Computational Mechanical Study of the Blood Flow for the Application to Clinical Cardiovascular Medicine

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1. Purpose

In industrialized societies, cardiovascular deaths are significant, sometimes occupies the top of the list of causes of deaths. It is also well known that most of cardiovascular deaths are related to the atherosclerosis. Although centuries of studies have been conducted on the cause of the atherosclerosis or the atherogenesis, we have not been successful to understand the whole process of the initiation and development of the disease. It is well known that atherosclerosis preferentially occurs at specific arterial sites being related to the localization of blood flow parameters, particularly the wall shear stress (WSS) distribution. Even more important is the mechanism of the events that lead to deaths of patients. The final vascular events that induce fatal outcomes, such as acute coronary syndrome, are now strongly suspected of being triggered by the sudden mechanical disruption of an atherosclerotic plaque on an arterial wall. Subarachnoid hemorrhage, which is another very sudden, fatal disease, is mostly the direct result of rupture of a cerebral aneurysm. Therefore, both the onset and final consequences of tragic fatal vascular diseases are inseparably connected to mechanical events that occur on the vascular wall, which are strongly suspected of being influenced by blood flow conditions.

Consequently, the fluid-solid mechanical interactions between blood and the vascular wall must be analyzed in order to predict, diagnose, and prevent the fatal results of these vascular diseases. This is clearly not a task that can be performed by conventional experimental or theoretical methods used in physiological mechanics. It is usually prohibitively difficult to measure detailed mechanical properties in a living system, and they are too complicated to be studied elegantly in a theoretical framework alone. Therefore, we have been placing stress on the necessity to use computational studies to elucidate the mechanism of such disease, to refine the diagnostic measures, and to develop invasive and non-invasive treatments. We discuss in the present report our ongoing studies of various aspects of the cardiovascular system using computational mechanics.

2. Recent Developments

When we conduct computational mechanical studies on the cardiovascular system, we can distinguish several major difficulties including;

(1) Complex three dimensional (3D) geometry of the system,
(2) Unsteadiness of the blood flow,
(3) Flexible and deformable vessel wall,
(4) Non-Newtonian viscosity of the blood, and
(5) Biological and dynamic response of the system

They are all very important and extremely difficult problems. These characteristics themselves are strongly non-linear and they interact each other in a very complex manner that again introduces higher order of non-linearity. Even by utilizing highly sophisticated engineering methods of computational mechanics, it is still very difficult a task to model and analyze the interactions between the blood flow and the vascular wall. In the present report, three recent progresses accomplished in our laboratory will be shown.

1) Integrated Modeling of the Cardiovascular System

Combination of the complex 3D geometry and the unsteady pulsating blood flow generates very complex phenomena, particularly in the large arteries such as the aorta. We have already shown that the complex 3D configuration of the human aorta, including its curvature and torsion, determines the global nature of the blood flow and its vortical structure. It is even more complex in the unsteady case. We discussed it with respect to the pathogenesis of the aortic aneurysm, another fatal disease. The aneurysm is a pathological expansion of the arterial wall, due to mechanical weakening of the local vessel wall. This local weakening may be due to local high shear stress and the biological responses of the components of the vessel wall to it. However only the aortic flow was analyzed in the previous studies neglecting the contributions of the intra-cardiac flow development. Therefore we build a model combining the left ventricle and the aorta with proper spatial connective configuration. Visualizing the diastolic flow from the left atrium to the left ventricle and consecutively the systolic flow from the left ventricle to the aorta, complex vortices were found to occupy whole flow tract. They were not any more simple secondary flow type vortices. We are now comparing the computed results with the measured velocity distribution in the human aorta by using a phase contrast cine MRI method.

2) Fluid-Solid Interactions Studies of the PWV measurements

Recently so-called pulse wave velocity (PWV) measurements are widely used in clinical evaluation of the aging and atherosclerosis. Based on a theoretical analysis using one dimensional wave equation, an expression called the Moens-Korteweg formula is known to be derived and is used to estimate the stiffness, in other words, the aging alteration or progress of the atherosclerosis. However, our computational fluid-solid interaction model studies of physiological and pathological arteries revealed that the PWV measurements alone fail to provide objective criterion to assess the overall stiffness of the vascular system because of various local geometrical and pathological changes. This was particularly true when we modeled the aneurysm in which the aortic diameter locally increases and therefore the Moens-Korteweg formula estimates the slow down of the PWV. Due to 3D flow phenomena, the PWV increased in some cases. These complex phenomena should be further studied with a combination of computational mechanical and signal analysis methods to yield a novel measure to support clinical diagnosis using the pulse wave propagation phenomenon.

3) Application of the Particle Method

So far most of studies of computational mechanical analysis of the blood flow have been utilizing some kind of continuum modeling. In the conventional continuum modeling, the computed domain of fluid or solid is divided into computational grids in order to spatially discretize the whole domain. There are many restrictions in the formation of the computational grids and therefore it is extremely difficult to construct an appropriate grid system for objects with complex geometry, such as the cardiovascular system. Moreover, as pointed out in the introduction of the chapter, the blood is no more a uniform fluid if we are interested in rather a smaller scale, including arteriolar, capillary, or microvascular flow phenomena and also near wall phenomena in the larger arteries. In these regions, the size and the real shape of the cellular components of the blood, including the red blood cells (RBC) , the white blood cells, and the platelets, affect the flow field to a great extent. Some of global nature of the blood including the non-Newtonian viscosity is believed to occur because of these fluid-solid mechanical interactions. We devised a method to analyze interactions between the RBC and the plasma, in which the RBC and the plasma were modeled by using unified technique of particle representation. Among many proposed particle methods, we applied the moving particle semi-implicit (MPS) method. This was thought to be suitable to analyze viscous flows. It was shown that complex interactions between the fluid (plasma) and the RBC were properly analyzed and deformations of the RBC membrane reported in experimental studies were successfully reproduced. Though this analysis is two dimensional at the moment, three dimensional unsteady computation method is under development.

4) Clinical Interface for Rapid Modeling and Analysis

We have been developing a comprehensive computational analysis support system that includes the preprocessing of medical images, segmentation, structure registration, database and human interfaces, mesh generation, and the final evaluation of the computed results. Since our ultimate goal is to build a system that can assist clinicians in diagnosis, treatment planning, and following-up patients with cardiovascular diseases, and since patients differ in terms of anatomical configuration and disease condition, a wide variety of patient data must be accumulated, not only for statistical analysis, but also to improve the processing system. Therefore, a comprehensive database that includes patient data, medical images, computational models, and computed results must be constructed within the scope of our current projects. When a computational analysis is utilized in a clinical situation, there are several additional requirements. They are the exactness and speed of all processes. In some circumstances, clinical diagnosis and treatment decisions must be made very quickly. This is particularly true if the system to be developed is aimed at emergency treatment, such as for unstable angina, which sometimes leads to the acute coronary syndrome and sudden cardiac death. This is why we started the project called CREAM (Computational Risk Estimation And Management for Cardiovascular Disease) with the support of the Japan Science and Technology Cooperation (a subsidiary of the Ministry of Education, Culture, Sports, Science, and Technology). By the end of the project, we should have a system composed of several subsystems, including medical image retrieval and storage, analysis to extract the information necessary to build computational models, a modeling system with properly defined boundary conditions, a multi-scale computation system using GRID computers over a nation-wide high-speed computer network, a sophisticated visualization system, and a comprehensive tool to support clinical decisions in real situations.

5) Conclusion and Future Studies

Computational analysis is nowadays one of fundamental means of scientific and engineering research together with theoretical and experimental approaches. It is particularly useful to understand the phenomena that are too complex to analyze with theoretically simplified method or non-invasive experimental procedures. Need for the scientific, in other words, reproducible and evidence based decision support is now widely acknowledged in various fields of clinical medicine. Computational method based on rapidly advancing medical imaging technologies is probably only measures to implement objective guidelines to assist clinical decision. Studies shown in this report is a part of our comprehensive project to establish computational decision support system for cardiovascular clinical medicine.

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