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Evaluation of effect of aneurysm model material on coil contact force and catheter movement

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Abstract

To ensure safe coil embolization for cerebral aneurysms, it is important to investigate the contact force between a coil and an aneurysm wall. Therefore, in our previous study, we developed an experimental system for measuring the contact force between a coil and an aneurysm biomodel. However, because the aneurysm model was made of silicone rubber, its physical properties, such as the friction coefficient, differed from those of aneurysms *in vivo*. Therefore, in this study, we made an aneurysm model using poly (vinyl alcohol) hydrogel (PVA-H) and evaluated the effect of the model material on the contact force. In addition, we acquired images during the experiment and evaluated the behavior of the coil and catheter and the relationship between the catheter movement and the contact force. A commercially available coil was inserted through a catheter into two types of aneurysm models (silicone rubber and PVA-H), and the effects of the model material and the catheter tip position (near dome, at the center, and near neck) were evaluated. The contact force and the total movement of the catheter tip for the PVA-H model were smaller than those for the silicone rubber model. The contact force (total catheter movement) was greater (smaller) when the catheter tip was inserted deeper into the silicone rubber model. These results suggest that the state of contact between the aneurysm and the coil affects the contact force and the catheter movement and that these two values are related.

Keywords: Endovascular treatment, Cerebral aneurysm, Coil embolization, Contact force, Catheter, Phantom, First coil

1. Introduction

Endovascular treatments, in which a treatment device such as a catheter is inserted into a blood vessel to directly approach a lesion, have become increasingly popular worldwide. In this study, we focus on coil embolization, which is an endovascular treatment for cerebral aneurysms that involves forming a basket-shaped coil frame in contact with the inner wall of an aneurysm (Ishida et al., 2016; Neki et al., 2016; Sousa et al., 2019). After a frame is formed by the first coil, which must be an appropriate size, several coils are placed in the aneurysm within the coil frame. Therefore, the selection of the first coil is important for the coil embolization of cerebral aneurysms. Moreover, inappropriate manipulation of the device might even lead to intraoperative rupture of the aneurysm (Cloft et al., 2002). However, there are no quantitative criteria regarding the position of the microcatheter tip, rate of coil insertion, or coil type (shape,

secondary diameter, and flexibility). Neurointerventionalists thus set these parameters based on their experience and skill level. For example, in clinical situations, they make decisions about where to place the microcatheter in the aneurysm and which coil to use through a trial and error process. Various methods have been applied to investigate coil and microcatheter behavior using numerical analysis (Chiang et al., 2013; Fujimura et al., 2018; Morales et al., 2013; Otani et al., 2015; Takashima et al., 2017, 2014, 2009, 2007, 2006; Toma et al., 2017). Moreover, experiments using blood vessel biomodels made of silicone rubber (Haraguchi et al., 2013; Ikeda et al., 2005; Matsunaga et al., 2017; Nagano et al., 2010; Takashima et al., 2021), acryl (Lamano et al., 2014) or poly (vinyl alcohol) hydrogel (PVA-H) (Haga et al., 2020; Kosukegawa et al., 2008; Ohta et al., 2004; Takashima et al., 2017, 2014), mimicking living tissue, have been conducted. An experiment without a biomodel, in which a delivery wire was inserted into a microcatheter, has also been conducted (Shintai et al., 2019). On the other hand, although excessive stress on the aneurysm wall appears to be the major cause of intraoperative rupture of the aneurysm, few studies have assessed the state of contact between a coil and an aneurysm (Lamano et al., 2014). A previous study found a difference between the coil insertion force and the contact force of a coil on the aneurysmal dome using an aneurysm model (Lamano et al., 2014).

In our previous study (Takashima et al., 2021), we developed an experimental system for measuring the contact force between a coil and an aneurysm biomodel (Fig. 1) and evaluated the influence of the microcatheter tip position and secondary coil diameter through experiments. When the catheter tip was inserted deeper into an aneurysm (especially near the dome), the contact force increased. The contact force also increased when the secondary coil diameter was increased and the catheter tip was near or at the center of the dome. However, because the aneurysm model in our previous study was made of silicone rubber, its physical properties differed from those of aneurysms *in vivo*. For example, the surface friction coefficient for silicone rubber is much larger than that for an aneurysm. Therefore, in the present study, we made an aneurysm model using PVA-H and evaluated the effect of the model material on the contact force. PVA-H has a lower surface friction coefficient than that for a biomodel made of silicone elastomer (Ohta et al.,

Fig. 1 Photograph and illustration of the experimental apparatus for measuring the contact force between a coil and an aneurysm model. The inside of the aneurysm model was photographed by Cams 1 and 2. The proximal part of the coil was fixed on the automatic stage.

2004) and its dynamic viscoelasticity is similar to that for blood vessels (Kosukegawa et al., 2008). In our previous study, the behavior of the coil and catheter inside the aneurysm model was not visually examined. Therefore, we acquired images during the experiment. We also developed a program to track the movement of the catheter tip and evaluated the relationship between the catheter movement and the contact force. The obtained results concerning the effects of the biomodel material and the catheter tip position are expected to be useful in actual surgical procedures, to allow optimal selection of experimental biomodels, and to lead to improved interventional neuroradiology robotic systems (Beaman et al., 2021; Miyachi et al., 2019; Mendes Pereira et al., 2019).

2. Methods

2.1 Experimental system

We used the experimental apparatus developed in our previous study (Takashima et al., 2021), which is shown in Fig. 1. The base of the coil (Target 360 ULTRA, Stryker, USA, secondary coil diameter: 5 mm) was gripped by an air chuck and inserted into the cerebral aneurysm model through a microcatheter (Excelsior SL-10, Stryker, USA) using an automatic stage (SGSP20-85, Sigma Koki, Japan). The entire catheter was housed in a reel. The coil insertion length was 80 mm (volume embolization ratio: 7%) under all conditions. The contact force between the coil and the cerebral aneurysm model was measured by a force sensor (SFS080F100M0R5U6IO, Leptrino, Japan, resolution: 0.005 N) attached to the model (+y direction in the bottom-right row in Fig. 1, sampling frequency: 10 Hz). We applied a 10-Hz low-pass filter in software to the data from the force sensor. Two USB cameras (Cams 1 and 2, L-835, Hozan Tool, Japan, screen resolution: 1280 × 960, 30 fps) with C-mount lenses (SM 2516-MP3, Shodensha, Japan) were positioned at two sides of the aneurysm model to acquire images during the experiment. Cams 1 and 2 were set along the z- and x-axes, respectively.

Figure 2 (a) shows a schematic diagram of the cerebral aneurysm model used in this study. The model shape is the

Fig. 2 Aneurysm model. (a) Schematic diagram, and photographs of (b) silicone rubber model, (c) PVA-H model, and (d) results for edge detection along green line. The aneurysm model was placed on the force sensor as shown in Fig. 1. The effects of catheter tip position (bottom, middle and top) and model material (silicone rubber and PVA-H) were evaluated.

same as that used in our previous study. It consists of an aneurysm-like sphere (inner diameter: 5 mm) and a blood-vessel-like cylinder (inner diameter: 4 mm). We used a model made of silicone rubber and a model made of PVA-H. Figures 2 (b) and 2 (c) show the appearance of these models, respectively. For the preparation of the silicone rubber model, two-solution-mixed silicone rubber (KE-106, Shinetsu Kagaku Kogyo, Japan) was poured into a mold fabricated using a three-dimensional printer, allowed to harden, and removed from the mold. For the preparation of the PVA-H model, similar to our previous studies (Takashima et al., 2017, 2014), a 12 wt% PVA solution was poured into an acrylic box containing a mold and then frozen to promote PVA crystallization. After gelatinization, the mold material was removed using the lost-wax technique. The cylinder and sphere centers were located on the y -axis, and the aneurysmal center was located at $y=2.5$ mm (see Fig. 2 (a)).

During this experiment, the interior of the aneurysm model was filled with distilled water. The rate of coil insertion was 1.0 mm/s, as in previous studies (Nagano et al., 2010; Takashima et al., 2021). The initial position of the microcatheter tip placed on the central axis of the blood vessel was set to 1.0, 2.5, or 4.0 mm. These values correspond to positions around the aneurysmal neck (bottom), at the aneurysmal center (middle), and around the aneurysmal dome (top), respectively. The insertion experiment was repeated five times under the same conditions.

2.2 Method for tracking catheter tip position

In our previous study, the behavior of the coil and catheter inside the aneurysm model was not visually examined. In an actual procedure, it is necessary to control the catheter tip position appropriately (Haraguchi et al., 2013; Nagano et al., 2010). Therefore, in this study, we developed a program for tracking the catheter tip position based on images acquired by the two cameras. The program was developed in the LabVIEW environment (National Instruments, USA). The method of tracking the catheter tip is as follows. The edges in the acquired images were detected using the difference in brightness between the catheter and the background along the red line in Fig. 2 (a). Figure 2 (d) shows the results of edge detection. The average of the coordinates of the two edges obtained using edge detection was used as the catheter tip position. The total movement during coil insertion was then calculated as the sum of the movements (absolute values) at 0.033-s intervals. Cams 1 and 2 were used to calculate the catheter tip positions along the x - and z -axes, respectively.

3. Results

Figure 3 shows the dependence of the contact force on the insertion length for different catheter tip positions in the case of the silicone rubber and PVA-H models. The contact force fluctuated drastically for the silicone rubber model at the top and middle positions. In contrast, it was relatively stable for the PVA-H model. Note that because the resolution of the force sensor used in this study was 0.005 N, the transition of the force below 0.005 N would be not accurate.

Fig. 3 Example of dependence of contact force along the y -axis on the insertion length for the silicone rubber and PVA-H models. (a) Top, and (b) middle and bottom positions.

Figures 4 and 5 respectively show the average contact force and the total movement for the silicone rubber and PVA-H models. Figures 6 and 7 show the appearance of the coil and catheter after coil insertion into the silicone rubber and PVA-H models under each condition. For the PVA-H model, at the top position, it was difficult to calculate the catheter

tip position because both the catheter and coil deviated from the aneurysm (Fig. 7 (c)). As shown in Fig. 4, there was a large difference in the average contact force when the catheter tip was near the aneurysm dome (top position). This is the same tendency that was reported in previous studies (Lamano et al., 2014; Takashima et al., 2021). As shown in Fig. 5, the total movement of the catheter in the PVA-H model was smaller than that in the silicone rubber model. The total movement of the catheter followed the opposite order (top < middle < bottom), as shown in Fig. 5. In particular, there was little difference in the total movement of the catheter at the bottom and middle positions. At the top position, the total movement was small.

Figures 8 and 9 show the dependence of the catheter tip position on the insertion length for the silicone rubber and PVA-H models, respectively. The total amount of movement in Fig. 5 was calculated as the sum of the positional changes

Fig. 4 Average $\pm$ standard deviation (SD) for contact force between coil and aneurysm model (silicone rubber and PVA-H) along the y-axis. The average and SD are calculated from 5 measurements for each condition.

Fig. 5 Average $\pm$ SD for total movement of catheter tip in silicone rubber and PVA-H models. The average and SD are calculated from 5 measurements for each condition.

Fig. 6 Appearance of coil and catheter after 60 mm of insertion into silicone rubber model. (a) Bottom, (b) middle, and (c) top positions.

Fig. 7 Appearance of coil and catheter after 80 mm of coil insertion into PVA-H model. (a) Bottom, (b) middle, and (c) top positions.

in the xz -plane at 0.033-s intervals. The initial movement of the catheter tip in the PVA-H model (bottom position, blue dashed ellipse in Fig. 9 (a)) was smaller than that in the silicone rubber model. Moreover, the initial movement of the catheter tip at the middle position (red dashed ellipse in Fig. 9 (b)) is larger than that at the bottom position (Fig. 9 (a)) in the PVA-H model. On the other hand, as shown in Figs. 8 (b) and 9 (b), the number of catheter tip vibrations for the PVA-H model was smaller than that for the silicone rubber model.

Figure 10 shows the trajectory of the catheter tip when placed at the bottom and top of the silicone rubber aneurysm model. The bold lines show the inner wall of the blood vessel model if the model was manufactured to the specifications shown in Fig. 2 (a). As shown in Figs. 8 (a) and 10 (a), the catheter continued to move circumferentially during coil insertion when at the bottom position. In contrast, the catheter tip stayed in the same position (green dashed ellipses in Fig. 8 (c)) and moved slowly when at the top position.

Figure 11 shows the relationship between the average contact force and the total catheter movement. For the silicone rubber model, there was a significant correlation ($r = -0.73$, $p < 0.01$) between the average contact force and the total catheter movement, although there were large variations in the results for the top position (brown dashed ellipses). In contrast, no significant correlation was found for the PVA-H model.

Fig. 8 Example of dependence of catheter tip position on insertion length for silicone rubber model. (a) Bottom (b) middle and (c) top positions.

Fig. 9 Example of dependence of catheter tip position on insertion length for PVA-H model. (a) Bottom and (b) middle positions.

Fig. 10 Examples of trajectory of catheter tip in silicone rubber model. (a) Bottom and (b) top positions.

Fig. 11 Relationship between average contact force and total movement of catheter tip.

4. Discussion

4.1 Effect of aneurysm model material and catheter tip position

The friction coefficient for the silicone rubber model is larger than that for the PVA-H model. Ohta et al. (2004) reported that the coefficient of friction for the PVA-H and silicone rubber models were 0.2 and more than 0.4, respectively (dry condition, counter-face: hard chrome). When the coil tip was restricted by static friction, the coil gradually deformed as it was inserted, and the contact force gradually increased. The resulting repulsive force pushed against the aneurysm wall. At the top and middle positions, the transition from static to kinetic friction caused a drastic change in the contact force in the high-friction silicone rubber model, as shown in Fig. 3.

For the silicone rubber model, coil movement was restricted on the aneurysm wall by the high friction, and the contact force continued to increase. As described in our previous study (Takashima et al., 2021), assuming a cantilever structure, since the contact force is inversely proportional to l^2 (l : the distance between the catheter tip and aneurysmal wall (model dome)), there were marked differences between the bottom/middle and top areas. In contrast, for the PVA-H model, for which friction is small, the coil was not restricted on the aneurysm wall and slip occurred. Consequently, as shown in Fig. 7 (c), the coil deviated significantly from the PVA-H aneurysm model when the catheter tip was near the aneurysm dome (top position). As a result, the average contact force was small, as shown in Fig. 4. In other words, these results suggest that the friction at the aneurysm wall is important for determining the appropriate coil placement.

The difference in the friction coefficient between the two model materials also affects catheter movement. A head-swinging phenomenon called paint-brushing action (Nagano et al., 2010; Stidd et al., 2014) was generated at the tip of the catheter by the reaction force caused by the static friction between the coil and the aneurysm wall. Therefore, the number of catheter tip vibrations for the silicone rubber model was larger than that for the PVA-H model due to the difference in the friction coefficient between the two model materials (Figs. 8 and 9). On the other hand, the initial movement of the catheter tip in the low-friction PVA-H model was small (Fig. 9 (a)). Moreover, because the contact force increased as the catheter tip was inserted deeper into the aneurysm (Fig. 4), the reaction force applied to the catheter tip increased. Therefore, due to the increased reaction force, the initial movement of the catheter tip at the middle position (red dashed ellipse in Fig. 9 (b)) is larger than that at the bottom position (blue dashed ellipse in Fig. 9 (a)) in the PVA-H model.

At the top position in the silicone rubber model, as shown in Figs. 6 (c), 8 (c) and 10 (b), the inserted coil pressed the catheter tip against the aneurysm wall and tip movement was restricted. The total movement of the catheter at the top position was thus small. The catheter moved to a position where the coil could be easily deformed by the paint-brushing action. Therefore, when the catheter was restricted and could not move, the inserted coil did not easily deform and the contact force increased. For example, when the catheter tip was restricted (green dashed ellipses in Fig. 8 (c)), the contact force increased (green dashed ellipses in Fig. 3 (a)). Moreover, when the catheter tip was inserted deeper into the aneurysm (especially near the dome), there was insufficient space for deployment of the coil. Therefore, when the coil had a distorted shape (Figs. 6 (b) and 6 (c)), the contact force increased.

As described above, the state of friction between the coil and the aneurysm wall affects the behavior of the coil and catheter during coil insertion. When the biomodel is used in the experiment, the difference in the friction coefficient between the two model materials is considered to be large.

On the other hand, when the catheter tip can move easily at the bottom, the contact force became low and the coil was properly packed. From the viewpoint of the risk of rupture (high contact force) and the shape of the coil placed in the aneurysm, the microcatheter tip should be placed around the aneurysmal neck. These results can be applied to actual surgical procedures. Furthermore, optimizing the insertion conditions will pave the way for improvement of interventional neuroradiology robotic systems, which are being rapidly developed (Beaman et al., 2021; Miyachi et al., 2019; Mendes Pereira et al., 2019). It may also be possible to estimate the contact force based on catheter movement during an actual procedure.

4.2 Future issues

In this study, the coil was gripped by an air chuck and the coil insertion speed was constant. However, in an actual procedure, the coil insertion speed is not constant. It was reported that the insertion force in a silicone aneurysm for insertion at a constant moderate speed by a motor is lower than that for manual intermittent insertion by a physician; in the former situation, the coil moves outside the aneurysm because static friction occurs when insertion is paused (Haraguchi et al., 2013; Nagano et al., 2010). Similarly, the friction force for the PVA-H model in this study may be smaller than that during an actual procedure, and coil deviation may have occurred. Moreover, a physician moves the catheter tip to a site that is not densely packed with coils to insert the coils with a small insertion force (Nagano et al., 2010). Therefore, we will evaluate the effects of intermittent coil and catheter movement in future studies.

Neurointerventionalists do not continuously grip the coil; they release it according to the situation. In addition, as shown in Fig. 1, the movement of the catheter along the y-axis was restricted. The forced insertion of the restricted coil through the restricted catheter would cause the contact force to increase. We would thus like to evaluate the effect of the coil and catheter restrictions in the future.

In this study, we used a wide-necked aneurysm model and coil deviation may have occurred. The possibility of catheter tip deviation during coil insertion may be reduced by inserting the catheter tip deeper into the aneurysm; however, the increase in the contact force on the aneurysmal wall must be considered. Therefore, an evaluation using aneurysm models of various shapes is necessary. To prepare new aneurysm models, the incorporation of microsensors such as ultrasound displacement sensors and fiber-optic pressure sensors (Haga et al., 2020) should be considered, because the force measured in this study was the sum of the contact force distribution between the coil and the aneurysm model. Furthermore, because the force measured in this study was very small and similar to the resolution of the force sensor, it is necessary to use a high-resolution sensor.

5. Conclusion

In this study, we evaluated how the contact force and catheter movement change depending on the aneurysm model material and the catheter insertion position when a coil is inserted into a cerebral aneurysm biomodel. The contact force and the total movement of the catheter tip for the PVA-H aneurysm model were smaller than those for the silicone rubber model. The contact force was greater when the catheter tip was placed deeper into the aneurysm made of silicone rubber (bottom < middle < top). The total movement of the catheter followed the opposite order (top < middle < bottom). Based on these results, it is considered that the state of contact between the aneurysm wall and the coil affects the contact force and the movement of the catheter, and that these two values are related. When the biomodel was used in an experiment, the difference in the friction coefficient between the two model materials was large. On the other hand, when the catheter tip could move easily at the bottom, the contact force became low and the coil was properly packed. These results could be applied to actual surgical procedures and for improving interventional neuroradiology robotic systems.

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