Coupled analysis of the cardiovascular flow field and deformation of the blood vessel

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Abstract: This research considered stenosed coronary artery, including the bypassed grafts, as an example to simulate the flow fields inside the arteries and shear stresses and deformations of the vascular walls. The simulated area included the neighborhood of the coronary artery graft since it was the most susceptible area to recurrence of the same problem even after the coronary bypass surgery. In this research, we are trying to establish a coupled model for fluid dynamics and structural mechanics such that a more realistic simulation of the vascular flow field inside the deformable blood vessel under varying pressure can be done. The coupled simulation model will then be used to analyze the vascular flow field of the stenosed coronary artery and to study the influence on the vascular flow due to the deformation of the blood vessel.

Introduction

Cardiovascular system is responsible for the blood circulation of the human body. Following the change of daily diet during the recent years and progress of the medical research, cardiovascular disease has been recognized as a dominant problem for elderly men in Taiwan. Although most treatments of the cardiovascular diseases are effective in practice, the possibility of complication is still significant. Therefore, the study of the hemodynamics and vascular flow analysis remains to be worthwhile [1,2]. The characteristics of the vascular flow filed has been explored by many researchers, but the analysis coupling the deformation of the blood vessel is still scarce.

The varying blood pressure may cause deformation of the blood vessel and thus affect the vascular flow. Therefore, it is necessary to take the deformation into account during the vascular flow analysis. In this research, we are trying to set up the three-dimensional vascular analysis model for fluid dynamics and structural mechanics such that a more realistic simulation of the vascular flow field inside the deformable blood vessel under varying pressure can be done.

The coupled simulation model will then be used to analyze the vascular flow field of the coronary artery [3] and to study the influence on the vascular flow due to the deformation of the blood vessel. The variation and distribution of the physical properties of the vascular flow may be revealed more precisely from this study.

In vivo, the blood flow is driven by the regular cardiac systole and diastole. Therefore, the pressure of the blood flow that varies with cardiac cycle applies on the wall of the vessel, and deforms the vessel. There is a mutual interaction between the blood flow and the deformation of the blood vessel.

This research performs the coupled analysis of the computational fluid dynamics and structural mechanics to study the stenosed coronary bypass. We simulate numerically the blood flow through the coronary artery bifurcation and the deformation and stress distribution of the vascular wall. By taking data from simulation of the different blood flow velocities, which causes different degrees of deformation of the wall of the blood vessel, we gather various information of the flow field near junction region of a stenosed coronary. The result of this study is helpful clinically in the blood vessel pathology study and the treatment of the vascular diseases.

Materials and Methods

This research takes the anastomosis model of the coronary artery bypass [3] (Fig.1), which is built as the analytical intersection of two cylinders of the same diameter *D*. The left anterior descending coronary diameter is approximately equal to 3 mm[4]. As commonly found in the previous studies[5,6], the diameter of the graft is considered the same as the main artery to simplify the end-to-side anastomosis geometry and the junction angle is set to be 45°. The choice of a unique value for this angle allows us to assess the specific implications of a narrowing upon flow patterns at the junction.

The model includes a 75% lumen axisymmetric stenosis defined by the Gaussian equation[7],

$$\frac{R(x)}{R_0} = 1 - \frac{1}{2}\exp\left(-\frac{4x^2}{R_0^2}\right),$$

where $R(x)$ is the radius of the constricted tube and R_0=1.5 mm. The origin of the Cartesian co-ordinates system (O, x, y, z) is the intersection of the axes of each tube.

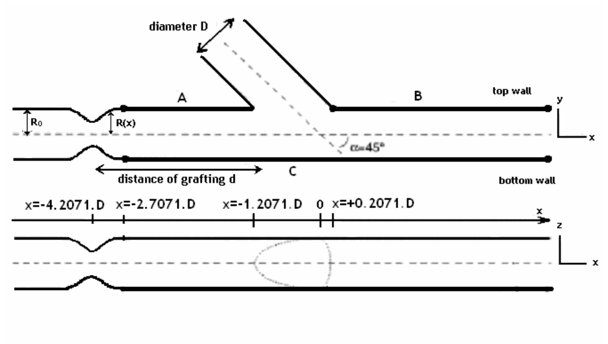


Fig.1. The nastomosis model of the coronary artery bypass

The blood is treated mathematically as an incompressible Newtonian fluids. The governing equations are the three-dimensional time-dependent Navier-Stokes equations, which express the conservation of linear momentum:

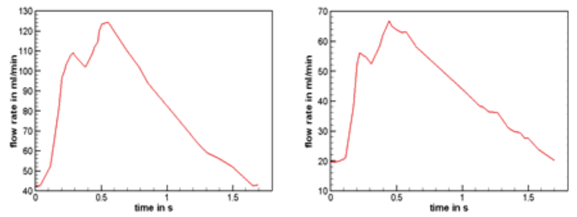
$$\rho\left(\frac{\partial v}{\partial t}+v\cdot\nabla v\right)=-\nabla p+\mu\nabla^2 v,$$

where v=velocity, p=pressure, μ=viscosity, andρ=density. For blood, ρ=1080k kg /m^3 and μ=3.88×10^{-3}kg/m·s. These equations are subjected to the incompressibility condition, which expresses the conservation of mass:

$$\nabla\cdot v=0,$$

These outlet conditions are imposed at 15*D* downstream from the anastomosis in order to avoid perturbations on the upstream flow field.

The inlet flow is preset as in Fig.2 according to the mass flow velocity generated by the cardiac cycle[8].



(a) (b)

Fig.2. The simulated flow rates in vivo. (a)Left internal mammary artery graft. (b)Right coronary artery.

The homogeneous isotropic shell elements are considered for the simulation of the vascular wall. The thickness of the vessel wall is preset as 0.24mm. The Young's modulus and Poisson's ratio are 36.1Mpa and 0.499, respectively. The density of the vascular wall is 1060 kg/m^3. The inlet and the outlet of the blood vessel are considered fixed as the boundary conditions in the simulation.

In this research, the solid-fluid coupled analysis is performed sequentially. The results of the blood flow field are first obtained and fed into the structural model to find the deformation of the wall of the blood vessel. The new position of the wall is then taken as the new boundary of the blood flow analysis. These procedures are repeated until satisfactory results are obtained.

The commercial finite element analysis software ANSYS is adopted in the solid-fluid coupled analysis in this research. In the blood flow analysis, the hexagonal structured mesh (FLUID 141) (Fig.3) is considered, and there are 112,112 hexagonal elements and 117,553 nodes in total. In the structural part, the thin shell element (SHELL 181) is used, and there are 8,752 elements and 8,833 nodes in total. The total computing time needed in IBM P690 computer is about 25 hours.

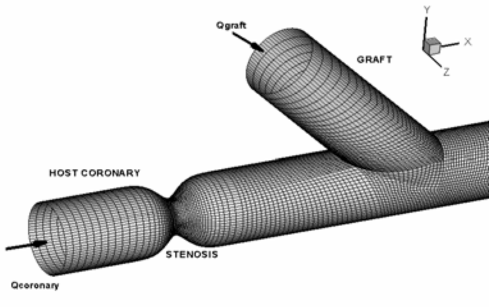


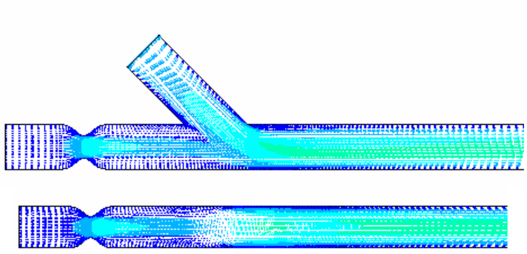
Fig.3. Numerical modeling of the anastomosis of a stenosed carotid bypass.

Results

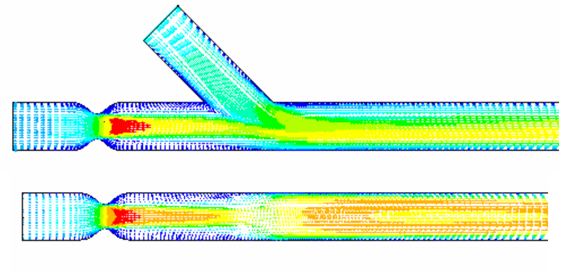
In this research, we hope to observe the characteristics of the flow field after a stenosed coronary bypass and study how the vascular flow velocity and shear stress affect the vascular wall. Then we can further explore the pressure applied on the vascular wall and its accompanying deformation. Since the blood is driven by the periodic beats of the heart, the vascular flow velocity varies accordingly, and so does the deformation of the vascular wall. A normal blood vessel and stenosis blood vessel are studied numerically in this research. Four different points in the period of a heart beat are studied to solve the resulted flow fields such that the deformation of the vascular wall under different flow conditions may be revealed.

Analysis of the vascular Flow Field

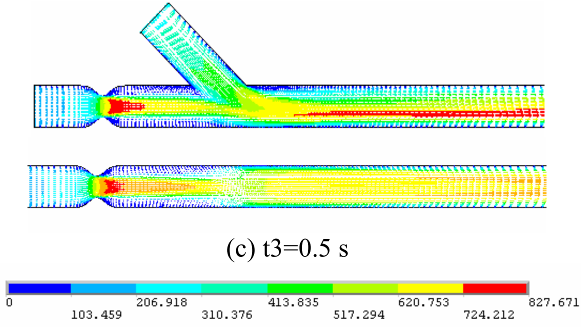
The flow field pertaining to the temporal variations of the blood flow rate due to the heart beat is analyzed in this study. The in vivo data shown in Fig. 2 are taken as the inlet boundary conditions in the analysis, and three values at three different points of the period of the heart beat are selected for computation of the vascular flow velocities. The longitudinal velocity profiles are plotted in x-y planes (Fig.4)



(a) t1=0.1 s



(b) t2=0.4 s

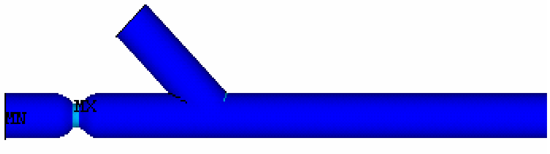


(c) t3=0.5 s

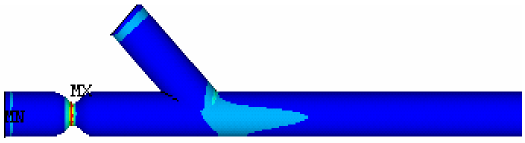
Fig.4. Comparison of the velocity vectors projection in symmetry plane x-y and y-x.

The deformation of the vascular wall may change the boundary of the vascular flow and many other flow characteristics such that the flow field of the neighborhood of the coronary artery graft is influenced by the deformation of the vascular wall with backflows generated near the vascular wall of the region from the stenosed area to the junction. It can be observed from Fig. 4 that the larger the velocity is in the artery graft, the lower the position of the maximum velocity appears behind the junction, and thus the velocity in the upper part of the artery behind the junction becomes smaller and causes deposition of the impurities on the surface of the vascular wall.

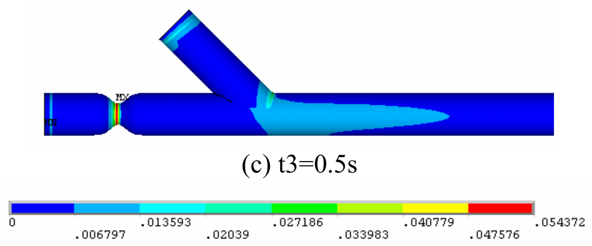
Figure 5 shows the distribution of the shear stress on the vascular wall caused by the blood flow. Since the blood flow rate increases in the grafting at time t_3, the shear stress on the vascular wall in the junction increases accordingly. The region of small shear stress tends to become stenosed since the impurities are easier to deposit on the surface of the wall.



(a) t1=0.1s



(b) t2=0.4s



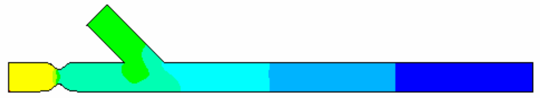
(c) t3=0.5s

Fig.5. Distribution of the shear stress on the vascular wall of the carotid arteries

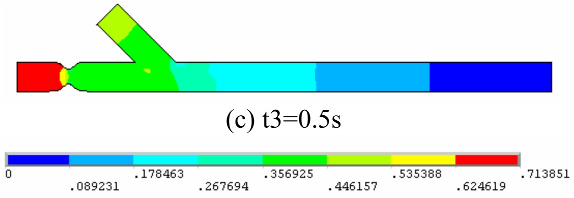
Analysis of the deformation of the vascular wall

The deformation of the vascular wall may change the boundary of the vascular flow and many other flow characteristics. By the solid-fluid coupled computation, we can perform the analysis of the deformation of the vascular wall in cardiac cycle corresponding to the blood flow variations caused by the heart beats. Figure 6 reveals the pressure distribution on the vascular wall. When the heart contracts, we can find that the blood flow rate approaches its maximum value, and the blood pressure becomes large and focuses on the bifurcation region.

(a) t1=0.1s



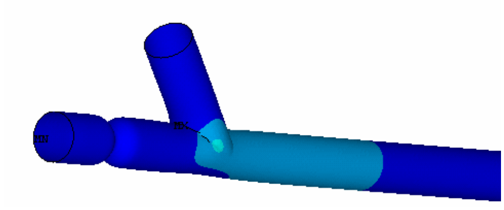
(b) t2=0.4s



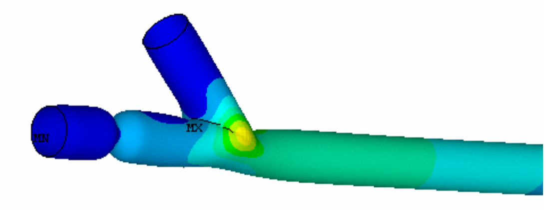
(c) t3=0.5s

Fig. 6. The pressure distribution on the vascular wall of the coronary artery at time t1, t2 and t3.

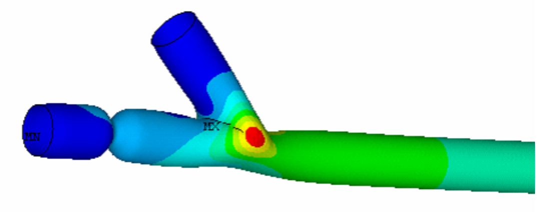
The deformation plots of the vascular wall at three different time instants are shown in Fig. 7, while the two cross-section deformation plots of the carotid at these instants are shown in Fig. 8. We can see that the larger the blood pressure is applied on the vascular wall of junction, the larger deformation of the vessel is caused at the same place. In other words, the blood vessel expands with the increase of the blood flow rate. In addition, since the inlet and outlet sides are fixed in the analysis model, there is an unbalanced side force such that the blood vessel moves downward.



(a) t1=0.1 s



(b) t2=0.4 s



(c) t3=0.5 s

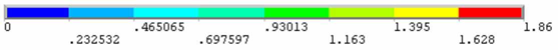


Fig.7. The deformation of the vascular wall at each instant of the coronary artery at time t1, t2 and t3.

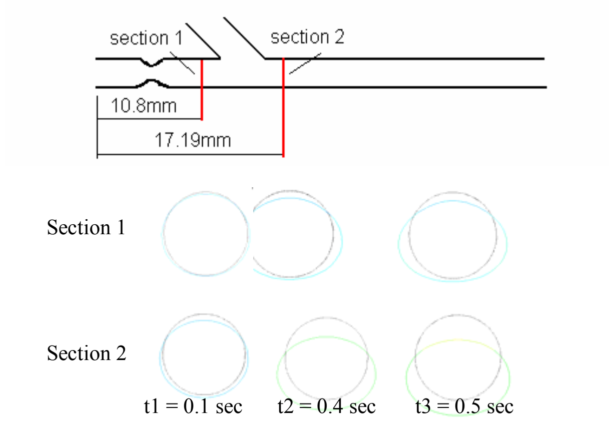


Fig.8. The cross-section deformation plots in the two regions of the coronary artery at time t1, t2 and t3.

Discussion

The purpose of this research is to integrate the technologies in computational fluid dynamics and solid mechanics, and to compute the vascular flow field, blood pressure, shear stress, deformation of the vascular wall, etc., so that the actual vascular flow characteristics can be explored. The periodic change of the blood flow rate in the coronary artery and the interaction between the blood flow and the vascular wall are analysed. Furthermore, the deformation of the vascular wall in the actual blood flow situation is simulated.

This study adopts the solid-fluid coupled numerical simulation model, which can compute the temporal interaction between the fluid dynamics and structural mechanics of the vascular flow. This model can be applied to the analysis of the anastomosis of a stenosed coronary bypass in which the vascular flow field changes with the deformation of the vascular wall. Therefore, the hemodynamics can be studied without being limited to a specific instant and fixed boundary. The result of the analysis can provide useful information for clinical medicine and be used in the research of the pathology and development of the medical instruments.

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