Blood Flow and Pressure Change Simulation in the Aorta with the Model Generated from CT Data

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Abstract: We have performed the blood flow and the pressure change simulation in the aorta with the model generated from CT (Computerized Tomography) data. There have been some previous researches related to the aortic valve and the blood flow in the aorta. Some works simulated the aortic valve behavior with artificial models, and others investigated the blood flow in the aorta with models generated from MRI (Magnetic Resonance Imaging) data. In this paper, we demonstrate the simulation of the blood flow and the pressure change in the aorta with a model generated from CT data, which model includes not only the aorta but also the left ventricle. In the simulation, blood flows into the left ventricle through the mitral valve, the pressure increases according to the blood flow that moves into the left ventricle through the mitral valve, and the aortic valve opens by the pressure increase in the left ventricle. Finally, we have confirmed that the pressure change in the left ventricle corresponds to a literature value.

1 INTRODUCTION AND RELATED WORKS

There is a valve called "aortic valve" between the aorta and the left ventricle in our hearts, and some kinds of surgeries are performed if the valve falls into malfunction. There are mainly two types of surgeries: AVR (Aortic Valvular Replacement) and AVP (Aortic ValvuloPasty). AVR replaces the dysfunctional live valve with a prosthetic one. The surgery is not so difficult; however, taking warfarin is necessary to prevent blood from coagulating. On the other hand, AVP retrieves the valvular function by repairing the dysfunctional live valve. Taking wafarin is not necessary; however, the surgery is very difficult so that the preoperative computer simulation is needed. For the simulations, there have been some previous researches related to the aortic valve and the aorta.

(Hart et al., 2000) presented two-dimensional fluid-structure interaction model, and (Hart et al., 2003) expanded the model into three-dimension, and visualized the maximum principle Cauchy stresses in the leaflets of the aortic valve. On the other hand, (Cheng et al., 2004) investigated the fluid velocity distribution and the wall shear stress on a bileaflet mechanical heart valve. In the simulation, there are two types of materials: blood and aorta. Blood is fluid and the aorta is a solid body so that fluid-solid interaction should be considered. (Loon et al., 2005) used Navier-Stokes equation for the blood flow and hyperelastic Neo-Hookean model for the solid deformation. (Carmody et al., 2006) used FEM (Finite Element Method) for the simulation of fluid-structure interaction. (Mukai et al., 2014) employed a particle method to simulate the aortic valve behavior by considering heart's pulsation. (Hsu et al., 2014) and (Hsu et al., 2015) used Lagrangian-Eulerian methods for fluid-structure interaction. They created artificial models for the simulations, and the models were not generated from medical data such as CT or MRI.

On the other hand, (Seo et al., 2011) generated a simulation model from CT images, and simulated the flow characteristic in the aortic arch. (Wendell et al., 2013) generated an aorta model from MRI to investigate the behavior of the aortic valve. (Mukai et al., 2016) also generated the simulation model from CT data. These aortic models used for the simulations were realistic because they were constructed with a real data; however, they did not have the left ventricle part. Then, (Le and Sotiropoulos, 2013) used a simulation model including the left ventricle for the simulation of fluid-structure interaction between the blood flow and a mechanical heart valve.

In the previous researches, some used artificial models to simulate the aortic valve behavior and others used simulation models generated from real data;

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however, the target valves for the simulation were prosthetic. Therefore, in this paper, we demonstrate the blood flow and the pressure change simulation in the aorta with a particle simulation model generated from CT data, and confirm that a live aortic valve opens by the pressure increase in the left ventricle. In addition, we investigate if the pressure change in the left ventricle corresponds to a literature value.

2 MODEL GENERATION

In the simulation, there are two types of materials to be treated: blood and the aorta. Blood is fluid and the aorta and the aortic vavle are solid bodies so that we have to consider the interaction between them. Especially, the topology of blood changes according to the opening and the closing of the aortic valve. For the topological change, particle methods are suitable rather than FEM. Then, we employ a particle method for the simulation, and the simulation model constructed with particles should be generated from a medical data. Figure 1 shows the CT images of a heart used for the generation of the simulation model. The data is composed of 114 images, and the images are numbered from the top to the bottom. The format of the image is "bitmap" and the resolusion is 512×512.

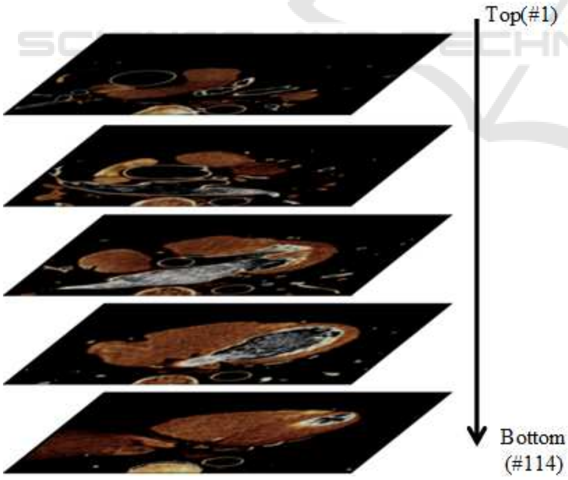

Figure 1: CT image data of a heart.

On the other hand, Figure 2 shows a vertical cross 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. Pseudo color is mapped to each part for easy recognition.

In order to generate the particle model of the aorta, it is the best way to extract the target region from the volume data shown in Figure 1; however,

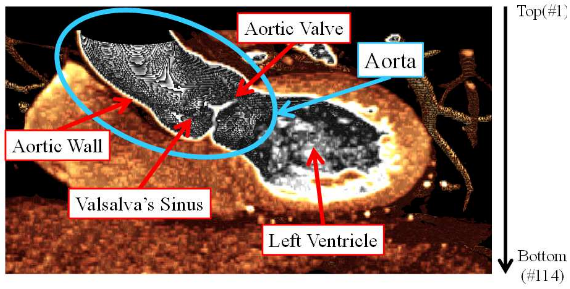

Figure 2: Vertical image of the heart.

the model size would be about 30M voxels because the image resolution is 512×512 and the number is 114. 30M particles are too much for a normal PC to handle in the main memory so that the data reduction is necessary. On the other hand, some breaks or holes would happen in the aorta model if the image data is simply reduced. In addition, in particle methods, extra particles are needed outside of the model since a high speed particle might jump out of the aortic wall if the aortic wall is thin. Then, the model generation algorithm is as follows.

<Particle model generation algorithm>

1. The resolution of the CT image data is reduced to 64×64 from 512×512.
2. Every four image plane is extracted for the model generation.
3. The reduced image is binarized and the target voxels are extracted as a closed region by manual.
4. The closed region is filled with voxels and the two outer voxels are extracted as the aortic wall elements.
5. The two extra voxels are added outside of the aortic wall model as dummy voxels for the simulation.
6. The particle model is generated by combining all voxel data.

The particle model is generated in three dimension, and Figure 3 shows a cross section of the particle model generated from the CT data. The right lower part is the left ventricle and the upper left part is the aorta. The central part that has a different color is the aortic valve, and the hole in the left ventricle is the mitral valve. Figure 4 is another cross section of the model viewed from a different angle. The lower part is the left ventricle and the upper part is the aorta. The right part next to the left ventricle is the mitral valve. Here, the aortic valve is not so clear on the CT image so that the aortic valve model is generated by manual from the shape of the valsalva's sinus. Figure 5 shows the particle model of the aortic valve, which leaflets are differentiated by different colors.

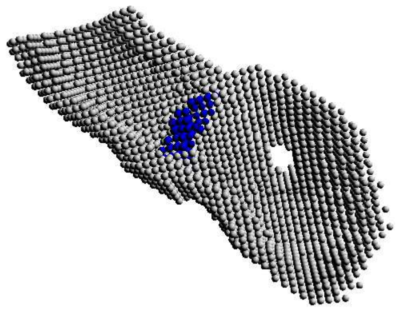

Figure 3: Particle model of the aorta and the left ventricle.

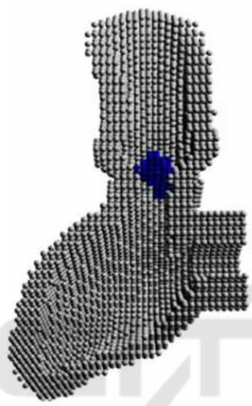

Figure 4: Particle model viewed from a different angle.

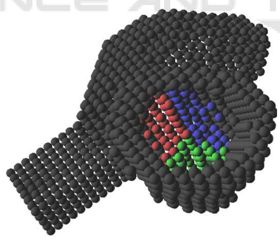

Figure 5: Particle model of the aortic valve.

3 SIMULATION METHOD

In this simulation, a particle method is used because the topology of blood changes often according to the opening and the closing of the aortic valve. There are mainly two types of particle methods: SPH (Smoothed Particle Hydrodynamics) and MPS (Moving Particle Semi-implicit). In general, SPH is used for compressible fluid, while MPS is used for incompressible fluid. Blood is generally treated as incompressible fluid so that we employ MPS (Koshizuka, 2005) for the simulation.

Two kinds of governing equations are used for the continuous body simulation: Cauchy's equation of motion and equation of continuity, which are written as the following (Eqs. (1) and (2)).

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

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

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 (Eqs. (3) and (4)).

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

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

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 (Eqs. (5) and (6)).

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

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

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 (Eq. (7)) is obtained, which equation is applied to analyze the behavior of the aortic 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 (Eqs. (8) and (9)).

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

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

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 (Eq. (10)) is obtained as follows, which is applied to analyze the behavior of blood.

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

4 SIMULATION RESULTS

The simulation was performed with a normal PC (Personal Computer), which has i7-3770K CPU (Central Processing Unit) and GeForce GTX570 GPU (Graphics Processing Unit). The simulation time for 1[step] corresponds to 0.1[ms] in real time, and the particle radius was 2 [mm]. Figure 6 shows the visualization of the pressure inside the left ventricle and the aorta.

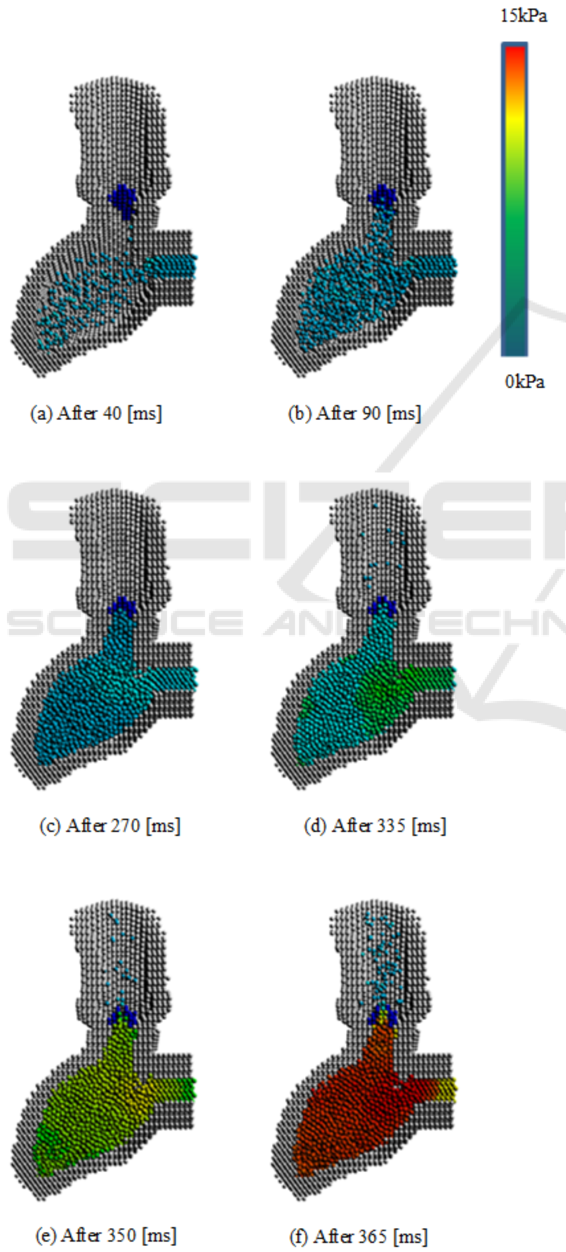

Figure 6: Visualization of the pressure in the left ventricle and the aorta.

At first, particles are flown into the left ventricle through the mitral valve (See Figure 6 (a)). Then, the pressure in the left ventricle is gradually increased (See Figure 6 (b) and (c)). When the pressure difference between the left ventricle and the aorta is high, the aortic valve opens and some particles (blood) flow into the aorta (See Figure 6 (d) and (e)). When the pressure in the left ventricle becomes high, many particles flow rapidly into the aorta (See Figure 6 (f)).

On the other hand, Figure 7 and 8 show the pressure change of the left ventricle and the aorta, respectively. As particles flow into the left ventricle through the mitral valve, the pressure in the left ventricle increases. The pressure in the aorta also increases a little bit later after the aortic valve opens by the pressure in the left ventricle. There are some variances of the pressure at the maximum level because particles flow from the left ventricle to the aorta, and the pressure is unsteady at the time.

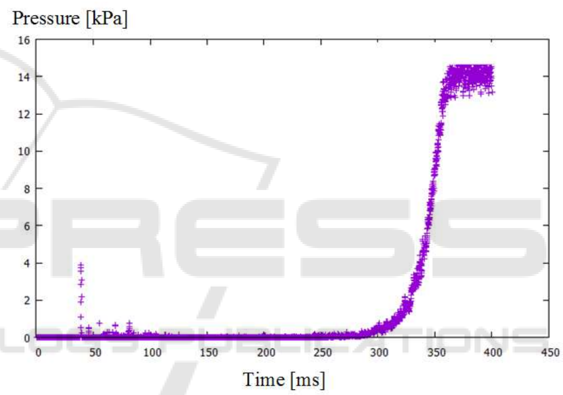

Figure 7: Pressure change in the left ventricle.

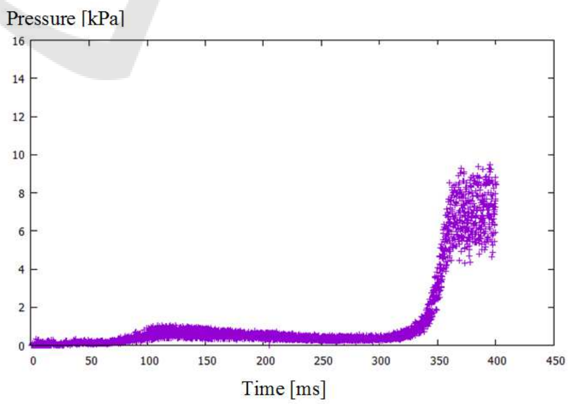

Figure 8: Pressure change in the aorta.

Here, Figure 9 shows the diagram of the pressure change of the left ventricle and the aorta in one heart pulsation (Izawa, 2009; Levick, 2011; Klabunde, 2012; Silbernagl and Despopoulos, 2009). At the atrial systole stage, the pressure of the aorta is higher than the left ventricle, and the aortic valve closes. At the isovolumetric contraction stage, blood flows into the left ventricle and it is filled with blood. In addition, the left ventricle shrinks isovlumetrically so that the pressure of the left ventricle rapidly increases to the same level as the aorta. Actually at the rapid ejection stage, the pressure of the left ventricle becomes slightly higher than the pressure of the aorta. Therefore, the aortic valve opens. While blood flows from the left ventricle to the aorta, the pressure of the left ventricle is almost the same level as the pressure of the aorta although the pressure of the left ventricle is slightly higher than the pressure of the aorta. After some blood has flowen from the left ventricle to the aorta, the pressure of the left ventricle gradually decreases at the reduced ejection stage. Thus, the aortic valve closes. After the aortic valve closes, the left ventricle expands isovolumetrically at the isovolumetric relaxation stage, and the pressure of the left ventricle rapidly decreases. If the aortic valve closes correctly, no blood flows back from the aorta to the left ventricle and the pressure difference between the aorta and the left ventricle increases. At the rapid filling stage, blood flows into the left ventricle so that it is filled with blood again at the reduced filling stage.

On the other hand, Figure 10 shows the diagram that has the simulation results overlaid on Figure 9, where the pressure value is changed to SI unit. From the figure, the pressure of the left ventricle corresponds well to the literature value; however, the pressure of the aorta does not correspond to the literature value. One reason is that particles flown into the aorta from the left ventricle spread out because the aorta does not form a closed region. The other is that the initial pressure of the aorta is zero although the aorta in the actual heart has some blood from the beginning.

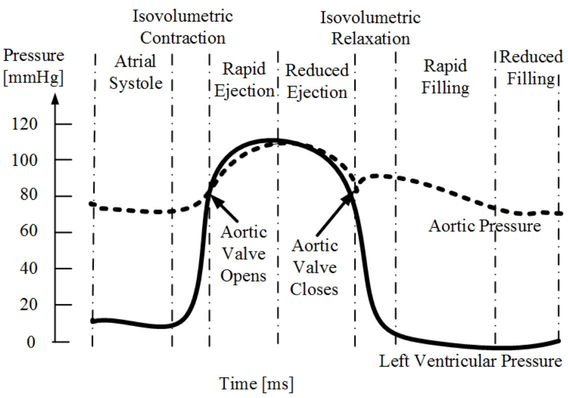

Figure 9: Diagram of the pressure change in one heart pulsation.

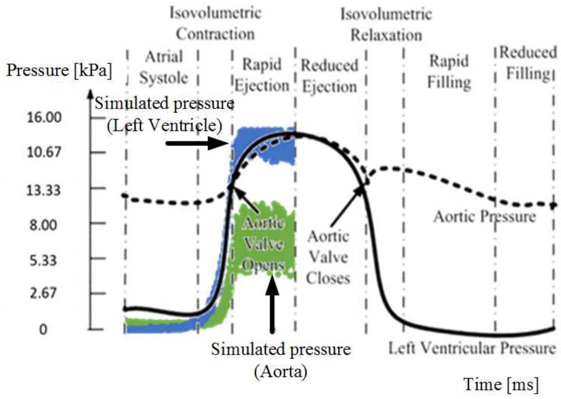

Figure 10: Pressure comparison between the simulation results and a literature value.

5 CONCLUSIONS

In this paper, we have demonstrated the blood flow and the pressure change in the aorta with the particle model generated from CT data. We employed a particle method for the simulation because particle methods are useful for the topology change of the blood by the opening and the closing of the aortic valve. In order to perform the simulation, we had to generate the model with particles and a precise model needs too many memories to handle with a normal PC. Then, we have constructed the particle model by reducing the original CT image data and also by attaching additional particles outside the model to prevent particle explosion.

In the simulation, there are two types of materials to be handled so that two types of equations, Cauchy-Navier and Navier-Stokes equations, should be solved. The simulation results were visualized with particles. In the visualization, we have confirmed that particles flew into the left ventricle through the mitral value, the aortic valve opened by the pressure of the left ventricle, and finally particles flew into the aorta.

In the comparison of the simulation results with a literature value, the pressure change in the left ventricle corresponded well to the literature value, while the pressure change in the aorta did not. This is due to the openness of the aorta and the emptiness of the blood in the aorta at the beginning.

Then, we have to try the simulation with the model having a closed region of the aorta and confirm that the pressure change in the aorta also corresponds to the literature value. In addition, we have treated the aortic valve as an elastic body; however, the aortic wall was treated as a solid body instead of an elastic body in this simulation. In the future, we plan to perform the simulation by treating the aortic wall as an elastic body.

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