Catheter and guidewire simulator for intravascular surgery (Comparison between simulation results and medical images)

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Abstract — **We have developed a system to simulate a catheter and guidewire in blood vessels for surgical planning, intra-operative assistance and the design of new catheters. The guidewire model is composed of viscoelastic springs and segments. The proximal part of the guidewire model is constrained by the catheter model, which is fixed and assumed to be a rigid tube. The blood vessel model is a circular elastic cylinder, whose shape is defined by the centerline and the radii. Collisions between the guidewire model and the blood vessel model are calculated and the contact forces are determined according to the stiffness of the vessel wall. In our previous study, we evaluated the effects of the parameters of the guidewire and the blood vessel on the simulation system using a torus-shaped vessel model. However, in clinical applications, numerical data should be acquired by image processing of data on the vasculature acquired from the patient. Therefore, in this study, we used patient-specific data and compared the simulation results with medical images for validation of the simulation system. It was shown that guidewire position can be determined using our simulation system.**

Keywords —**Computer-aided surgery, Intravascular surgery, Surgical planning, Catheter, Numerical analysis**

I. INTRODUCTION

Catheters and guidewires are used in the treatment of infarctions and aneurysms. As the point of insertion is often the thigh, the catheters and the guidewires must be 1 m in length for treatment of the brain. However, the procedure is very difficult due to the small diameter and tortuousity of blood vessels. In addition, surgeon sensory perception (visual and tactile) is severely reduced during manipulation in such surgery, as these tools are long and flexible, and have few degrees of freedom. Therefore, various catheter simulators have been developed in order to make intravascular treatment safer [1-9].

For training, many simulators also include a haptic interface, with which medical students or physicians operate the virtual guidewire. We have also developed a system to simulate a catheter in blood vessels [10, 11]. However, this system was developed in order to predict the course of approach to a lesion and to present numerical results and animations for surgical planning, intra-operative assistance and the design of new catheters. Consequently, a physician can easily judge for each patient whether intravascular surgery is more suitable than open surgery, and determine the type of guidewire to be used in preoperative surgical planning. In addition, this system can aid the more rapid approach to lesions by comparing the course of the catheter on X-rays and the simulated route in this system. Moreover, using animations, the disease and treatment can be easily understood by patients, and can be explained by the physician.

In our previous study [10, 11], we evaluated the effects of the parameters of the guidewire and the blood vessel models on the simulation system. There, we inserted a guidewire model based on a commercial guidewire into a torus-shaped vessel model and calculated the trajectory of the guidewire tip and the reaction force. However, as actual cerebral arteries have very complex structures, it is difficult to confirm whether the simulation model accurately represents practical situations. In clinical applications, these numerical data should be acquired by image processing of the section data of the vasculature acquired from the patient.

Therefore, in this study, we used patient-specific data and compared the simulation results with medical images in order to validate the simulation system.

II. METHODS

A. Modeling of blood vessels from patient data

In this study, we used two types of image data with aneurysms growing near the arterial circle of Willis (DICOM format). The characteristics of the data are illustrated in Table 1. Many cerebral aneurysms grow at the bifurcation between the internal carotid artery and the posterior communicating artery, the anterior communicating artery (Acom) and the bifurcation of the middle cerebral artery. The age of most patients is between 50 and 60 years [12].

O. Dössel and W.C. Schlegel (Eds.): WC 2009, IFMBE Proceedings 25/VI, pp. 128–131, 2009.
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Table 1. Characteristics of DICOM data.

Case	Portion	Sex	Age	Resolution (mm/pixel)	Slice thickness (mm/pixel)
A	Acom	M	54	0.15	0.15
B	Acom	F	74	0.15	0.15

The procedure to calculate the centerline of the blood vessel from DICOM data is as follows. The following procedures are conducted for each cross-section:

1. Reduction of noise
2. Extraction of blood vessel area
3. Removal of small objects
4. Calculation of the center of the blood vessel area in each cross-section

Then, the calculated centerline data of the blood vessels was smoothed and interpolated. The guidewires used in surgery were present in the blood vessel images. Therefore, the actual guidewires are seen as dark points in each cross-section. In this study, the actual positions of the guidewires were also calculated by the above-mentioned procedure and were compared with simulation results.

B. Calculation of geographical features of blood vessels

It is necessary to calculate the geographical features of blood vessels in order to quantitatively evaluate the simulation results. In this study, we calculated the curvature (κ) and torsion (η) as geographical features using the data on blood vessel centerline ($\boldsymbol{p}$) as follows [13]:

$$\kappa = \left| \frac{d^2 \boldsymbol{p}}{ds^2} \right| \tag{1}$$

$$\eta = \frac{1}{\kappa^2} \left[\frac{d\boldsymbol{p}}{ds}, \frac{d^2 \boldsymbol{p}}{ds^2}, \frac{d^3 \boldsymbol{p}}{ds^3} \right] \tag{2}$$

where s is the arc length of the vessel centerline. These values were approximated by difference equations using discrete values ($\boldsymbol{p}$).

C. Simulation model

The guidewire model is composed of viscoelastic springs (2 degrees of freedom) and segments (n = 17, length: 2.5 mm, outer diameter: 0.34 mm). We calculated the contact force vector between the guidewire and vessel, as well as the induced moment of each segment, and then calculated the effects of these forces and moments on other segments. The motion of the guidewire is represented by the Newton-Euler equations of motion. We obtained actual data using a commercial guidewire and used the results in the simulation. The insertion length is larger than that of the guidewire model (40 mm). The proximal end of the guidewire is connected with the distal end of the catheter model by springs in order to eliminate the effects of this part. The catheter model was fixed and assumed to be a rigid tube.

The vessel is a circular elastic cylinder, whose shape is defined by the centerline and the radii (= 2 mm). The centerlines that determine the shape of the whole vessel are represented by numerical data ($\boldsymbol{p}$). Deformation of the vessel tube in the radial direction is modeled with an elastic coefficient.

In this study, we inserted the guidewire model into the vessel model and calculated the trajectory of the guidewire tip. To determine whether there is contact between the guidewire and the vessel, the distances between the joints and the tip of the guidewire model, as well as the centerline of the vessel, were calculated.

D. Simulation procedure

The simulation procedure is as follows. Ideally, it is necessary to calculate the whole vessel from the insertion point of the thigh to the lesion. However, the surgery is difficult, particularly when the guidewire is near the lesion. Therefore, the initial condition of the simulation is set for when the guidewire is near the lesion, and then proceeds as follows.

1. The guidewire model, which is inserted 41 mm from the catheter, is fixed along the centerline of the blood vessel model (Fig. 1, left).
2. The fixation of the guidewire on the centerline is freed and the guidewire model contacts the blood vessel wall (Fig. 1, right). In this procedure, the proximal end of the guidewire is fixed.
3. The proximal end of the guidewire model is pushed or pulled at a constant speed (1 mm/s) in each direction (+ 6 mm → -3 mm → +3 mm).

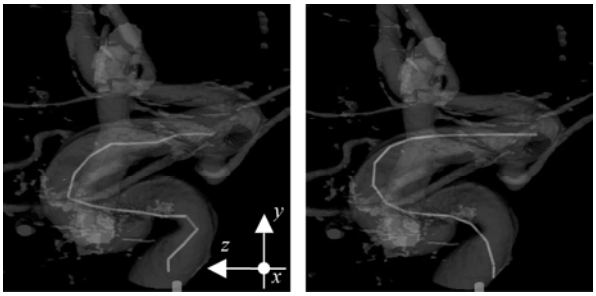

Fig. 1. Simulation model (case B).

Based on the above assumptions, we calculated the Newton-Euler equations of motion using the contact force at every finite time step, using numerical differentiation formulas. The time steps were not fixed in order to make the relative errors smaller than permissible values (10^{-3}) at each time step. When contact occurred within a time step, we divided the time step at the contact point.

III. RESULTS AND DISCUSSION

A. Geographical features of blood vessels

Calculated centerlines of blood vessels are shown in Fig. 2. In case B, it was difficult to calculate the centerline when $y = 7$ because the centerline was parallel to the cross-section of the blood vessel. Calculated curvature and torsion of blood vessels are shown in Fig. 3. The curvatures in both cases are almost same. When $y = 7$ to 8 in case B, the curvature is almost zero (arrow) because the centerline was interpolated linearly. The torsion of the centerline in case A is larger than that in case B. The reason is that the centerline in case B does not change along the x-axis, as shown in Fig. 2, left.

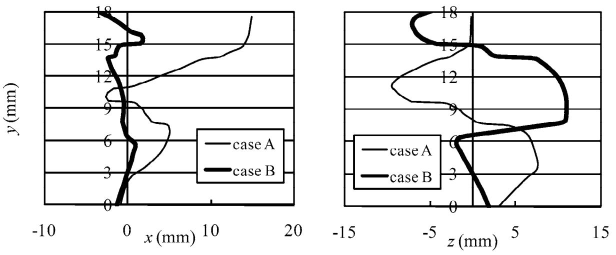

Fig. 2. Centerlines of blood vessels.

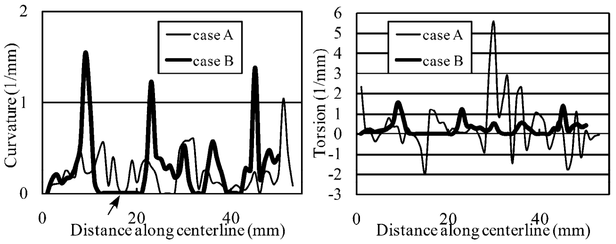

Fig. 3. Curvature and torsion of blood vessels.

B. Simulation results

Simulation results are shown in Fig. 4. With the repetition of the push-pull motion, the guidewire model approaches the actual guidewire position seen as a black curve (Fig. 4, left to right). The same tendency was seen in the trajectory of the guidewire tip (Figs. 5, 6). In this study, the initial position of the guidewire tip was near the lesion and was determined without considering the route from the thigh. However, the position can be determined accurately. This setting of the initial position is able to reduce simulation time.

In case A, the guidewire model was bent more than in case B. This is because the position of the guidewire tip along the y-axis in case A is smaller than in case B. Therefore, the distal end proceeds even when the proximal end is pulled ("-3 mm" in Fig. 5). In case B, the positions of the guidewire tip were almost same because the tip was pushed against the vessel wall near the bending point. Namely, since the tip of the guidewire model was not bent, it was difficult to pass through the bending point.

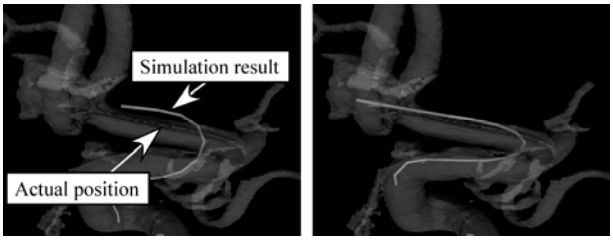

Fig. 4. Simulation results (case A).

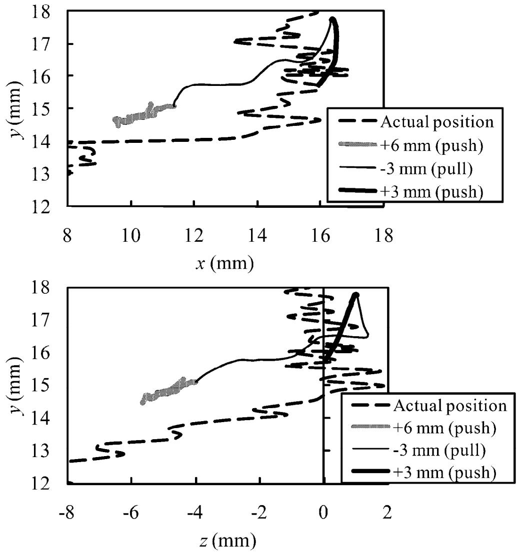

Fig. 5. Trajectory of guidewire tip (case A).

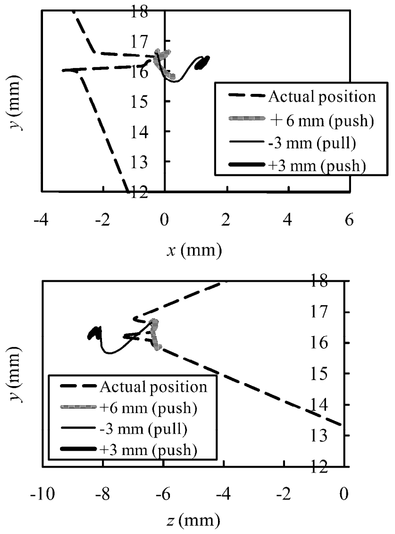

Fig. 6. Trajectory of guidewire tip (case B).

C. Statistical analysis of geographical features of blood vessels

Numerous cerebral aneurysms are treated without subjective symptoms. Therefore, it is necessary to clearly explain the patient-specific disease and the risks of surgery to the patient individually.

In this study, we calculated the geographical features of blood vessels in order to accurately evaluate the simulation results. On the other hand, it is estimated that the occurrence and rupture of the cerebral artery has a relationship with the specific geometry of the blood vessel and blood flow. For example, most saccate aneurysms grow at the bifurcation of the arterial circle of Willis [14]. Thus, blood vessels with aneurysms have some common characteristics. Moreover, the guidewire path appears to be reproducible in vivo [15]. In the future, we would like to construct a database of simulation data and to statistically analyze the relationships between aneurysms and various geometries. Consequently, the difficulties of surgery may be quantitatively evaluated by the geometric parameters of the blood vessels.

IV. CONCLUSIONS

In this study, we used patient-specific data and compared simulation results with medical images in order to validate the simulation system. It was shown that guidewire position could be determined using our simulation system.

ACKNOWLEDGMENT

The authors would like to thank Fukuyama Transporting Shibuya Longevity Health Foundation for supporting this research.

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