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Blood Flow Simulation of Virtual Simulation System for Vascular Interventional Surgery

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Abstract **- In the virtual simulation training system for interventional surgery, most people focus on how to model blood vessel, catheter and guide wire. However, little research has been done on the effect of intravascular blood on interventional surgery. Blood is a kind of viscous fluid, so as the catheter or guide wire advances, retreats, or rotates through the blood vessel, the blood produces a kind of viscous force in the movement of the catheter or guide wire. It can affect the accuracy of the operation. In order to realize real simulation, firstly, the Smoothed Particle Hydrodynamics (SPH) method is applied to the study to simulate physical blood flow. Secondly, the Marching Cube method is adopted to render physical model, which can establish a good blood flow model. The method can also be used to simulate bleeding on organs or skin surfaces. Finally, we achieve the blood flow in blood vessel which is modeled by tensor - mass method. The experimental results show that the SPH method for blood simulation has a very real effect, and the simulation of intravascular blood flow is of great significance for the further study of interventional surgery.**

Index Terms - Virtual reality surgery training system, SPH, Marching Cube, Multi-model simulation

I. INTRODUCTION

Vascular intervention has some advantages: it does not require the use of a scalpel, the damage is small, and there is little pain; but at the same time, the doctor's operation is unskilled at first, which leads to a problem of low accuracy [1], [2]. The virtual training system can solve this problem better, which provides training opportunities for novice doctors and increases the success rate of surgery. At present, most of the research on virtual training systems mainly focuses on the simulation model of blood vessels, guide wires and catheters, and the collision detection between them. The Guolab of Beijing Institute of Technology has done a lot of research on the virtual simulation training of vascular interventional surgery [3], [4], [5]. However, there is no attention to the effect of intravascular blood on interventional surgery.

But we all know that blood is an incompressible liquid and it is sticky. When the catheter and the guide wire move forward inside the blood vessel, the blood inside the blood vessel will have a viscous force on the catheter and the guide wire. It will affect the advancement, retreat, rotation and other actions of the catheter and the guide wire to some extent, which will affect the accuracy of the simulation of the interventional surgery system. Therefore, when we research the virtual training system, it is very necessary for us to carry out simulate and model about blood in the blood vessels.

In the simulation of blood flowing, some scholars at domestic and abroad have conducted different researches on different aspects and made some progresses. Basdogan uses two different models for two different types of bleeding [6]. Using the Particle System Model to simulate the arterial vascular bleeding, using the surface flow model to simulate the surface flow model, which is based on the wave equation proposed by Kass [7]. P. Oppenheimer proposed a video capture method based on video capture, but this method is not suitable for changes in the surface of organs (such as cutting, deformation, etc.) [8]. L. Raghupathi also proposed two independent models, a volume model based on static fluid mechanics to simulate the effect of massive blood pooling [9]. The other is a particle system model, to simulate the free flow of blood. Matthias Muller, Simon Schirm and others realized, special effects scene based on smoothed particle hydrodynamics (SPH) method using 3000 particles to achieve blood vessel rupture under no user interaction [10]. Deschamps use the embedded boundary method to simulate the blood flowing in the blood vessels, and he achieved some simulation effects, but the real-time and realism of the simulation needed to be improved [11]. Cebral etapplied computational fluid dynamics to study blood flow models in arterial vessels [12].

There are also many research institutions in China that has carried out simulation on blood flow phenomena. Professor Xiong Yueshan of National University of Defense Technology proposed a relatively simple model to simulate a curved blood trough formed by small blood flow [13]. He used the method of metaball to draw the blood trough, only considering the simulation of the dynamic effect of the bleeding front end, and the blood trough part is drawn statically. This dynamic and static simulation method effectively reduces the computational cost, improves the realism, and has good real-time performance. Xu Kai of the National University of Defense Technology proposed two models of bleeding, which were respectively used to simulate the two types of bleeding in virtual knee arthroscopy [14]. One is a simulation of a small amount of columnar bleeding caused by the puncture of the outer surface of the knee joint, using a method based on metaball drawing. The other is to deal with a large amount of bleeding after the surface of the organ is cut, and the blood will spread on the surface of the organ, and a blood flow model based on the diffusion equation is proposed. Zheng Guangchao of Shanghai Jiao Tong University adopted a grid-based stable half-Lagrangian method to achieve endoscopic bleeding simulation, which oozes blood from the viscera, fills the entire field of view, and blurs the visual effect [15]. The Institute of Basic Medical Sciences of the Chinese Academy of Medical Sciences has studied coronary circulatory hemodynamic, which again raises the importance of hemodynamic for medicine [16]. Sun Qi of Shanghai Jiao tong University used CFD method to simulate the bleeding in the cavity-lung anastomosis structure [17]. His simulation results can directly reflect the flow characteristics of the flow field, and can analysis the influence of various factors on hemodynamic performance, and provide a method for clinical evaluation of the advantages and disadvantages of cavity-lung anastomosis.

Blood flow is a very complicated phenomenon, and different individuals, different organs and different environments can cause different blood flowing phenomena. The simulation of blood flowing in virtual interventional surgery has higher requirements for the simulation of blood, not only requires its form to be realistic, but also requires real-time flowing. The realization of realism and real-time will occupy computer resources. If the sense of reality is high, the blood movement will be delayed, giving a false feeling. If the real-time is high, the blood form description will be weakened and the visual effect will be affected. If the sense of reality is over-emphasized, it will lead to delayed movement of blood, giving people an unreal feeling; if the real-time nature is over-emphasized, it will lead to a weakening of the blood form description and affect the visual effect. Therefore, seeking the unity of realism and real-time feeling, how to improve the effect of both at the same time, has become the key to study the blood flow phenomenon in virtual interventional surgery.

II. SPH MODEL METHOD

SPH actually is a particle-based interpolation method [18], [19], [20], [21], [22]. In 1983, Reeves first proposed the concept of a particle system (particle system) [23].The particle system is a typical algorithm based on the dynamic random growth principle model. It is also the most successful graph generation algorithm that has been considered to be the most successful simulation of irregular fuzzy objects [24].

A. Navier-Stokes Equation

The N-S equation is a nonlinear partial differential equation that reflects the basic mechanical laws of viscous fluid flow, which is very important in fluid mechanics. It mainly describes the relationship between the acceleration, pressure, viscous force of the fluid particles and the gravity acting inside the fluid. The N-S equation is one of the most difficult equations for nonlinear equations at present, and it is very difficult to find its exact solution.

The N-S equation can be described as:

$$\rho(\frac{\partial \vec{v}}{\partial t}+v\bullet \qquad {}^{2}\vec{v}-\nabla P+\rho g \tag{1}$$

Where, the density of the fluid is ρ, the speed is v, the pressure is P, and the viscosity coefficient is u.

B. SPH Basic Theory

The construction of SPH equation has two key steps. The first step is the integration representation, which can also be called, “Kernel function approximation”. The second step is "particle approximation". The method of the "nuclear function approximation", which can convert the function describing the field into the integration of the multiplication of any function and kernel function. Then, the integration generated by the approximation of the kernel function is expressed as the sum of discrete particle by the way of "particle approximation". That is, the integration series expression, which transforms the entire flow field into a series of particle expressions, each of which can be expressed by surrounding particles, so that the force of the entire flow field is loaded by these particles.

After the approximation of the function describing the field is transformed into the relevant continuous integral, it is discretised and transformed into a form of summation of all particles in the support domain. Among them, the support domain is showed in Fig.1.

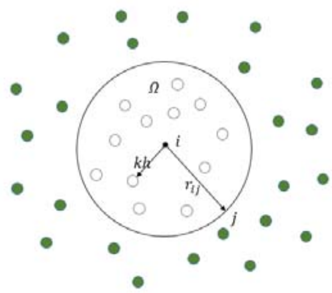


Fig. 1. Diagram of the support domain.

C. Solving the N-S Equation by Using the SPH Formula

In the SPH method, the number of particles is constant, and the mass of each particle is also constant, and the particles move with the movement of the fluid, so that:

$$\begin{aligned} f &= \mu\nabla^2 \vec{v} - \nabla\rho + \rho g \\ &= f_i^v + f_i^p + f_i^g \end{aligned} \tag{2}$$

The three factors on the right can be regarded as the sum of three forces, which respectively are viscous force f_i^v, pressure f_i^p and gravity f_i^p.

Among them, its partial enlargement effect is shown in Fig. 3.

$$f_i^v = u\sum_{j=1}^{n}\frac{m_j(v_j - v_i)}{\rho_j}\nabla^2 w(x_i - x_j, h) \tag{3}$$

Where, ρ_j is the density of the particles, m_j is the mass of the particles, P_i and P_j are the pressure of the particles, $w(x-x_j,h)$ is a nuclear function.

Due to the two different particles in space, they are generally under different pressures, so they do not satisfy the symmetry of force. In order to make our simulated blood stable and true, we take the average of the pressure to correct it, as shown below:

$$f_i^p = -\sum_{j=1}^{n} \frac{m_j(P_j+P_i)}{2\rho_j} \nabla w(x-x_j,h) \tag{4}$$

The gravity has not changed, as shown in formula (2). In the process of simulating blood, by combining (2), (3), (4), the resultant force of the particles can be obtained. It is possible to simulate the state of motion of the blood.

D. *Experimental Results*

The blood result we use the SPH method to simulate is shown in Fig. 2.

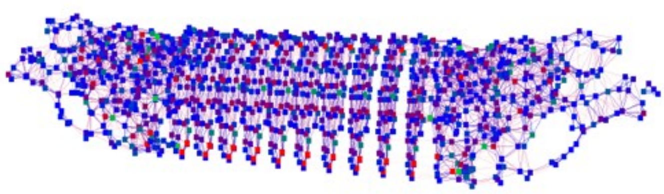


Fig. 2. Blood particle model constructed by SPH.

Among them, its partial enlargement effect is shown in Fig. 3.

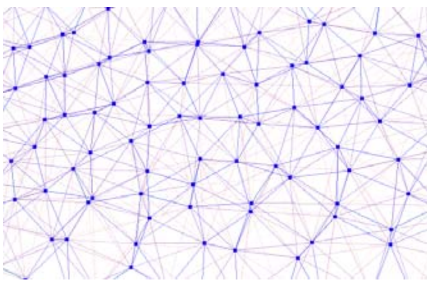


Fig. 3. Partial magnification of particles.

III. Marching Cube Method

The second part describes how to simulate the physical model of blood. When we build a physical model, we need to render the surface of the model in order to satisfy the authenticity. Surface rendering of fluids is also an important step in fluid simulation. Here we have chosen the Marching Cube method to render the surface of the blood model. The surface rendering of the 3D model is not only the MC method, but the MC method has the advantages of good quality of the generated mesh and high parallelism compared with other methods. Now I will briefly introduce it.

A. *Marching Cube Method*

Moving a cube is a classic way to generate isosurfaces from a density field [25-26]. It divides the density field into grids, the density field of the voxels of each corner of the voxel of the lattice is evaluated, and the form of the generated triangle is determined according to whether it is greater than a certain constant threshold. The schematic is showed in Fig. 4.

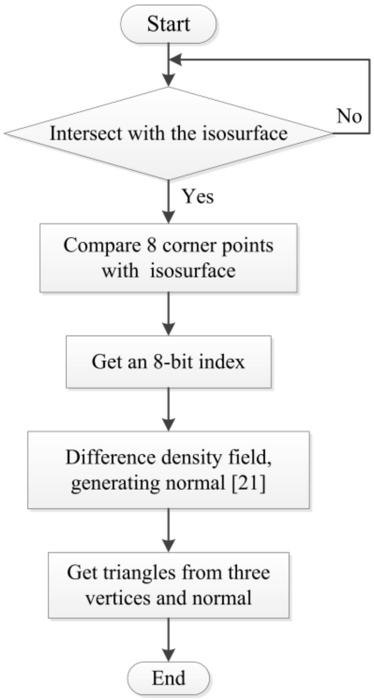


Fig. 4. Marching Cube algorithm flow chart.

In the above flow chart, the fourth step is to look up the table to determine which triangle vertices are connected. Among them, the checklist is the content shown in Fig. 5. It shows fifteen basic conditions corresponding to the Marching Cube algorithm [27], [28].

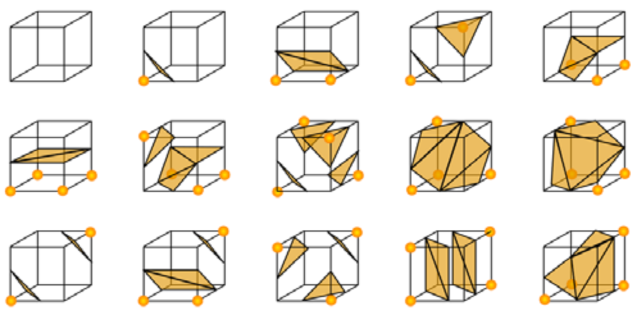


Fig. 5. The fifteen basic conditions corresponding to the Marching Cube algorithm.

B. *Experimental Results*

We perform surface rendering on the particle model established by using the SPH method. The experimental results is showed in Fig. 6.

We can see that this blood flow model, which we simulated is very intuitive, which is beneficial for further exploration below.

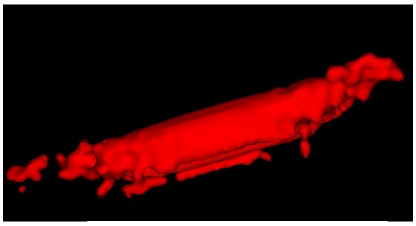


Fig. 6. Surface rendering of a blood model.

IV. Experiments and Validation

A. Experimental Preparation

A series of operations conducted in this experimental study were simulated on a Think Station with 16GB RAM and Intel Xeon (R) E51607 CPU. The construction of our SPH fluid model is based on a SOFA physics engine. SOFA is an open-source framework, targeted against real-time simulation, with an emphasis on medical simulation. The version of software required to configure SOFA in this lab is: SOFA 18.06, Visual Studio 2015, QT 5.6.0, and Boost 1.6.2.

The SOFA architecture applies multiple models to represent the results, it allows for several representations of the same object (such as mechanical, thermal and visual). These different representations are connected together by a mechanism called "mapping." Using these features, you can also interact with models that have very different characteristics. Among them, the mechanical model contains the physical properties of the object, the collision model enables the objects to interact in three dimensions, and the visual model makes our simulation more authentic. The three models are independent of each other and can be modified separately. In the end, the three models are synchronized by visual mapping and mechanical mapping to complete the simulation.

The scene graph of blood flowing model is expressed as Fig.7.

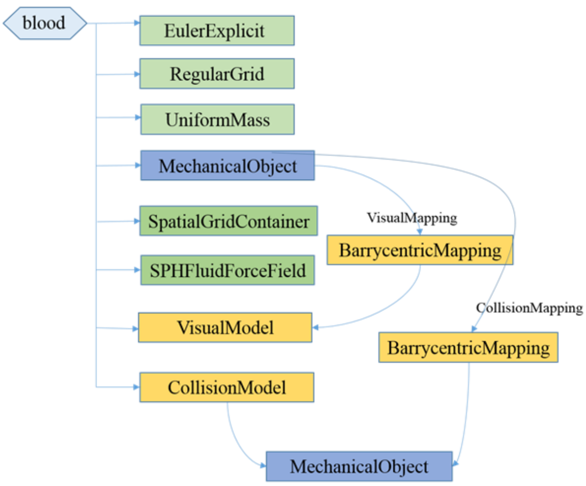


Fig. 7. Scene map of blood modelling.

During the different steps of the simulation (initialization, system assembly, solving, visualization), information needs to be recovered from all graph nodes. SOFA relies on an implicit mechanism: the Visitors. Visitors traverse the scene top-down and bottom-up and call the corresponding virtual functions at each graph node traversal. Visitors are therefore used to trigger actions by calling the associated virtual functions (e.g. animating the simulation, accumulating forces). Algorithmic operations on the simulated objects are implemented by deriving the Visitor class.

This approach hides the scene structure from the components, for more implementation flexibility and a better control of the execution model. Moreover, various parallelism strategies can be applied independently of the mechanical computations performed at each node. The data structure is actually extended from strict hierarchies to directed acyclic graphs to handle more general kinematic dependencies. The top-down node traversals are pruned unless all the parents of the current node have been traversed already, so that nodes with multiple parents are traversed only once all their parents have been traversed. The bottom-up traversals are made in the reverse order.

A common sequence diagram for SOFA simulation is showed in The Fig. 8.

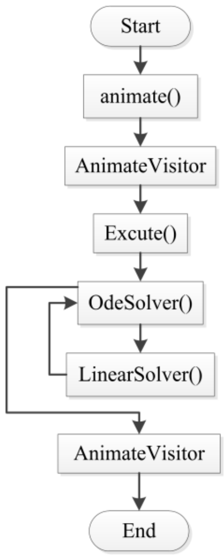


Fig. 8. Common sequence diagram of SOFA simulation.

B. Blood Modeling

The phenomenon of blood flowing is a very complicated process. It’s flowing in organs and skin surface can be seen as a phenomenon of free movement of blood. Therefore, the simulation of the flow of blood has profound practical significance.

First, we used the SPH method to model and construct a physical model of the blood; then we used the Marching Cube method to render the blood surface. The blood model obtained at this time has certain authenticity.

The radius of the SPH is 0.745, the viscosity coefficient is 45.0, and the mass of the particles is 1. The following is a simulation experiment of free flowing of blood, the experimental results are shown in the Fig. 9.

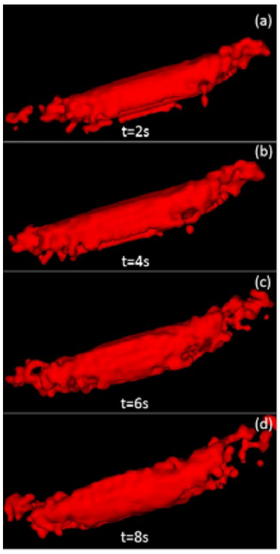


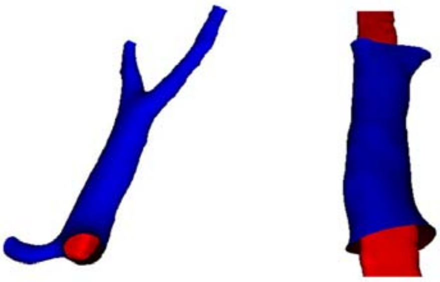
Fig. 9. Free flow of blood simulation diagram.

C. *Vascular and Blood Modeling*

Blood simulation is of great importance in vascular interventional surgery. First, it can make our simulations more realistic in visual. Secondly, blood has an influence on the advancement of the guide wire, so simulating it can improve the accuracy of our virtual training. Therefore, the interactive simulation of blood vessels and blood is of great significance for the continued study of vascular interventional surgery. In this section, we model the blood vessels using a mass tensor model and then interact with the blood model.

In this experiment, vascular was modeled by using a based tensor-mass method in which the Poisson's ratio is 0.5 and the Young's modulus is $500kPa$.

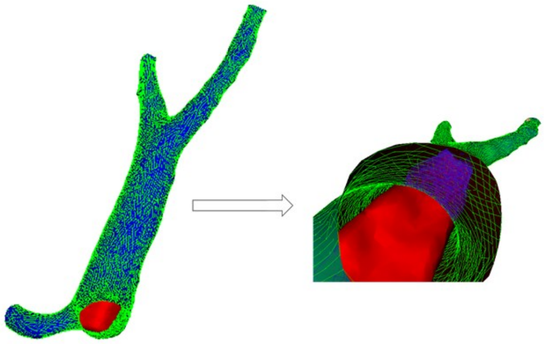
The overall effect of our simulation is shown below. Among them, the simulations of different types of blood vessels are shown in Fig. 10 (a) and (b).



(a) (b)

Fig. 10. Interactive simulation of different blood vessels:
(a) long blood vessel (its shape is complicated);
(b) short blood vessel (its shape is simple).

Then, we will introduce the situation simulated in Fig. 10 (b) in detail. Fig. 10 (b) is a model that the surface has been rendered. For the picture below, we can see the flowing of the blood. We will use the physical model to display it. Fig. 11 (a) is the physical model of Figure a, with a partial enlarged view as shown in Fig. 11 (b).



(a) (b)

Fig. 11. Physical simulation of vascular interaction and partial enlargement:
(a) physical model of Fig.10(a),
(b) partial enlarged view of Fig.11(a).

The following is a simulation of the flow of blood vessels in blood vessels. The experimental results are shown in Fig. 12 and Fig. 13.

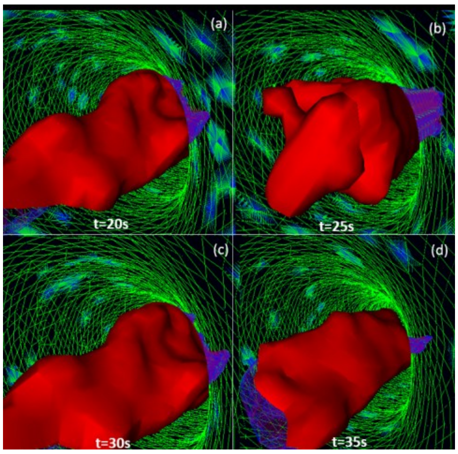


Fig. 12. Partial flow of blood in blood vessels at different times.

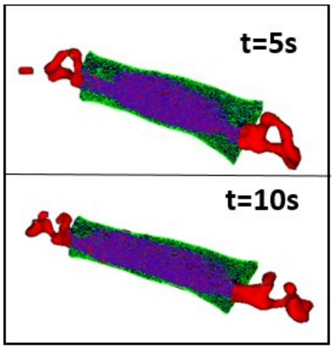


Fig. 13. Flow of blood in blood vessels at different times.

From this we can see that we can make an initial experimental simulation of the flow of blood in blood vessels, and we can get a good result.

In this experimental study, the simulation of the flow of blood, the simulation results in line with the basic laws of motion, the experimental results are highly authentic, and the model can be applied to the blood flow simulation of the organ or skin surface. The flow simulation of blood in the blood vessels is initially achieved, which is helpful for improving the real-time nature of the guidewire into the blood vessels. The blood simulations achieved in this paper will help to study the effects of heart beat on blood flow in the future.

IV. Discussion and Conclusion

The interventional virtual training system provides preoperative training for the operation of the interventional procedure. However, the current simulations mostly focus on blood vessels, catheters, and guide wires, but ignoring the blood inside the blood vessels, which affects the movement of the catheter and the guide wire. According to the characteristics of blood, this study uses SPH method for physical modelling, which can get a good physical model. Then, using the Marching Cube method to surface the blood, you can visualize it. Finally, we simulate the flow of blood in blood vessels. The blood vessel is modeled by using a tensor-mass method. The free movement of blood simulated on the surface of the organ and the flow of blood in the blood vessels have achieved good results.

This research is an inspiration for the interventional surgery simulation training system, which can inspire relevant researchers to engage in the blood flow inside the blood vessels and improve the authenticity and accuracy of the interventional surgery. Next, we will inject the guide wire into the blood when there is blood inside the blood vessel, so that we can more realistically restore the real situation of the interventional surgery. In addition, we will explore the use of CUDA and multi-threading technology to accelerate the simulation of the entire system and improve the authenticity of the simulation.

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