Application of Computational Fluid Dynamics (CFD) in Biotransportation of Complex Fluid in the Human System

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Abstract— Most of the pathological conditions are connected with anomalies in the flow of complex fluid (blood) and its interaction with various organs in the human system. A clear and detail understanding of the flow process and mechanism of interaction between the complex fluid (blood) and surrounding organs can help prescribes a proper diagnostic procedure in addressing pathological conditions in the human body. Computational fluid dynamics (CFD) coupled with other multiphysics relating structure and chemical reaction will be adopted to model this fluid-structural interaction within the biological context. This study intends to use Comsol Multiphysics modeling platform because of its robustness and the ability to coupled fluid-solid interaction with module for transport for concentrated species and reacting flow in normal duct and porous media.

Index Terms— Pathological conditions, Complex fluid, Mechanism of interaction, Diagnostic, Computational fluid dynamics , Multiphysics, Fluid-structural interaction, Human system.

1 INTRODUCTION

IT is on record[1], [2] that the cause of death for many in our modern age is due to irregularities in the physiological conditions of the internal body systems of human being. The systems which include the circulatory/cardiovascular, digestive/excretory, respiratory, renal/urinary system to mention but a few have one thing in common and that is the hemodynamics of blood within and around the various organs pertaining to each system. Blood, a complex fluid comprises of the plasma (clear extracellular fluid) and formed an element, is made up of blood cells and platelets[3]. About 99 % of the form elements consist of erythrocytes also known as red blood cells while the remaining 1 % comprises of the leukocytes (white blood cells) and platelets [4]. The alteration in the internal complex fluid (blood) flow process, organ dysfunctionality and lack of proper delivery of nutrients and supportive regulatory mechanisms essentials at different physiological sections are precursor to various fatal pathological conditions such as atherosclerosis, cardiovascular diseases, and malignant neoplasm (cancer). Most of these cases emanate or lead to distortion in the flow process of blood within the vessel and its interaction with various organs in the human system. The physiological study of flow and interaction of complex fluid with several organs in the body can be investigated via in vivo, in vitro-, and in silico approaches[5]. The in silico studies, the approach adopted in this work, involves the use of computational tool to simulate complex fluid (blood) flow and vessel dynamics, assess hypotheses of pathogen formation under regulated conditions. It also evaluates medical devices that have not yet been built and therapeutic procedures that are still awaiting implementation[6]. The in vivo approach is a direct application of the study on the system in question while in vitro study adopts a model system to mimic the real system of interest. The third approach which is in silico (computational), involves the use of computational tools and numerical experimentation to simulate the behavior of the system of interest. An in vivo studies of human physiological fluid flow processes was performed by the use magnetic resonance techniques to noninvasively estimate the quantity of blood for diagnosing cardiovascular disease, investigating pathologic condition mechanism and affirming assumption and prognosticating of mathematical models[6]. Some studies have been conducted on the modeling of the fluid-structure interaction effect on the human heart via in vitro measurements of animal heart and other modeled systems. Peskin and McQueen evaluated the flow-structure coupling of the heart by studying the lagrangian description of discretized elastic fiber filament in a flow channel as a model for the complex fluid interaction with the muscle fibers of the heart as well as the cardiac valves[7]. The in silico studies involves the use of computational tool to simulate complex fluid (blood) flow and vessel dynamics, assess hypotheses of pathogen formation under regulated conditions, and evaluate medical devices that have not yet been built and therapeutic procedures that have not yet been adopted[6]. The main challenge in today computational hemodynamics research is increasing pelvic on the necessity to develop an accurate modelling of blood flow characteristic and its interaction with its physiological environment. This work is set to investigate the flow processes of complex fluid and its physical interaction with the organ and tissue in the human system through computational method[5], [8]. The objective for now is to perform a preliminary study of the flow processes of complex fluid in the artery and how its flow parameters such as velocity and pressure affect the immediate cardiovascular organ and tissue. The modeling physics for the complex fluid flow process will be analyzed using computational fluid dynamics (CFD) while the response on the organ of interest as a result of the complex fluid interaction will be solved using the equation describing structural mechanics of solid materials. CFD is built on the premise of finite volume analysis while the structural mechanics solution adopts the finite element method[9]. This study will be adopting Comsol Multiphysics modeling platform because of its

robustness and the ability to coupled fluid-solid interaction with module for transport for concentrated species and reacting flow in normal duct and porous media[10].

2 Research Methodology

2.1 Material

The three basic materials used in the modelling are blood, artery and cardiac muscle. For blood, the density and dynamic viscosity are 1060 kg/m3 and 0.005 Ns/m2 respectively while density of the artery is 960 kg/m3 with Neo-Hookean coefficient μ for an hyperelastic behavior of 6.20·106 N/m2. The bulk modulus of the artery vessel is 20μ with a corresponding Poisson's ratio, v, of 0.45 and an elastic modulus of 1.0·107 N/m2. Cardiac muscle has a density 1200 kg/m3 and a coefficient μ of 7.20·106 N/m2 with bulk modulus of 20μ. The corresponding Poisson ratio v equals 0.45 while the equivalent elastic modulus equals 1.16·106 N/m2[10].

2.2 Simulation

Comsol Multiphysics was adopted as the modeling platform for the study. In this modeling, the fluid dynamics analysis is considered as a solution of the 3D Navier-Stokes equations, which can be applied in both stationary and time domain. Flow velocity is a solution of the Navier-Stokes equation applied to every fluid species in the field both spatially and temporally. In other words, the motion of fluids is governed by the Navier Stokes equation which stems from Newton's second law for fluids motion.

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$$\rho(\partial u/\partial t+u.\nabla u)=-\nabla p+\nabla\cdot(\mu(\nabla u+(\nabla u)^{\wedge}T))-2/3\ \mu(\nabla\cdot u)I)+F$$

u represents the complex fluid flow (blood) velocity, p is the blood pressure, ρ is the blood density, and μ is the blood dynamic viscosity. Step by step procedure for the simulation as performed in Comsol Multiphysics 5.3 software can be seen below:

- ☐ A 3D dimension is selected
- ☐ Selection of fluid-structure interaction, fixed geometry physics
- ☐ Definition of parameters such as time and relative pressure amplitude
- ☐ Generation of geometry was done by importing from structural mechanics module
- ☐ Setting of boundary conditions:

There are 6 pressure conditions for one single inlet and five different outlets. The pressure for the single inlets and five outlets respectively are are 126.09 mmHg, 125.91 mmHg, 125.415 mmHg, 125.415 mmHg, 125.415 mmHg, and 125.1 mmHg which are the mean values over a heart beating cycle. The equations for the time dependent analysis are set as (t) = (1- a) sin (πt) when 0 ≤ t ≤ 0.5s and f (t) = 1-αcos (2π (t-0.5)) when 0.5s ≤ t ≤ 1.5s[10]

- ☐ Selection of solid mechanics-linear elastic material
- ☐ Specification of parameters for solid structure (Aorta)
- ☐ Material specification as stated above
- ☐ Meshing of the geometry for computation and solution (Free Tetrahedral)
- ☐ Build All: to compute and solve the modeling equations

3 Results and Discussions

In the modeling of vascular system, the upper end of the artery (aorta) and its branched blood vessels are entrenched in cardiac biological tissue. The complex fluid (blood) applies pressure on the wall of the surfaces of the artery and its branches while causing deformation of the tissue in the process. The procedure involve coupling of two physics: 1) Fluid mechanics: It analyzes the blood flow parameter such as the velocity field and the pressure distribution in the blood. 2) Structural Mechanics: This addresses the mechanical deformation of the artery and the enclosing cardiac muscle.

Figure 1 depicts the velocity profile in the aorta and its branching. The velocity profile per cross sectional diameter changes at the different points and branching of the vessel as the fluid traverses the aorta curved path. Figure 2 shows the pressure along aorta curvature and its branching. The trend observe with the pressure distribution portrays a higher pressure at the inlet of the aorta which thereafter decreases as it flow past each branching and towards the outlet end. The decrease could be trace to skin friction effect of the wall and the form friction at each branching inlet. The shear stress on the outer wall of the aorta will likely be higher than what obtain within vessel wall due to centrifugal forces..

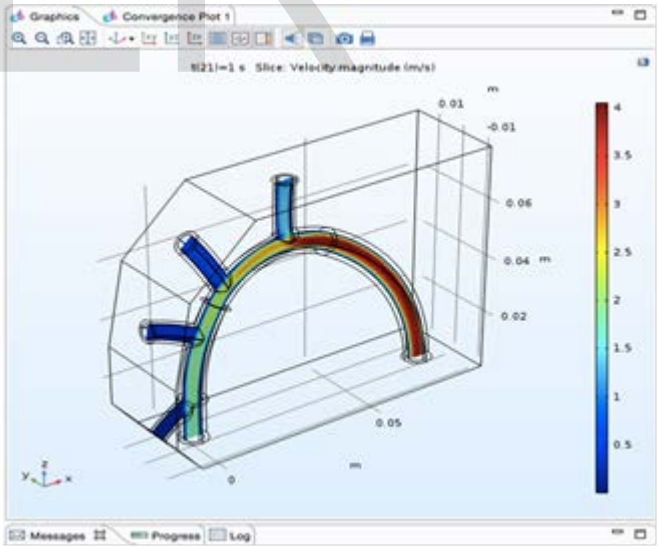

Fig. 1. Velocity field in the aorta and its ramification (branching) number, followed by one space.

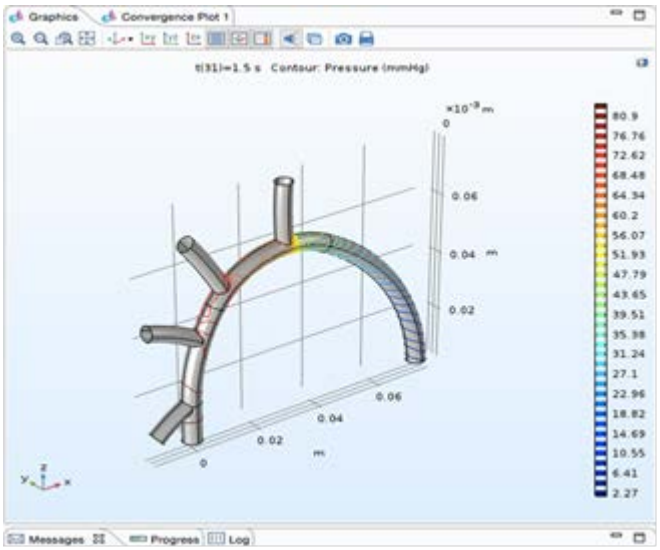

Fig. 2. Pressure contour distribution

4 Conclusions

within COMSOL multiphysics platform provides us with opportunity to evaluate stress effect of complex fluid flow on the The application of CFD in biological system is progressively becoming a useful tool in the field of medical science and biomedical engineering. With the cost and time reduce; CFD could be one of the valuable solutions for researchers and scientist to accomplish accurate result. A proper and detail understanding of flow processes and mechanism of interaction between blood and organs of the body are prerequisite to a better diagnostic and therapeutic procedure for any pathological condition of interest. Thus Comsol multiphysics modelling platform was adopted to do a preliminary work on the impact of blood flow on the artery and the surrounding cardiac tissue. The velocity field and pressure distribution of the blood within the aorta changes as flow traverses through the vessel. The coupling of CFD and structural mechanics modules within COMSOL multiphysics platform provides us with opportunity to evaluate stress effect of complex fluid flow on the deformation of aorta (Artery vessel wall) and cardiac muscle

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