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Numerical analysis and experimental observation of guidewire motion in a blood vessel model

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ABSTRACT

We have developed a computer-based system to simulate a guidewire in blood vessels for surgical planning, intra-operative assistance, and to facilitate the design of new guidewires. In this study, we compared simulation results with experimental results for validation of the simulation system. First, we inserted a commercial guidewire into a poly (vinyl alcohol) hydrogel blood vessel model using a two-axis automatic stage and measured the position of the guidewire tip and the contact force between the guidewire and the vessel. The experimental apparatus can be used not only for the validation of numerical analyses, but also as a simulation system. Second, similarly to the experiment, the motion of the guidewire in the blood vessel model was calculated when the proximal part of the guidewire model was pushed and twisted. The model of the guidewire is constructed with viscoelastic springs and segments, and the proximal part of the guidewire model is constrained by the fixed catheter model. Collisions between the guidewire and the vessel are calculated, and the contact forces are determined according to the stiffness of the vessel wall. The same tendency was seen in the trajectories and the contact force of both the experimental and simulated guidewire tips.

1. Introduction

Catheters and guidewires are used in the treatment of infarctions and aneurysms. However, the small diameter and tortuosity of blood vessels makes the procedure very difficult. Moreover, the length and flexibility of catheters and guidewires, as well as their limited number of degrees of freedom, severely reduce the surgeon's visual and tactile perception when manipulating these tools during surgery. Therefore, various catheter simulators using a computer or blood vessel biomodels have been developed in order to make intravascular treatments safer [1–18]. We have also developed a system to simulate a catheter and guidewire in blood vessels [19–22]. Our 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 as a communication tool between patients and the physician. These methods are also expected to be useful for analyzing the structure of guidewires and may help to facilitate the design of new guidewires.

In our previous studies [19,20], we evaluated the effects of the parameters of the guidewire and the blood vessel models on the simulation system. However, as actual cerebral arteries have very complex structures, it is difficult to confirm whether the simulation model accurately represents practical situations. Therefore, in this study, we compared the simulation results with the experimental results for validation of the simulation system and evaluated the parameters of the guidewire model. Note that, not limited to our group, there is a lack of studies comparing the dynamic motion of the guidewire in a blood vessel experimentally and using numerical analysis. One reason is that many catheter simulators are developed for training, and include a haptic interface, with which medical students or physicians operate the virtual guidewire, to provide feedback to the operator yielding a sensation similar to that encountered in actual catheter insertion. Therefore, most of these simulators are mainly evaluated by collaboration with experienced

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interventional radiologists, and the choice of parameters may consequently be subjective and of limited accuracy. Our experimental apparatus can be used not only for the validation of numerical analyses, but also as a simulation system. We conclude this paper by discussing the differences in and combination of the numerical and experimental simulation results.

2. Methods

2.1. Experiment

The experimental apparatus is shown in Fig. 1. We inserted a commercial guidewire (Terumo Corporation, GA1618S) into the vessel model using a two-axis automatic stage (Sigma Koki Co., Ltd., SGSP20-85(X), SGSP-40YAW). The methods for manipulating the guidewires include pushing, pulling, and twisting at the proximal portion from outside the human body. Similarly to these motions, the automatic stage has two degrees of freedom (translation along the *y*-axis and rotation around the *y*-axis). The automatic stage was controlled by software developed in a LabVIEW (National Instruments Co.) environment. The proximal part of the guidewire was fixed on the automatic stage with a torque device and moved along two motion patterns (A and B, Fig. 2). In both the motion patterns, the guidewire was rotated so that the tip matched the curved part of the vessel and the total number of movements was the same. However, the guidewire was translated and rotated at the same time and separately between the first and the second curved portions of the blood vessel model in motions A and B, respectively. The proximal part of the guidewire is constrained by a fixed needle mimicking a catheter to determine the initial position of the wire and to secure it along the *y*-axis. The minimum inner diameter of the needle was 0.51 mm. The distance between the centers of the blood vessel model and the needle was 1 mm. The outer diameter and the bending angle of the guidewire were 0.41 mm and 45°, respectively. The tip of the needle was located at $(x, y, z) = (-1, 0, 0)$.

The blood vessel model is also shown in Fig. 1. We used poly (vinyl alcohol) hydrogel (PVA-H) [15,16] to mimic an arterial wall and a torus-shaped vessel model whose inner diameter was 4 mm. This shape is the same as those used in our previous studies [19,20,22]. The 4 mm inner diameter is representative of the distal part of an internal carotid artery [23,24]. We defined the centerline by connecting a half circle of radius 4 mm (i.e., the curvature is 0.25 1/mm). Many cerebral aneurysms form at the internal carotid artery, which has a highly curved part called the carotid siphon [25]. In this curved part, the guidewire contacts the blood vessel wall, and friction from this contact makes control of the guidewire difficult. The curvature of many parts of the carotid artery is less than 0.5 1/mm [25,26]. The PVA-H model is sufficiently transparent to observe the guidewire. Moreover, PVA-H has lower surface friction compared with a biomodel made of silicone elastomer [17,18], and it was reported that the dynamic viscoelasticity of PVA-H was similar to that of blood vessels [15]. Dimethyl sulfoxide and water were mixed at 80 wt% and 20 wt%, respectively, and used as a solvent. PVA was dissolved in the solvent for a final concentration of 12 wt%. The PVA solution was cast into an acrylic box containing a

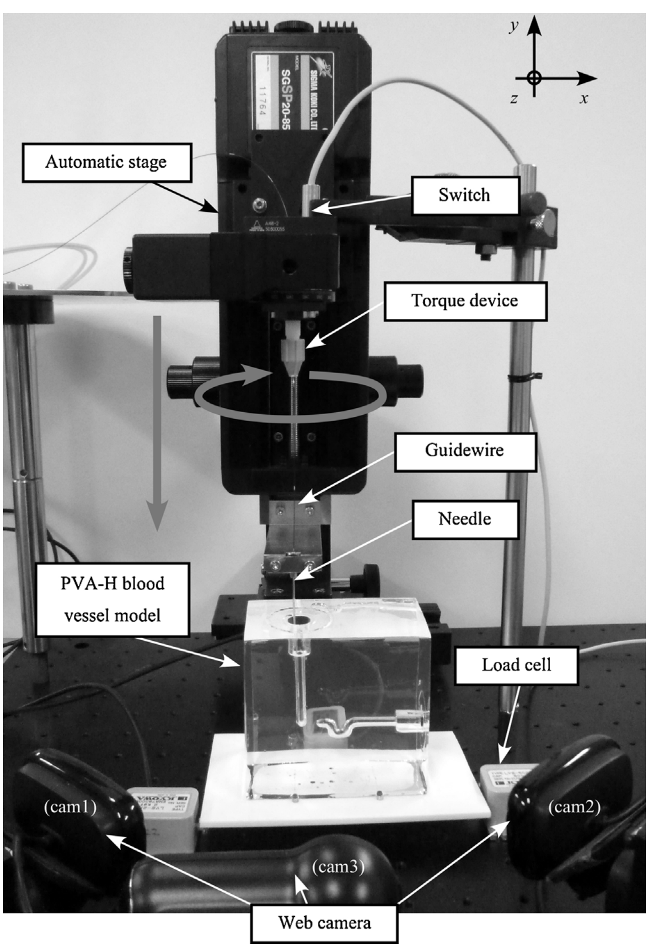

Fig. 1. Photograph of experimental apparatus.

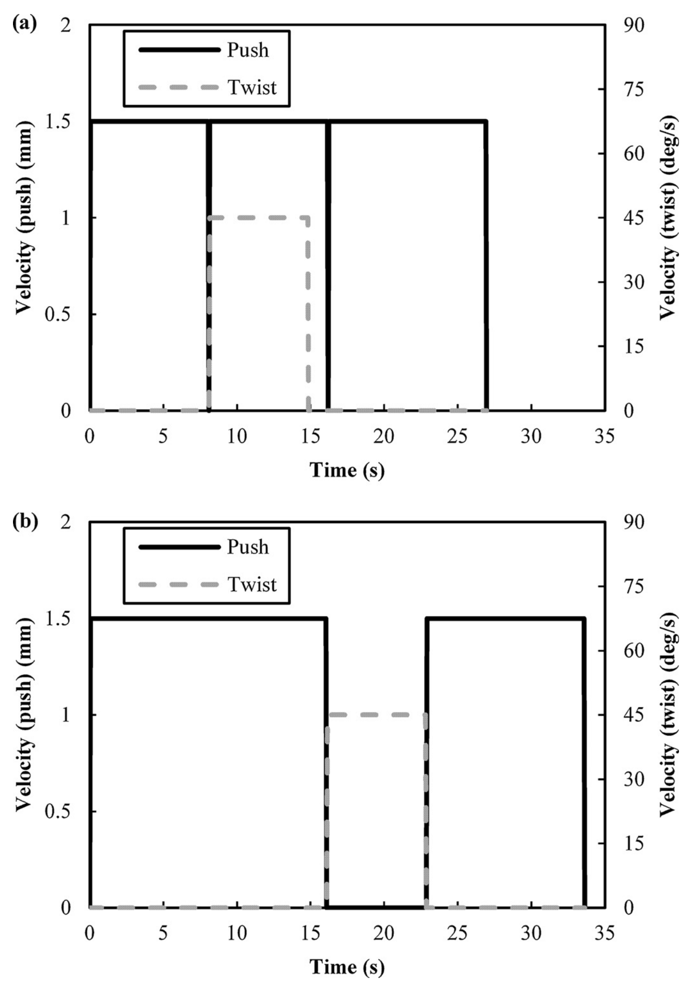

Fig. 2. Motion of proximal part of guidewire (a) Motion A and (b) Motion B. The directions of motion are indicated by the gray arrows in Fig. 1.