



Evaluation of Contact Force between Aneurysm Model and Coil for Embolization of Intracranial Aneurysms

Kazuto Takashima,¹ Yuta Ikeda,¹ Kiyoshi Yoshinaka,² Makoto Ohta,³ Koji Mori,⁴ and Naoki Toma⁵

Objective: To ensure safe coil embolization for intracranial aneurysms, it is important to investigate the contact force between the coil and the aneurysm wall. However, it is unclear how the catheter tip position and the diameter of the secondary loop of the coil influence the contact force. In this study, we measured the contact force between a coil and an aneurysm biomodel under different conditions.

Methods: A commercially available coil was inserted through a microcatheter into a silicone rubber aneurysm model at a constant speed (1 mm/s) using an automatic stage, and the contact force between the coil and the aneurysm wall was measured by a force sensor attached on the aneurysm model. The inner diameter of the spherical aneurysm was 5 mm. The effects of varying the position of the catheter tip (near dome, center, near neck) and the diameter of the secondary coil (4.5 mm) were evaluated.

Results: When the catheter tip was inserted more deeply into the aneurysm (especially near the dome), the contact force increased. The contact force also increased as the secondary coil diameter was increased with the catheter tip near and in the center of the dome.

Conclusion: These results suggest that the catheter tip position and the secondary coil diameter affect the contact force. In particular, the contact force should be considered large with the catheter tip near the dome to ensure safe coil deployment.

Keywords ► cerebral aneurysm, coil embolization, contact force, phantom, first coil

Introduction

For coil embolization of cerebral aneurysms, a serious complication, aneurysmal perforation, may develop if a

¹Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology, Kitakyushu, Fukuoka, Japan

²Health and Medical Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki, Japan

³Institute of Fluid Science, Tohoku University, Sendai, Miyagi, Japan

⁴Graduate School of Sciences and Technology for Innovation, Yamaguchi University, Ube, Yamaguchi, Japan

⁵Graduate School of Medicine, Mie University, Tsu, Mie, Japan

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Corresponding author: Kazuto Takashima. Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology, 2-4, Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka, 808-0196, Japan

Email: ktakashima@life.kyutech.ac.jp



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satisfactory procedure is not performed. A basket-shaped coil frame in contact with the inner wall of an aneurysm is formed by selecting the first coil in an appropriate size, in which the secondary coil diameter is as large as possible.^{1–3)} Subsequently, several coils are placed in the aneurysm within the coil frame; therefore, the selection of the first coil is important for coil embolization of cerebral aneurysms. However, no quantitatively effective criteria regarding the position of the microcatheter tip, rate of coil insertion, and coil type (shape, secondary diameter, and flexibility), which neurointerventionalists can determine, have been established; currently, these factors depend on neurointerventionalists' experience and skills. On the other hand, the behaviors of coils, microcatheters and guidewires have been evaluated using various methods such as numerical analysis and experiments with a blood vessel biomodel.^{4–19)} However, few studies have assessed the contact state between a coil and aneurysm.¹¹⁾

In this study, a coil was inserted into an aneurysm biomodel consisting of silicone rubber through a catheter using an experimental system that we developed, and the contact force on coil-frame formation was measured using

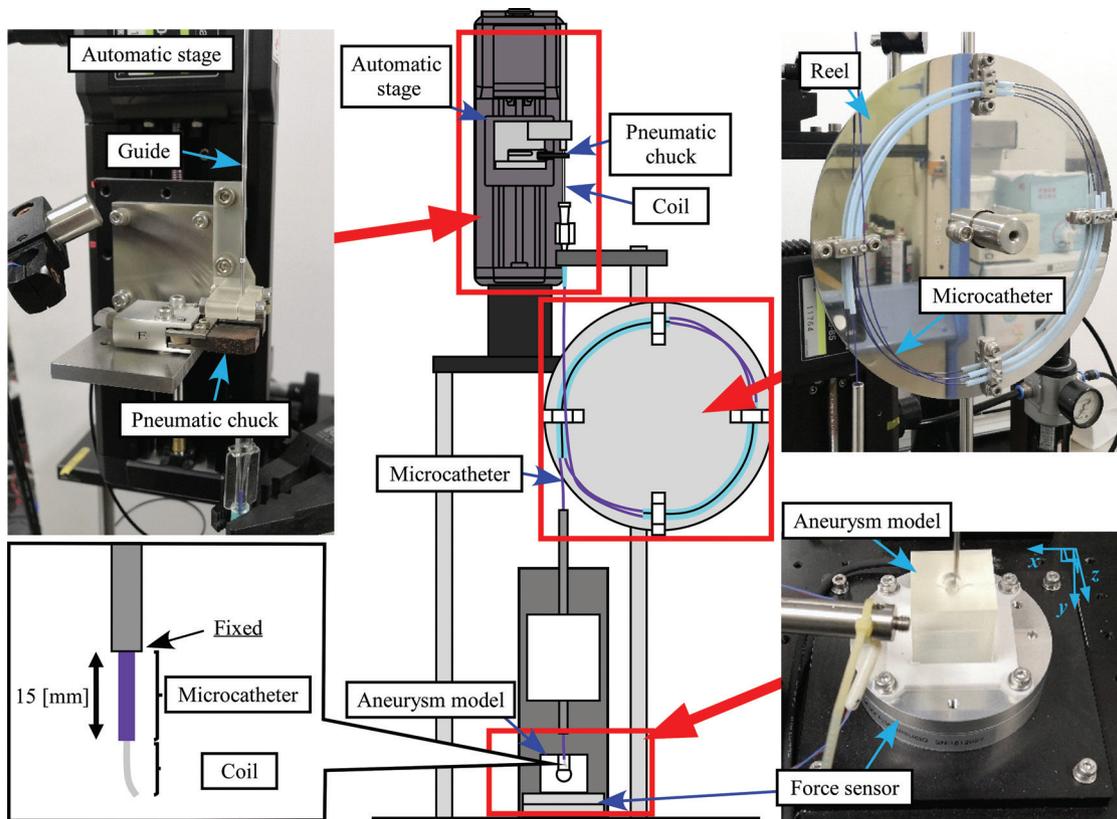


Fig. 1 Photograph and illustration of the experimental apparatus. The contact force between the coil and the aneurysm model can be measured using the apparatus. The proximal part of the coil was fixed on the automatic stage.

a force sensor attached to the model. Using the contact force as a criterion, we investigated the influence of the microcatheter tip position and secondary coil diameter.

Materials and Methods

Experimental system

The experimental system is shown in **Fig. 1**. The base of a coil was grasped with an air chuck (ACHK4-D; Misumi, Tokyo, Japan), and a coil was inserted into the aneurysm model through a microcatheter using an automatic stage (SGSP20-85; Sigma Koki, Saitama, Japan). The experimental system was prepared by altering a system that was developed to insert a catheter and guidewire in a previous study.¹²⁾ Briefly, a coil-grasping mechanism by a parallel air chuck (left upper row of **Fig. 1**) was added on a linear automatic stage for guidewire insertion. A combination of parallel air-chuck opening/closing and automatic stage motions facilitated filling exceeding the maximum travel length of the automatic stage. Air-chuck opening/closing with two electromagnetic valves and automatic stage motions were controlled using LabVIEW (National Instruments, Austin, TX, USA) through a personal computer. To

prevent coil deflection and slipping, a guide was set on the upper part of the parallel air chuck.

In conventional experimental systems for guidewire insertion,¹²⁾ only a portion (17 cm) of the catheter tip was cut and used. However, the coil end is flexible and it was impossible to insert a coil using the catheter tip alone. Therefore, we added a reel to house an entire catheter (right upper row of **Fig. 1**) and housed the flexible part of a coil in the catheter to facilitate smooth insertion.

The aneurysm model was placed on a force sensor (8SFS080F500M0R5U6IO; Leptrino, Nagano, Japan) to measure the contact force between the model and coil (+y direction in the right lower row of **Fig. 1**, sampling frequency: 10 Hz). Furthermore, we used a 10-Hz low-pass filter on software for recording data from the force sensor.

The aneurysm model used in this study is shown in **Fig. 2**. Its shape consisted of an aneurysm-like sphere (inner diameter: 5 mm) and blood-vessel-like cylinder (inner diameter: 4 mm). For preparation, two-solution-mixed silicone rubber (KE-106; Shinetsu Kagaku Kogyo, Tokyo, Japan) was poured into a mold prepared using a 3D printer (3510HD Plus; 3D Systems, Rock Hill, SC, USA), hardened, and removed from the mold. The cylinder and sphere centers

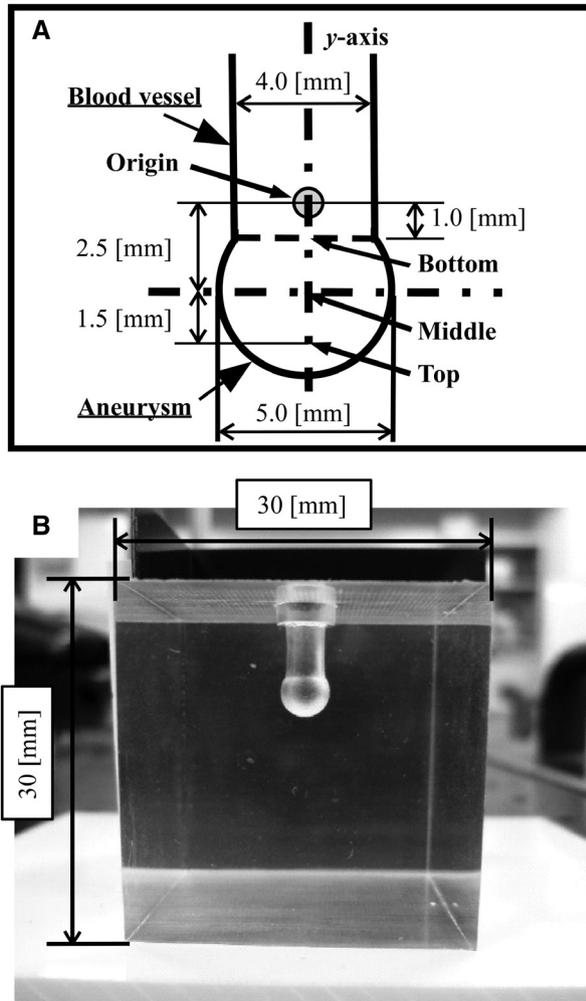


Fig. 2 Schematic diagram (A) and photograph (B) of aneurysm model made of silicone rubber. The aneurysm model was placed on the force sensor as shown in Fig. 1. The effects of varying the position of the catheter tip (Bottom, Middle, and Top) and the diameter of the secondary coil (4 or 5 mm) were evaluated.

were located on the y -axis, and the aneurysmal center was located on $y = 2.5$ mm, regarding the coordinate shown in Fig. 2 as an origin. During this experiment, the inner area of the aneurysm model was filled with distilled water.

Conditions for insertion into the aneurysm model

An insertion experiment was conducted by changing the initial position of a catheter and secondary coil diameter to evaluate the influence on the contact force. The initial position (y_c) of the microcatheter tip placed on the central axis of a blood vessel was set as 1.0, 2.5, and 4.0 mm. These corresponded to “around the aneurysmal neck,” “aneurysmal center,” and “around the aneurysmal dome,” and we defined these positions as “bottom,” “middle,” and “top,” respectively. The secondary coil diameters (D) were 4 mm,

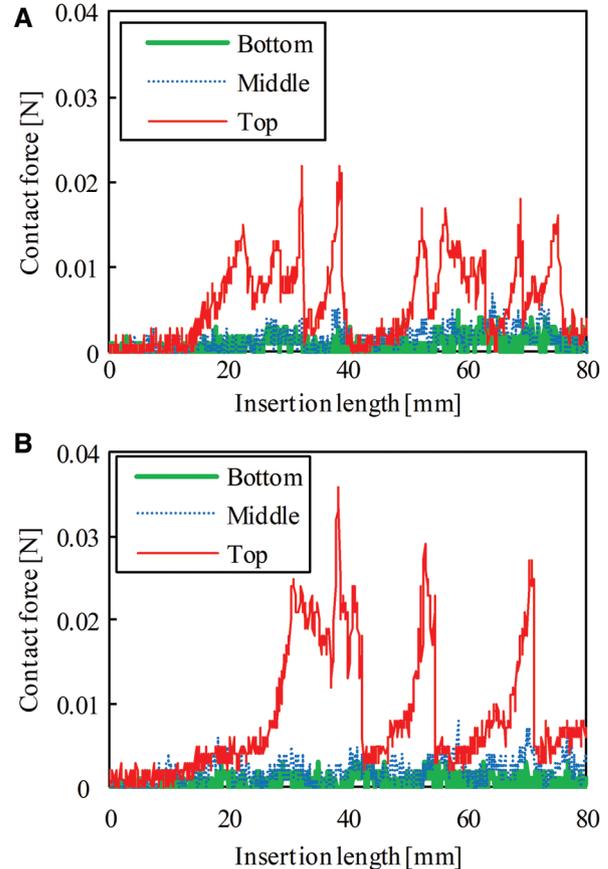


Fig. 3 An example of the relationship between coil insertion length and contact force along the y -axis. (A) $D = 4$ mm. (B) $D = 5$ mm. When the catheter tip was inserted more deeply into the aneurysm (Top), the contact force increased.

slightly smaller than the diameter of the aneurysm model, and 5 mm, the same diameter. As a coil, a complex coil to be deployed three-dimensionally, Target 360 Ultra (Stryker, Kalamazoo, MI, USA), was used. An Excelsior SL-10 catheter (Stryker) was used. The rate of coil insertion was 1.0 mm/s, as in previous studies,^{7,9,15} because there was no marked influence even when it was changed in a preliminary experiment. Furthermore, the coil insertion length was 80 mm (volume embolization ratio: corresponding to 7%) under all conditions. An insertion experiment was repeated five times under the same conditions. After the mean contact force per experiment was calculated, variance analysis was conducted. When there was a significant difference, multiple comparison was performed using the Tukey–Kramer method. In addition, to confirm the influence of the coil insertion length, data were extracted at 20-mm insertion intervals and a multiple comparison test was conducted by calculating the mean of the data per condition. For both variance analysis and multiple comparison, we used MATLAB (MathWorks, Natick, MA, USA).

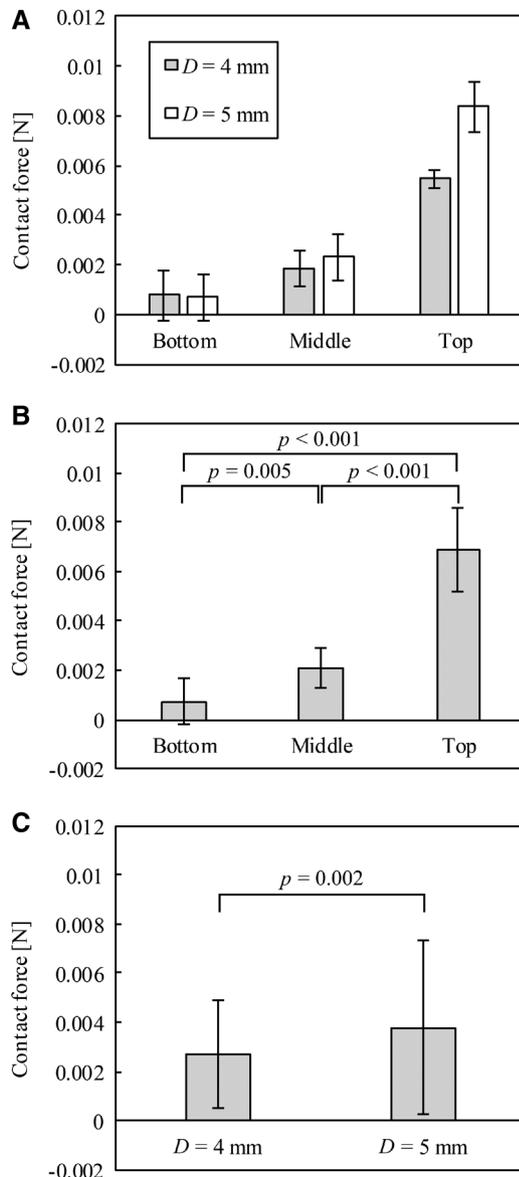


Fig. 4 Average contact force between coil and aneurysm model along the y -axis. **(A)** Each condition. **(B)** Catheter tip position exhibited a significant effect in the order of Top > Middle > Bottom. **(C)** Secondary coil diameter exhibited a significant effect of $D = 5 \text{ mm} > D = 4 \text{ mm}$.

Results

The relationship between the length of coil insertion and contact force under each condition, bottom ($\gamma_c = 1.0 \text{ mm}$), middle ($\gamma_c = 2.5 \text{ mm}$), and top ($\gamma_c = 4.0 \text{ mm}$), in a representative case (y -axis direction, vertically downward) is shown in **Fig. 3**. At the bottom, the contact force was small and there was no increase. At the middle area, the contact force was slightly greater than at the bottom, but it was approximately 0.002 N . On the other hand, at the top, the contact force increased/decreased periodically and repeatedly, as shown in **Fig. 3**.

The mean contact forces between the coil and model (y -axis direction, vertically downward) per condition, catheter tip position, and secondary coil diameter are shown in **Fig. 4A–4C**, respectively. The means \pm standard deviations per 5, 10, and 15 sessions are presented in **Fig. 4A–4C**, respectively. Furthermore, variance analysis demonstrated significant differences. The results of the subsequent multiple comparison test are shown in **Fig. 4B** and **4C**. As presented in these figures, there were significant differences regardless of combinations. In addition, the means \pm standard deviations per condition (secondary coil diameter: 4 and 5 mm, respectively), catheter tip position, and secondary coil diameter, which were calculated by extracting data at 20-mm insertion intervals, are shown in **Fig. 5A–5D**, respectively. Furthermore, the results of the multiple comparison test are shown in **Fig. 5C** and **5D**. At certain insertion lengths, there were no significant differences between the bottom and middle areas or between the two secondary coil diameters.

The influence of the catheter tip position and secondary coil diameter is presented below.

Influence of the catheter tip position

The mean contact force increased with the catheter tip position (Bottom < Middle < Top). In particular, there were marked differences between the bottom/middle and top areas; there were significant differences regardless of the insertion length.

Influence of the secondary coil diameter

The mean contact force per catheter tip position was compared. At the middle and top areas, the mean contact force at a secondary coil diameter of 5 mm was greater than that at a secondary coil diameter of 4 mm. At the bottom, there was no difference.

Discussion

Influence of the catheter tip position

In this study, the contact force was greater when the catheter tip was placed in the deeper area of the aneurysm. This tendency is consistent with that reported by Lamano et al.¹¹⁾ In particular, the contact force was markedly greater when the catheter tip was placed around the aneurysmal dome (top). The following two proposed reasons for this are as followed:

First, the distance between the catheter and dome of the aneurysm model was short (approximately 1 mm), and a

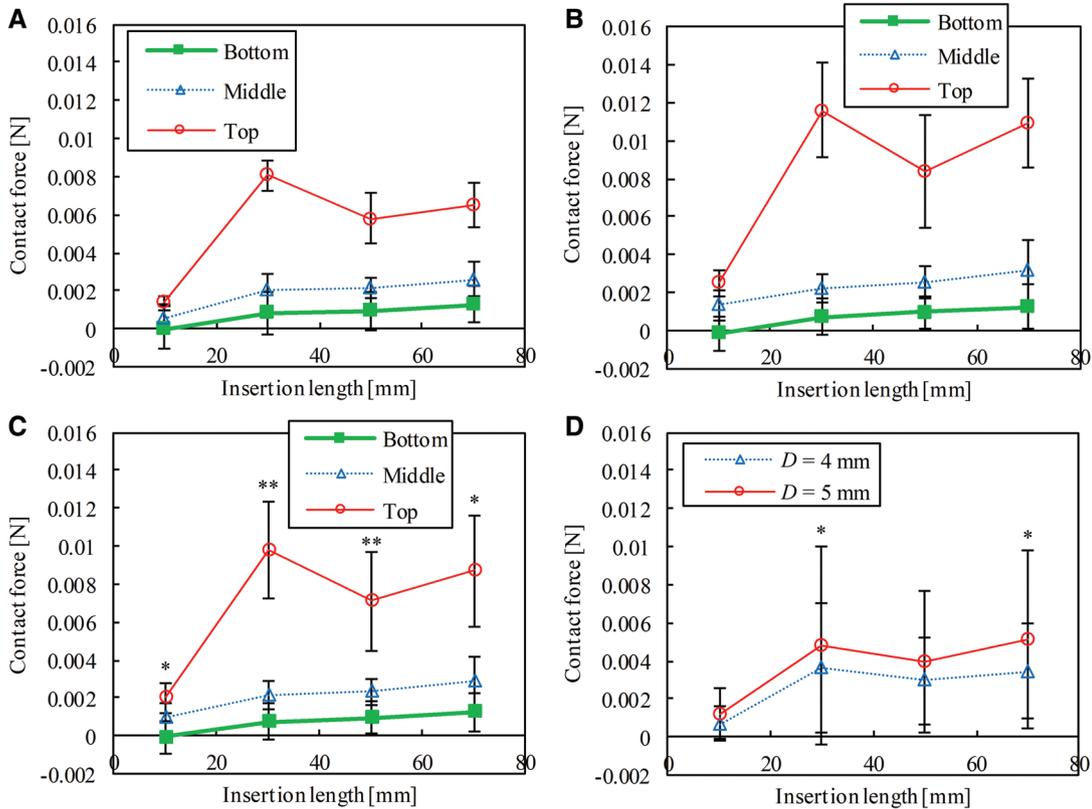


Fig. 5 Transition of the average contact force between coil and aneurysm model along the y-axis. **(A)** $D = 4$ mm. **(B)** $D = 5$ mm. **(C)** The catheter tip position exhibited a significant effect (* $Top > Middle > Bottom$; ** $Top > Middle, Bottom$). **(D)** The secondary coil diameter exhibited a significant effect (* $D = 5$ mm $>$ $D = 4$ mm).

coil appearing from the catheter tip vertically contacted the aneurysmal wall; therefore, it may have been contacted/restricted by the dome through the frictional force (**Fig. 6A**). When the catheter tip was placed at the aneurysmal neck or center, a coil appearing from the catheter tip obliquely contacted the aneurysm model through spherical deployment; it was slippery and the contact force was small. On the other hand, around the aneurysmal dome, the coil was not slippery, as described above; a force may have acted through the restricted coil until slipping, increasing the contact force. As shown in **Fig. 3**, the contact force irregularly and markedly increased/decreased. The coil and catheter tip may have been repeatedly released/restricted every time coil insertion exceeded a specific length of insertion through an increase in the contact force for similar reasons. However, in this study, the aneurysm model was prepared using silicone rubber, and its physical properties, such as the friction coefficient, differ from those of aneurysms *in vivo* (the surface friction coefficient of aneurysms *in vivo* is lower). If the model is similar to an aneurysm *in vivo*, a coil may not be restricted by the dome and the contact force may not increase.

Second, a short distance between the catheter tip and aneurysmal wall may have increased the moment. As shown in **Fig. 6B**, when the contact force W is added at the coil end through contact with the aneurysmal wall, regarding the catheter tip as a fixed end, the moment $W\delta$ is added at the end. Assuming a cantilever, the deflection of the tip (δ) when the moment M is added at its end is expressed using the following Equation (1).²⁰⁾

$$\delta = \frac{Ml^2}{2EI} \tag{1}$$

In this equation, l represents the distance between the catheter tip and aneurysmal wall (model dome). E and I represent Young's modulus of the coil and the moment of inertia of area, respectively.

When inserting $M = W\delta$ into the above Equation (1), the following equation is obtained.

$$W = \frac{2EI}{l^2} \tag{2}$$

When the y_c values are 1.0, 2.5, and 4.0 mm, respectively, as adopted in this study, the l values are 4.0, 2.5, and 1.0 mm, respectively. Using Equation (2), the W ratio is

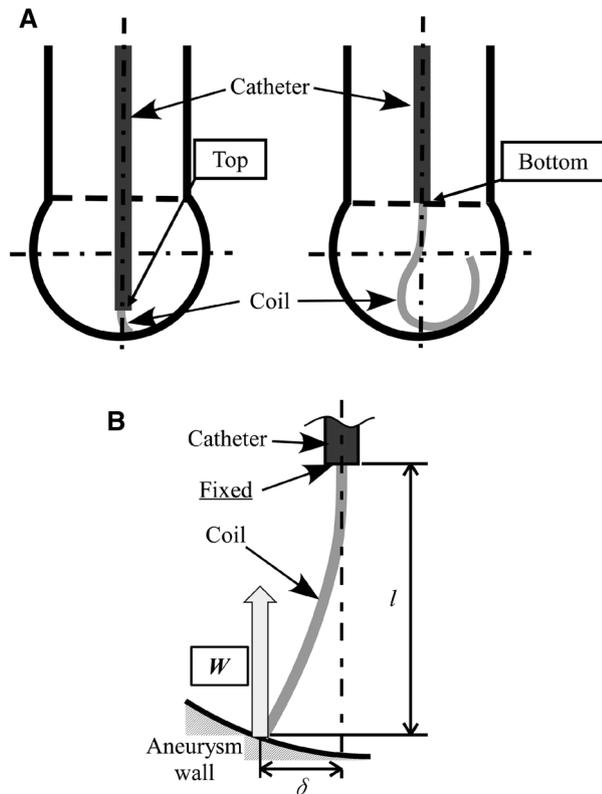


Fig. 6 Behavior of the catheter and coil. (A) Effects of catheter tip position on the contact angle between coil and aneurysm wall. (B) Coil tip displacement (δ) by contact force (W).

1:3:16. As demonstrated by this experiment, the contact force W increases with a decrease in the l value (when the distance between the catheter tip and model dome is shorter). As the contact force W is inversely proportional to l^2 , there are marked differences between the bottom/middle and top areas. However, the shape of the catheter changes and it cannot be regarded as a fixed end; this may have led to the differences being less marked than the above ratio.

This study revealed that the initial position of the intra-aneurysmal catheter tip influenced the contact force of the aneurysmal wall. The possibility of catheter-tip displacement out of the aneurysm on coil insertion may be reduced by inserting the catheter tip to the deep area of an aneurysm, but it must be considered that the contact force of the aneurysmal wall increases.

Influence of the secondary coil diameter

Matsubara et al. measured the coil insertion force using an optical sensor, and reported that the secondary coil diameter did not influence the maximum insertion force.⁷⁾ In this study, there were also little differences at several insertion lengths and at the bottom.

Merits of this method

The contact force measured in this study was smaller than the actual values (≥ 0.1 N) of the coil insertion force in previous studies,^{7,9,15)} and the pattern also differed. This was possibly because the contact force of the coil on the aneurysmal wall surface was directly measured in this study, whereas the coil insertion force at the neurointerventionalist's hand was measured in the previous studies. Briefly, Lamano et al.¹¹⁾ noted a difference between the coil insertion force and contact force of a coil on the aneurysmal dome using an aneurysm model; the difference may be similar to the above difference. As the influence of coil-catheter friction may have been present in the previous studies, the contact force on the aneurysmal wall surface, that is, the risk of aneurysmal injury, may have been more directly evaluated in this study.

Future issues

In this study, coil insertion behaviors were not examined visually, but direct visual observation may be necessary in the future. In this study, we used a wide-necked aneurysm model and coil displacement out of the aneurysm may have occurred. In addition, in certain catheter positions, the catheter tip may be pushed out of the aneurysm (kick-back phenomenon). On the other hand, many nonlinear phenomena may occur when inserting a coil. Matsubara et al.^{9,15)} reported that nonlinear friction between the coil and aneurysmal wall influenced the coil insertion force. In particular, a coil exhibits buckling distortion, but not simple bending deformation; it may be influenced by aneurysmal wall friction. In addition, when inserting a device for endovascular treatment, catheter deformity, that is, deflection, markedly influences insertion behaviors.¹²⁾ Shintai et al.¹⁰⁾ conducted an experiment in which a delivery wire was inserted into a microcatheter, and found that the difference between the insertion force at the hand and end-transmitted force was influenced by microcatheter flexion. In the future, coil/catheter-tip behaviors should be monitored using a camera and investigated in detail in addition to the contact force.

Furthermore, second or subsequent coil behaviors must be analyzed in the future. The insertion rate pattern may influence the coil insertion force.^{7,9,11,15)} Moreover, the contact force was greater when the secondary coil diameter was larger. On the other hand, several studies reported that the coil frame was more stable when the secondary coil diameter was larger, with a lower recurrence rate.¹⁻³⁾ For coil embolization, it is necessary to insert a coil without adding stress to the aneurysmal wall. In addition, the formation of a favorable coil frame is also necessary.¹⁻³⁾ The stabilization of framing may

be related to the coil-aneurysm contact area. On the other hand, stress on the aneurysmal wall surface, which is the ratio of contact force over contact area, increases when the contact area decreases under the same contact force. Therefore, the contact area must also be evaluated in the future.

Conclusion

In this study, we evaluated the contact force in an aneurysm model during insertion by changing the catheter tip position and secondary coil diameter. The following results were obtained:

- The contact force was greater when the catheter tip was placed in the deeper area of the aneurysm.
- When the catheter tip was placed at the center of the aneurysm or around its dome, the contact force at a secondary coil diameter slightly smaller than the diameter of the aneurysm model was smaller than that at the same secondary coil diameter as the aneurysm diameter.

In particular, the possibility of catheter-tip displacement out of the aneurysm on coil insertion may be reduced by inserting the catheter tip to the deep area of an aneurysm, but it must be considered that the force added to the aneurysmal wall increases.

Disclosure Statement

The authors declare no conflict of interest.

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