. Many ways exist to solve this problem and one of them is numerical fluid-structure interaction (FSI), which couples computational fluid dynamic (CFD) and finite element method (FEM). This approach is young but it allows work with real parameters of cardiovascular system, which cannot be contained in experiments [1].

Blood rheology is described as non-Newtonian fluid, however some works [2] still solve this problem with Newtonian rheology model of blood. The objective of this research is to discover differences between FSI simulation with Newtonian and non-Newtonian fluid. Recently the oscillatory blood flow by viscosity shearing dependent model [3] and quantification in effective viscosity of fluid in porous medium by Brinkman equation [4] have been carried out.

Materials and Methods

Commercial software (ANSYS) was used for numerical calculation of FSI. Transient structural was used as solver of FEM and a fluid domain was solved by Fluent (software for CFD). Both of the software were connected with System coupling. Whole domain was simplified, because numerical solution of FSI is time consuming process. Cross section of domain was only quarter circle. The length of fluid domain was 270 mm and its radius was equal to 10 mm. The geometry of structural domain had length 70 mm and was put 100 mm from fluid domains inlet. Inner radius was equal to fluid domain radius and its thickness was 2 mm. Symmetry boundary condition was used in fluid domain and Frictionless support boundary condition was applied on structural domain.

Meshes of fluid and structural domains were made up of hexahedral elements. Mesh of the structural domain had 4 200 quadratic elements. 3 elements were defined in radial direction, 20 elements were set in tangential direction and 70 elements were used in axial direction. Mesh of fluid domain had 25 elements in radial and 20 in tangential direction and 270 in axial direction. Fluid part was constituted by 108 000 elements. Maximal skewness of elements was 0.67 for fluid domain and 0.03 for structural domain. Maximum aspect ratio was 6.87 for fluid domain and 1.52 for structural domain. Both solutions were calculated as transient. The size of time step was 0.005 and blood flow in tube was considered as turbulent. Therefore k-omega STT turbulent model was used. The geometry of both domains was changing during FSI calculation and therefore dynamic mesh was applied [5]. Both fluids and material of vessel were considered as incompressible. Fluid density for both cases was 1050 kg·m^{-3}. The density of blood vessel material was equal to 1120 kg·m^{-3}. The material of structural domain was defined by 5- parameters Mooney-Rivlin model given in equation (1), and its parameters were used from work [5]. The parameters of material and liquids are shown in Table -1.

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{11}(I_1 - 3)(I_2 - 3) + C_{02}(I_2 - 3)^2 \qquad (1)$$

Two types of liquid were used for modeling of blood flow. The first model described blood as Newtonian fluid, which means blood had constant viscosity. The value of dynamic viscosity for Newtonian fluid was 3.45 m Pa·s.

The other model was more precise and considered blood as non-Newtonian fluid. This model is called Carreau and it is described by equation (2). Parameters of Carreau rheology model were used [6].

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (\dot{\gamma}\lambda)2]^{\frac{n-1}{2}} \qquad (2)$$

Table 1: Parameters of materials and Liquid properties.

Symbol	Materials and Properties	SI units	Value
W	Strain energy potential	Pa	-
C_{10}	Material constants	Pa	9267
C_{01}	-	Pa	3508
C_{20}	-	Pa	305463
C_{11}	-	Pa	118300
C_{02}	-	Pa	504507
$\bar{I}_1$	First deviatoric strain invariant	-	-
$\bar{I}_2$	Second deviatoric strain invariant	-	-
η	Dynamic Viscosity	Pa.s	-
$\dot{\gamma}$	Shear rate	s^{-1}	-
η_∞	Dynamic viscosity for infinity shear rate	Pa.s	0.00345
η_o	Dynamic viscosity for zero shear rate	Pa.s	0.056
λ	Time constant	s	3.31
n	Carreau fluid coefficient	-	0.375

Results and Discussion

Results showed that impact of axial non-Newtonian fluid flow through straight pipe was not as high as it could have been expected. Radial strain was almost the same as in case of Newtonian fluid flow. Maximal values of radial strain were for both cases about 11 %, which corresponded with strain of artery with stenosis.

These values fit great with used material model, whose parameters were gained from artery stenosis. Also other parameters, which were related with deformation as radial stress, were similar to the case with Newtonian fluid. Velocity profiles for both cases in two different time steps. Values of velocity profiles were taken from the middle of domain part with flexible wall (0.135 m behind the inlet). The velocity profiles were a little bit different, but not as much as it could have been expected.

This access to solution of biomechanics showed that use of non-Newtonian fluid had an impact on wall shear stress (WSS), which is displayed. The magnitude of wall shear stress was negatively connected with artery resistance. The maximum values of wall shear stress differed about 2.5 %. Nevertheless the average of values of the wall shear stress varied much more. Maximal difference of average values of wall shear stress was about 5 % higher for the case of non-Newtonian fluid.

Numerical solutions of fluid-structure interaction of flow through straight blood vessel were done for two different blood rheology models. Comparison of both solutions showed that an application of non-Newtonian fluid had negligible impact on radial deformations. Velocity profiles were a little bit different. The application of blood rheology model had especially an impact on wall shear stress of the flexible wall. Nevertheless, these solutions were done for turbulent flow and there could be possibility that use of non-Newtonian fluid could have bigger impact in case of laminar flow or in case of more complicated shapes of computational domains.

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