Particle-based Simulation on Aortic Valve Behavior with CG Model Generated from CT

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Abstract: We have tried to simulate the aortic valve behavior with a particle method. The simulation model has been generated from CT data; however, the model was a little bit distorted due to some diseases. The distorted model is not appropriate for the simulation because we have to simulate the aortic valve behavior for various kinds of conditions. Then, we have created the normal model by modifying the generated model. In order to simulate the aortic valve behavior, blood should be flown in the aortic model and particle methods are suitable for fluid simulation. On the other hand, FEM (Finite Element Method) is usually used for the simulation of elastic body such as the aortic wall and the aortic valve. However, it is difficult to calculate the mutual interaction between fluid and elastic body if two different kinds of methods such as particle method and FEM are adopted for one simulation. Therefore, we have applied a particle method for both of fluid and elastic body. As the result of the simulation, we have been able to visualize the blood flow and the pressure inside the aorta, and the stress distribution on the aortic valve.

1 INTRODUCTION

Computer graphics and virtual reality technologies have been progressed rapidly and their related systems are being developed especially in medical fields such as preoperative planning, surgical simulation, intraoperative navigation, and so on. Among them, some systems use robotic manipulators (Yeniaras et al., 2011). For the purpose of surgical training using virtual reality, the target organs are necessary and they are generated based on CT (Computed Tomography), MRI (Magnetic Resonance Imaging), MRA (Magnetic Resonance Angiography), PET (Positron Emission Tomography), and so forth. In order to generate the computer model used for the simulation or training, segmentation is needed in advance. There are mainly three types of segmentations: region model based level set segmentation, hierarchical segmentation, and hybrid segmentation of the two methods (Song et al., 2011).

In addition, there are many medical systems using computer graphics and virtual reality technologies, and they treat some organs such as brain, lung, stomach, liver, and so on. On the other hand, there are many blood vessels in our body and blood circulation is very important to keep our good conditions. Then, there are so many research works related to blood vessels (Kirbas and Quek, 2004). Blood vessels are also divided into some categories such as aorta, artery, vein, capillary, and so forth. Among them, the largest and the most important blood vessel is the aorta, which sends necessary nutrition from the heart to everywhere in our body through artery and capillary. Then, there are also some studies related to the aorta and the heart such as aortic diameter estimation using mono-static radar (Solberg et al., 2010), heart reconstruction based on volumetric imaging (Bajaj and Goswami, 2008), 3D volumetric shape reconstruction (Mukai et al., 2011), and blood stream simulation (Nakagawa et al., 2011b; Seo et al., 2011; Wendell et al., 2013).

Inside the aorta, there is a valve called the aortic valve, and the blood does not flow correctly if the aortic valvular dysfunction occurs due to some diseases. One disease is aortic valvular stenosis that narrows the aortic valvular port and makes blood flow unsmooth, which causes the high pressure difference between the left ventricle and the aorta. Another disease is aortic valvular insufficiency that closes the aortic valve incorrectly, which causes blood flow back from the aorta to the left ventricle. As a result, the aortic pressure remains lower even after the aortic valve closes. (Izawa, 2009; Levick, 2011; Klabunde, 2012; Silbernagl and Despopoulos, 2009).

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There are mainly two types of surgeries to cure the preceding diseases. One is aortic valvular replacement (AVR), which replaces the dysfunctional live valve with an artificial one. The other surgery is aortic valvuloplasty (AVP), which retrieves the valvular function by repairing the dysfunctional live valve. The surgeries are very difficult so that preoperative planning and simulation are necessary, and aortic valve simulations have been performed based on FEM (Hart et al., 2003; van Loon et al., 2005; Le and Sotiropoulos, 2013; Hsu et al., 2014; Hsu et al., 2015). In this method, FSI (Fluid-Structure Interaction) should be analized with two different models: Navier-Stokes equation for fluid and Neo-Hookean model for solid. Then, we have simulated the aortic valve behavior based on particle model for both fluid and elastic body (Nakagawa et al., 2012; Mukai et al., 2013; Mukai et al., 2014a; Mukai et al., 2014b; Mukai et al., 2015).

The model used in the previous research, however, was generated by referring to some medical books just for the purpose of general blood flow simulation with a normal aorta. Therefore, we report the generation of the simulation model based on CT data, and the visualization of the blood flow, the pressure inside the aorta and the stress distribution on the aortic valve.

2 MODEL GENERATION

2.1 Aorta Model

The simulation model of the aorta is generated from CT data. The CT image data of the heart is shown in Figure 1, which is composed of 114 images, and is numbered from the top to the bottom. The image format is "bitmap" and the size is 512×512.

On the other hand, Figure 2 shows the vertical section image of the heart, which explains the locations of the aorta, the aortic wall, the aortic valve, the Valsalva's sinus, and the left ventricle.

Figure 3 is the polygon model generated from the CT data. In order to simulate the aortic valve behavior, the model surrounded by the blue rectangle is necessary. In addition, blood should be flown in the aorta for the simulation, and some extended simulation areas are necessary above and below the target model because blood comes from the left ventricle and goes to the aorta with some velocity.

Figure 4 (a) and (b) show the extracted model from Figure 3 and the aorta model generated by adding cylinders above and below the extracted model for the simulation of blood flow, respectively. However, the added cylinders are not on the same line since the extracted model is a little bit distorted. If this generated aorta model is used for the simulation, blood does not flow smoothly in the aorta so that we cannot investigate correctly the aortic valve behavior caused by the blood flow.

On the other hand, the Valsalva's sinus is composed of three cusps. Then, we have decided to select one cusp from the Valsalva's sinus, and generate the simulation model by combining three cusps copied from one cusp. Figure 5 shows the generated simulation model. Red parts are selected and copied cusps, and gray parts are connection part and cylinders located above and below the target area. Two cylinders

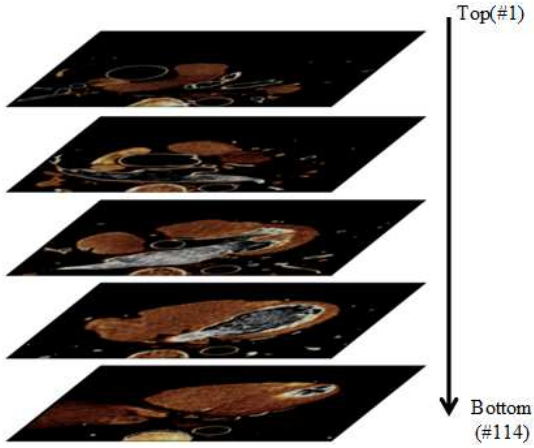

Figure 1: CT image of the heart.

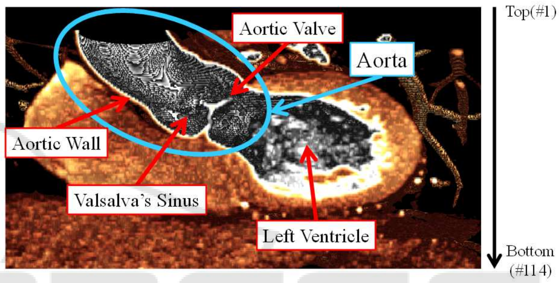

Figure 2: Vertical image of the heart.

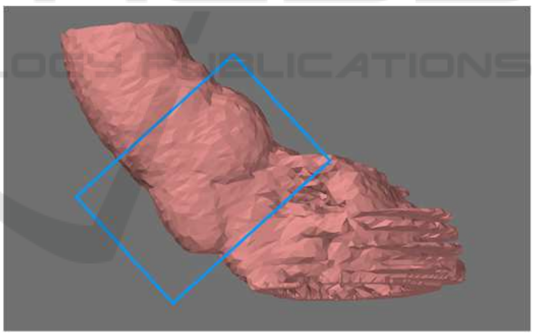

Figure 3: Polygon model of the aorta and the left ventricle.

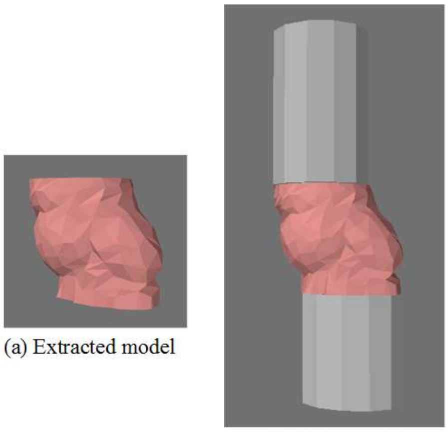

Figure 4: Extracted model and generated aorta model.

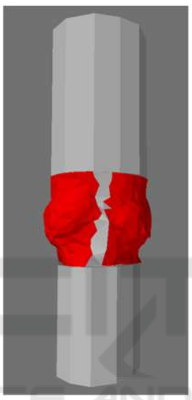

Figure 5: Simulation model.

above and below the target area are on the same line.

2.2 Aortic Valve Model

It was difficult to generate the aortic valve model from CT data because the valve image is not so clear compared with the aortic wall that we have decided to generate the aortic valve model by referring to a medical book (Arai, 2003). Figure 6 shows the polygon model of the aortic valve, which is composed of three cusps.

Now, we have the both models of the aortic wall and the aortic valve; however, those models are composed of polygons. The aortic wall and the aortic valve are elastic body so that FEM is usually used for the simulation. However, our purpose is the aortic valve behavior caused by blood flow. Blood flow is fluid and the topology is changed by the opening and closing of the aortic valve. In general, particle method is used for the simulation of fluid. Here, there is one problem, that is the collision detection and the mutual interaction between the fluid and the elastic body. If two different methods are adopted for the simulation, it is difficult to detect the collision between the fluid and the elastic body and to convey the force from the fluid to the elastic body. Therefore, we have decided to use a particle method for both materials: fluid and elastic body. Then, we have to transform the polygon model to a particle model with depth peeling method (Nakagawa et al., 2011a). The particle models transformed from the polygon models are shown in Figure 7.

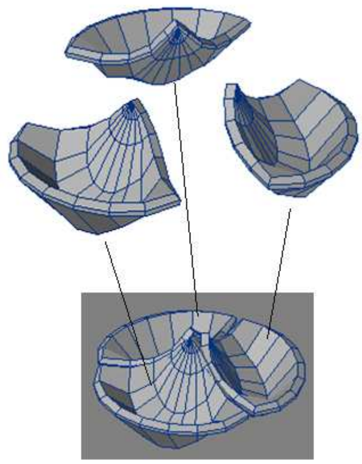

Figure 6: Aortic valve model.

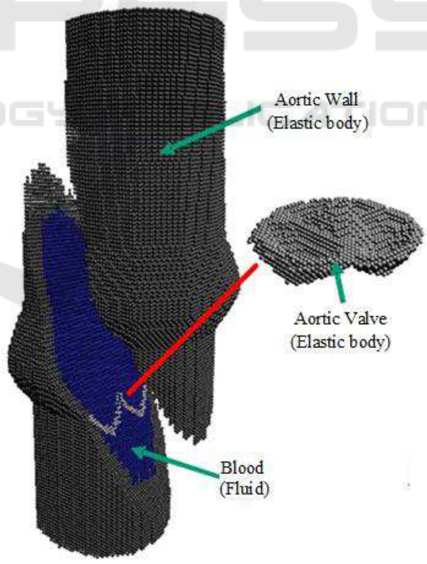

Figure 7: Particle model of the aortic wall and valve.

3 SIMULATION

In this simulation, a particle method is used. There are two types of particle methods: SPH (Smoothed Particle Hydrodynamics) and MPS (Moving Particle Semi-implicit). In general, blood is treated as incompressible fluid so that we use MPS (Koshizuka, 2005) for the simulation.

3.1 Governing Equations

Two kinds of governing equations are used for fluid simulation: Cauchy's equation of motion and equation of continuity, which are written as the following.

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \sigma + \mathbf{b} \tag{1}$$

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0 \tag{2}$$

where, ρ is density, $\mathbf{v}$ is velocity, t is time, σ is stress tensor, and $\mathbf{b}$ is body force acceleration such as gravity.

In addition, the constitutive equation of elastic body is described as follows.

$$\sigma^e = \lambda \mathrm{tr}(\varepsilon)\mathbf{I} + 2\mu\varepsilon \tag{3}$$

$$\varepsilon = \frac{1}{2}\left\{\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right\} \tag{4}$$

where, σ^e is stress of elastic body, ε is strain tensor, $\mathbf{I}$ is unit tensor, $\mathbf{u}$ is displacement, λ and μ are lame constants, which are expressed as follows.

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)} \tag{5}$$

$$\mu = \frac{E}{2(1+\nu)} \tag{6}$$

where, ν is Poisson's ratio and E is Young's module.

By substituting Eqs.(3) and (4) for Cauchy's equation (Eq.(1)), the next Cauchy-Navier equation is obtained, which equation is applied to analyze the behavior of the aortic wall and valve.

$$\rho \frac{D^2\mathbf{u}}{Dt^2} = (\lambda + \mu)\nabla(\nabla \cdot \mathbf{u})\mu\nabla^2\mathbf{u} + \mathbf{b} \tag{7}$$

On the other hand, the constitutive equation of fluid is written as the following.

$$\sigma^f = -p\mathbf{I} + 2\eta\mathbf{D} \tag{8}$$

$$\mathbf{D} = \frac{1}{2}\left\{\nabla\mathbf{v} + (\nabla\mathbf{v})^T\right\} \tag{9}$$

where, σ^f is stress of fluid, p is pressure, $\mathbf{I}$ is unit tensor, η is viscosity, $\mathbf{D}$ is tensor of strain velocity, and $\mathbf{v}$ is velocity. By substituting Eqs.(8) and (9) for Eq.(1), Navier-Stokes equation is obtained as follows, which is applied to analyze the behavior of blood.

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \eta\nabla^2\mathbf{v} + \mathbf{b} \tag{10}$$

3.2 Simulation Results

The simulation was performed with a normal PC, which has i7-3770K CPU and GeForce GTX570 GPU. The simulation took about 1[s], and the simulaiton time for 1[step] corresponds to 0.1[ms] in real time.

The number of particles for the aortic wall and valve were about 9k and 900, respectively. On the other hand, the number of blood changes from about 26k at the beginning to 42k at the end of the simulation, because some particles are added as the particle in the left ventricle becomes shorter. The added particles are provided from solid particles constructing the cylinder below the target area. The numbers of solid particles that are located above and below the target area are 25k and 52k for the aortic wall and blood, respectively.

In the real heart, there is heart pulsation, which causes the blood flow from the left ventricle to the aorta; however, the particles are flown with sinusoidal velocity in the simulation.

Figures 8 shows the visualization of the pressure inside the aorta. At the initial state, the pressures in the aorta (top side) and the left ventricle (bottom side) are the same. As blood flows from the left ventricle to the aorta, the pressure in the left ventricle is a little bit higher than the aorta. By the pressure difference, the aortic valve starts to open. During the opening of the aortic valve, the pressure in the left ventricle is higher than the aorta. However, the pressure difference becomes gradually small and the aortic valve starts to close.

On the other hand, Figure 9 shows the visualization of the stress distribution on the aortic valve. The scale is different from that of the pressure to use the dynamic range efficiently. The opening and closing mechanisms are the same as that of the pressure; however, the stress value is higher than the pressure. High stresses occur at the root of the cusps especially when the aortic valve is opening and closing.

4 CONCLUSIONS

In this paper, we have reported the particle-based simulation on the aortic valve behavior. The simulation model was generated from CT data; however, the generated model was a little bit distorted due to some diseases, and the model was not suitable for the general purpose of the simulation so that we have modified

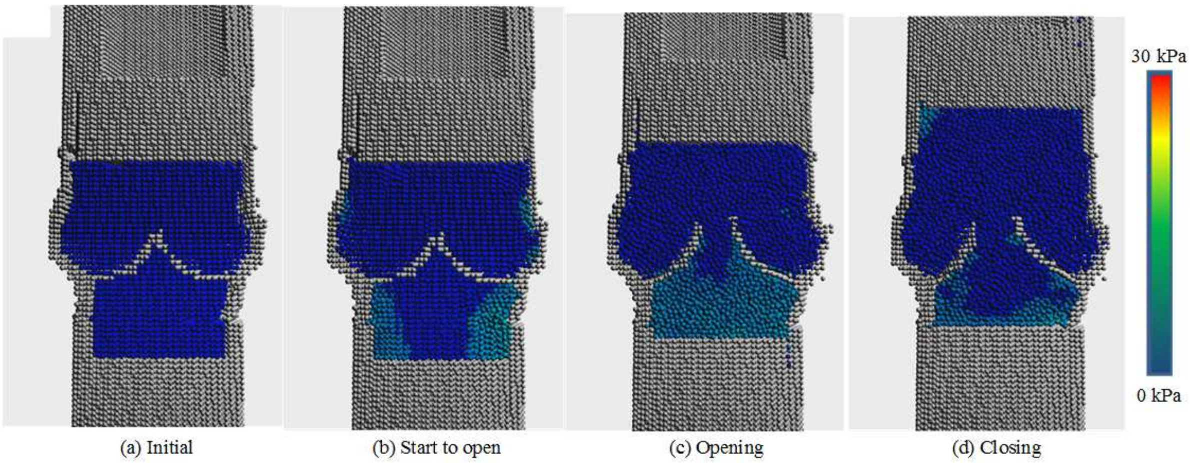

Figure 8: Pressure inside the aorta.

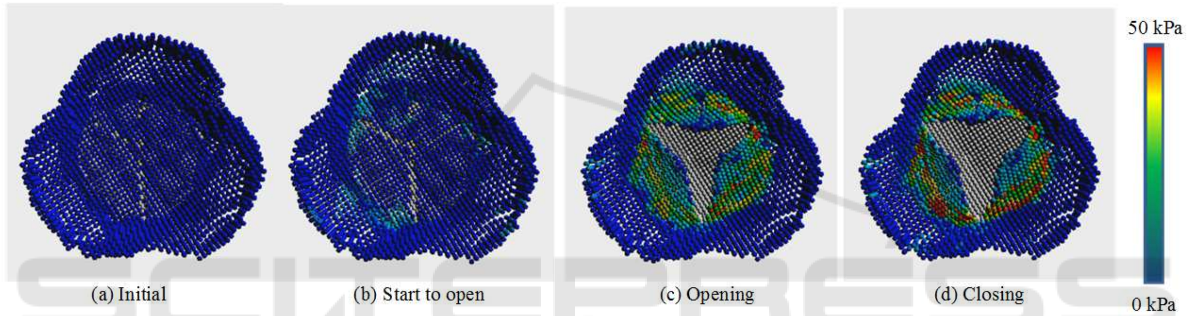

Figure 9: Stress distribution on the aortic valve.

the model by combining three copied cusps.

In addition, the simulation has to treat two different materials: fluid and elastic body. Particle method is suitable for fluid simulation, while FEM is suitable for elastic body simulation. However, it is difficult to treat mutual interaction between two materials if we use two different methods. Then, we have adopted a particle method in this simulation so that the simulation models were transformed from polygons to particles for the particle based simulation. We have also used two different but unified equations for the simulation: Cauchy-Navier equation and Navier-Stokes equation for elastic body and fluid, respectively, which are introduced from Cauchy's equation of motion by changing the constitutive equation according to the materials: elastic body and fluid, respectively.

Finally, we have been able to perform the simulation, and visualize the pressure inside the aorta and the stress distribution on the aortic valve. We have also found that high stresses occur at the root of the cusps when the aortic valve is opening and closing.

In the real heart, the heart pulsation causes the blood flow; however, we did not consider the heart pulsation in this simulation. Therefore, we have to calculate the blood velocity based on the heart pulsation. In addition, we have to validate our method by comparing the simulation results with the real video, and also expand the simulation method to perform many kinds of simulations for the planning of real surgeries.

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