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Author(s) 著者	奥田, 洋輝
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RESEARCH ARTICLE

Stiff coils enhance shape retention and pressure resistance in an aneurysm model even at low volume

Hiroki Okuda, Naoki Hirokawa, Masato Saitoh, Akemi Otani, Masanori Someya, Yoko Usami and Koh-Ichi Sakata

Department of Radiology, Sapporo Medical University School of Medicine, Sapporo, Japan

ABSTRACT

Purpose: To elucidate the characteristics of 3 D frame coils and identify the optimal coil for visceral aneurysms.

Material and methods: Using a vascular model, we compared the postembolization coil distribution and repulsive force of three coils: Guglielmi detachable coil (GDC; stock wire diameter, 0.004 in; primary diameter, 0.015 in), Target XL (0.003, 0.014), and Target XXL (0.003, 0.017). Additionally, the coil area, roundness, and center of gravity were quantitatively compared. The coil repulsive force was measured by compressing the postembolization vessel model with a digital force gauge.

Results: There were no significant differences in the coil area and roundness among the three coil types. Compared with the Target coils, the GDC deployed evenly along the vessel wall, its center of gravity was less displaced, and although it had the lowest embolic density, its repulsive force was greater regardless of the number of coils used.

Conclusions: GDC coils with a larger stock wire diameter and a smaller primary diameter unfolded evenly along the wall and had a greater repulsive force. Coil stiffness contributes to coil stability and shape retention, indicating the possibility of preventing recurrence by selecting a frame coil with a focus on coil stiffness.

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KEYWORDS
Visceral aneurysm; coil embolization; stock wire diameter; primary diameter; coil stiffness

Introduction

Coil embolization is widely indicated for true visceral aneurysms, and coil packing is often used to maintain blood flow to peripheral organs. In the case of cerebral aneurysms, high coil packing density is considered important to prevent recurrences. Intraprocedural aneurysm rupture (IAR) is often reported in these aneurysms [1,2], and small aneurysm size has been cited as one of the risk factors [3–5]. Although IAR can occur at any of the three steps, one study suggested that the incidence of IAR is highest during framing and a stiff coil is one of the causes [4]. Some operators use relatively soft framing coils to avoid IAR and compensate for blood flow resistance by increasing the volume embolization ratio (VER) [6]. The indication for treatment of true visceral aneurysms is a diameter of $\geq$ 20 mm [7–9], which is larger than that of cerebral aneurysms. Therefore, the risk of IAR during coiling is low, and in fact, our search of the literature did not reveal any reports of the rupture. Inevitably, the number of coils used is large, increasing the medical costs.

Despite these differences, we wondered whether the coil embolization method for visceral aneurysms should be the same as that for cerebral aneurysms, which is to increase the filling rate. We hypothesized that if the framing coil, which is directly pressured by the blood flow from the parent artery, is stable, recurrence can be prevented even with a small amount of filling coils, and we focused on the force exerted by the coil vertically to the aneurysm wall. There are few basic studies on coil characteristics and aneurysm wall loading. The coil stiffness is considered to have a large influence on the repulsive force and is mainly determined by the primary and stock wire diameters.

Therefore, the goal of this study was to identify the optimal framing coil by considering the coil characteristics due to the difference in stiffness using silicon models.

Material and methods

Coils

Three types of coils from the same manufacturer (Stryker, Fremont, CA, USA) were used in the

CONTACT Hiroki Okuda hiroki.okuda@sapmed.ac.jp Department of Radiology, Sapporo Medical University School of Medicine, Sapporo, Japan

Table 1. Stock wire diameter and primary diameter of the various coils, and details of the coils used in the experiments under fluoroscopy.

	Stock wire Diameter (inch)	Primary diameter (inch)	Secondary diameter (mm)	Coil length (cm)	Coilvolume (mm^3)
GDC® 18–360° Coils	0.004	0.015	24	40	46
			20	33	38
			18	40	46
Target® XL 360 Standard Coils	0.003	0.014	24	50	50
			20	50	50
			18	50	50
Target® XXL 360 Coils	0.003	0.017	24	50	73
			20	50	73
			18	50	73

experiments: Guglielmi detachable coil (GDC® 18 − 360° coils), Target XL (Target® XL 360 standard coils), and Target XXL (Target® XXL 360 coils). These coils have a three-dimensional structure (open-loop type) with the same wire material, pitch.

The stock and primary wire diameters are unique to each coil type, with the GDC having the largest stock wire diameter and the Target XL having the largest primary diameter (Table 1). The secondary diameter and coil length were used differently for each experiment.

Qualitative and quantitative tests of coil distribution under fluoroscopy

First, to investigate the characteristics of the three coil types, we observed the shape and distribution of the coils deployed in an aneurysm-shaped silicon model (FAIN-Biomedical, Okayama, Japan; saccular, diameter 20 mm, neck length 20 mm). For framing, we used coils with a 24-, 20-, and 18-mm secondary diameter, one of each type. The volume of the GDC is the lowest for the same secondary diameter (Table 1).

For qualitative analysis, the shape and distribution of the deployed coils was observed by naked eye from the side and top views (Figure 1(A)). For quantitative analysis, we deployed the coils under fluoroscopy and analyzed their distribution on the fluoroscopic images using ImageJ software (National Institutes of Health, Bethesda, MD, USA), also from the side and top views (Figure 1(B)).

To compare the three coil types, we measured the embolic coil area, roundness, the distance between the center of the aneurysm model and the centroid of the coil mass (center-centroid distance), and the gravity component of the center-centroid distance (center-centroid distance—gravity direction). ImageJ can calculate area and pixel value statistics (luminance values) for the selected area. We automatically calculated the roundness and the area of the inside from the coil perimeter (yellow), and the centroid and distance from the pixel values (Figure 1(C)). The area indicates the spread of the coil during deployment. Roundness ranges from 0 to 1, with 1 indicating circularity; the closer to the maximum value, the closer to a perfect circle. The formula is $4 \times \text{area}/[\pi \times (\text{square of the major axis})]$. The smaller the value of the center-centroid distance, the more uniform the distribution. The center-centroid distance—gravity direction indicates a bias toward the direction of gravity when observed from the side.

Compression test

Next, we measured the vertical force exerted by the various coils on the wall of aneurysm-shaped and cylindrical silicon models by stepwise compression using a digital force gauge (Imada, Aichi, Japan) (Figure 2(A,B)). Since the aneurysm itself is not deformed during embolization in actual clinical practice, measurements were taken at a compression of less than 0.5 mm for the cylindrical type and at 0.5 mm for the aneurysm type (low compression). In addition to the coil volume, coil stiffness is considered to have a significant effect on the repulsive force. The main indices include the stock and primary wire diameters. In order to verify the difference in the repulsive force by comparing the coil stiffness, the same secondary diameters and materials were selected and the conditions were matched as much as possible.

In the cylindrical model, embolization was performed as tightly as possible to eliminate embolization coil variability and maintain uniformity within the model (Figure 2(A)). The ratio of the coil volume to the cylinder volume in the embolization area was measured (cylinder VER). A cylindrical model with an inner diameter of 5 mm was embolized with GDC (coil length, 40 cm), Target XL (50 cm), and Target XXL (50 cm), each with a secondary diameter of 16 mm. The embolized models were compressed at

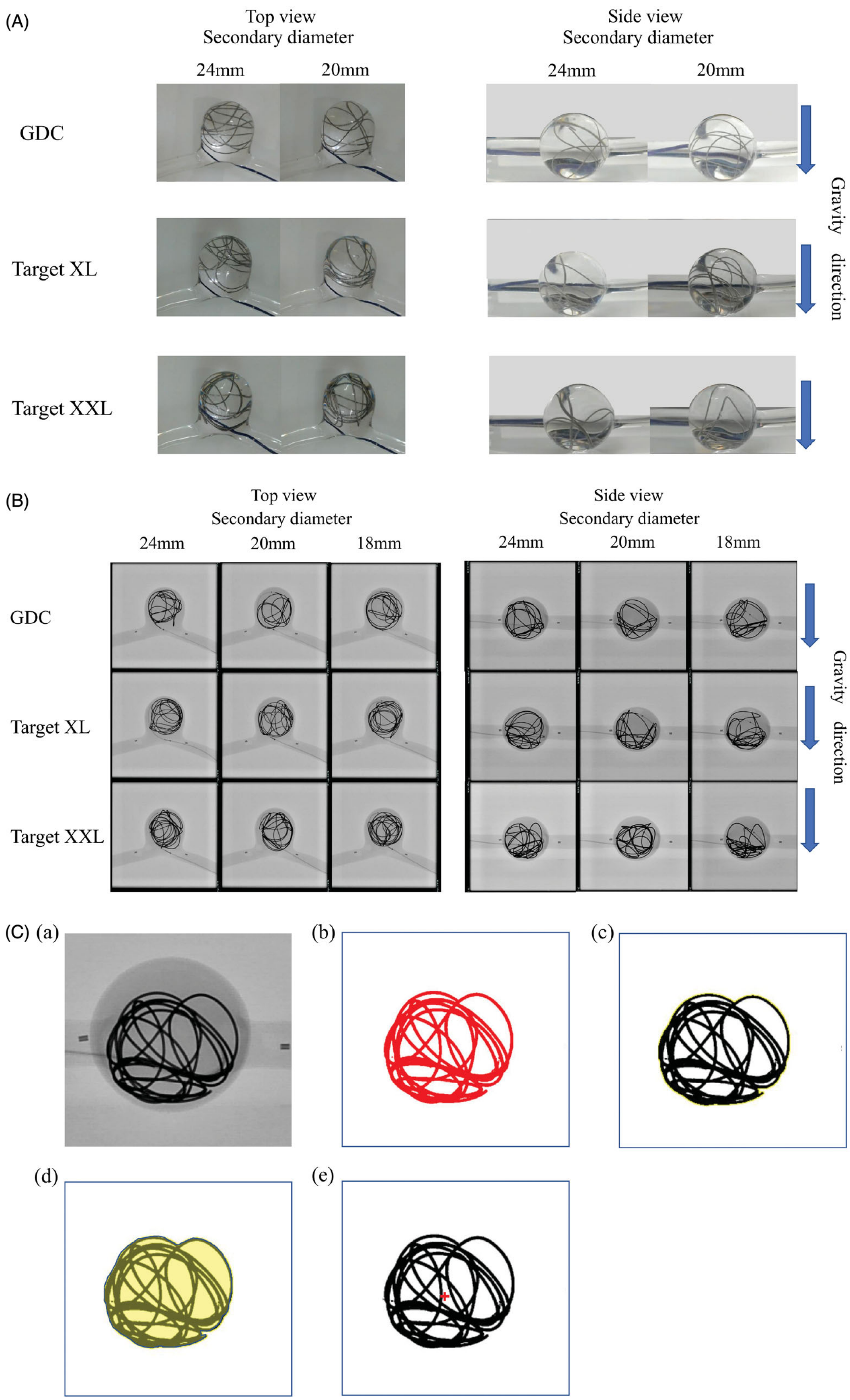

Figure 1. (A) Representative images after coil embolization. For framing, the aneurysm silicon model was embolized using GDC, Target XL, and Target XXL coils with secondary diameters of 20 and 24 mm, and their behavior was observed from two directions (top and side view). (B) Representative images after coil embolization (under fluoroscopy). Three types of coils with secondary diameters of 18, 20, and 24 mm were used for embolization and evaluated from two directions (top and side view). (C) Coils were deployed in an aneurysm silicon model under fluoroscopy and analyzed with ImageJ software (a). Only the coil was recognized by binarization (b), and the roundness (c), area (d), and centroid (e) of the coil mass were automatically calculated. The cross indicates the centroid. (D) Coil mass removed from the model after the aneurysm model compression test

Figure 1. (Continued)

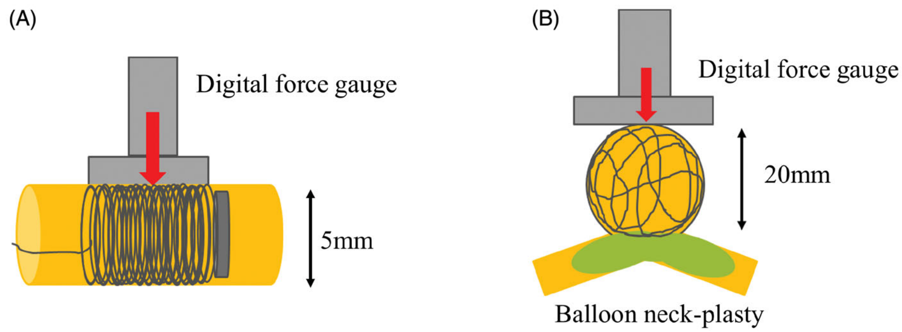

Figure 2. Measurement of the repulsive force of a coil on the vessel wall using a digital force gauge. (A) Cylindrical model: measurement on the coil that was compressed as much as possible. (B) Aneurysm model: measurement of the repulsive force for each number of coils up to seven.

0.1-mm intervals to compare the repulsive force of the coils (Figure 2(A)).

In the aneurysm-shaped model, the same model as in the fluoroscopic quantitative test, coils with a secondary diameter of 24 mm were embolized first, with smaller coils piled up in sequence (Table 2). Between one and seven embolization coils were used. The repulsive force was measured at a compression of 0.5 mm for every embolization and compared among the three coil types (Figure 2(B)). For both the cylindrical and aneurysm models, the pre-embolization force of the silicon material was subtracted from the measured values so that only the repulsive force of the coils remained. These physical studies were performed by interventional radiologists with more than five years of experience.

In the fluoroscopic quantitative test, each group was measured five times, and in the compression test, each model was measured three times, and the average values were used.

Coil volume and coil volume percentage in the silicon model (VER) were calculated as follows: Coil volume = (primary diameter)^2 × length × π/4; VER (%) = (total coil volume/aneurysm volume) ×100.

Statistical analysis

One-way ANOVA was used for comparison of the measurements of the three coil types in the fluoroscopic and compression tests, and Tukey-Kramer's test was used for post-hoc analysis. All data were analyzed using R, version 3.6.3 (R Foundation, Vienna, Austria) and tested for significance at $p < .05$.

Results

Qualitative and quantitative tests of coil distribution under fluoroscopy

In the qualitative analysis, from the top view, all coils were circular and generally aligned with the aneurysm wall. From the side view, Target XL and XXL were biased in the gravity direction, while the GDC deployed along the aneurysm wall (Figure 1(A)).

In the quantitative analysis, from the top view, there was no significant difference in the area or roundness among the coils. The GDC center-centroid distance was significantly smaller than those of Target XL and XXL (Figure 3(A)). From the side view, the center-centroid distance—gravity direction of the GDC was significantly smaller than those of the other coils. There was no significant difference in the area, roundness, or center-centroid distance among the coils, but the GDC had the highest roundness value (Target XL-GDC, $p = .0548$) and the smallest center-centroid distance. Furthermore, there was less data

Table 2. Specifications of coils used in the embolization order in the aneurysm model.

	GDC				Target XL				Target XXL			
Number of embolized coils	Secondary diameter (mm)	Coil length (cm)	Accumulative VER (%)	Accumulative Volume (mm^3)	Secondary diameter (mm)	Coil length (cm)	Accumulative VER (%)	Accumulative Volume (mm^3)	Secondary diameter (mm)	Coil length (cm)	Accumulative VER (%)	Accumulative Volume (mm^3)
1	24	40	1.1	46	24	50	1.2	50	24	50	1.7	73
2	24	40	2.2	92	24	50	2.4	100	24	50	3.5	146
3	22	40	3.3	138	22	50	3.6	149	22	50	5.2	220
4	22	40	4.4	184	22	50	4.8	199	22	50	7.0	293
5	20	33	5.3	222	20	50	6.0	249	20	50	8.7	366
6	20	33	6.2	260	20	50	7.1	298	20	50	10.5	439
7	18	40	7.3	306	18	50	8.3	348	18	50	12.2	512

variation for the GDC than for the other coils (Figure 3(B)).

Next, the center-centroid distance and the center-centroid distance—gravity direction were evaluated for each coil secondary diameter on the side view images (Figure 3(C)). In the secondary diameter groups of 18 and 24 mm, the center-centroid distance of the GDC was the smallest, particularly in the gravity direction, with a significant difference. At 20 mm, the center-centroid distance—gravity direction of the GDC and Target XXL were significantly smaller than that of Target XL, and the center-centroid distance of Target XL was significantly greater than that of Target XXL.

Compression test

In the cylindrical model compression test, the cylinder VERs of the GDC, Target XL, and Target XXL coils were 14%, 25%, and 23%, respectively, with the GDC having the lowest embolic density. When compressed stepwise with a digital force gauge, there was a positive correlation between compression displacement and repulsive force for all coils. Regardless of the displacement, the repulsive force was greatest for the GDC, followed by the Target XL and XXL coils (Figure 4(A)). The GDC was significantly more resilient than Target XXL at compressions of 0.1, 0.3, and 0.4 mm ($p = .0429$, .0351, and .0177, respectively).

In the aneurysm model compression test, when embolized with a single coil, the repulsive force of the Target coils was negative, which was due to the very small force of the coil itself and was included in the measurement error. When embolization was performed using two to seven coils, the repulsive force of the GDC with the smallest VER for any number of emboli was greater than that of the Target coils (Table 2, Figure 4(B)). There was a significant difference among the three coil types in the case of one- and five-coil embolization, and only between the GDC and Target XL in the case of six-coil embolization. Furthermore, when the coil mass was removed from the aneurysm model after the compression test, there was a strong tendency for the GDC to retain its shape (Figure 1(D)).

Discussion

In this study, there was no significant difference in coil area and roundness after embolization among the three types of coils, but the GDC had less center-of-gravity shift and deployed more uniformly along the

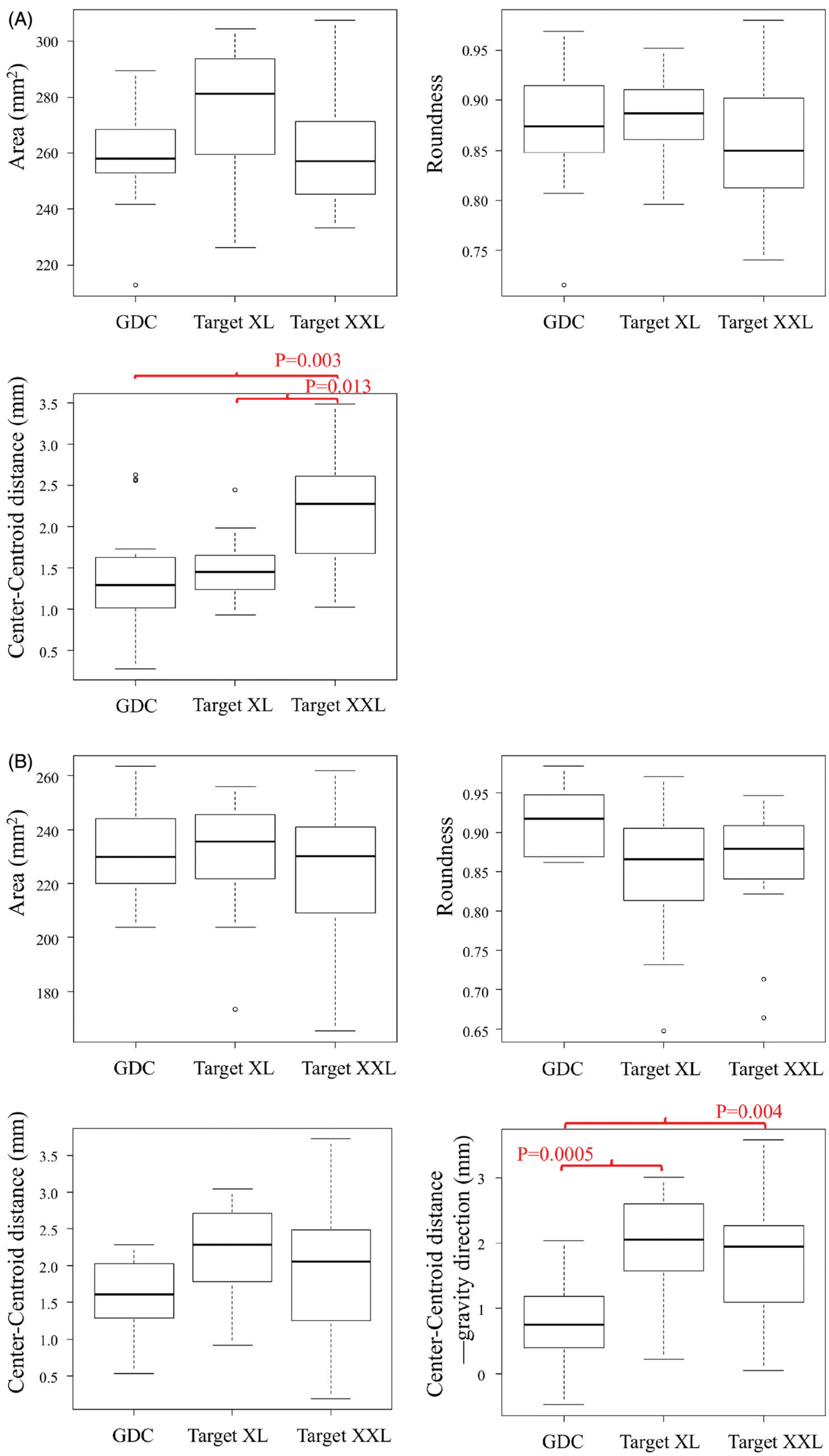

Figure 3. (A) Comparison of the coil distribution in the aneurysm model based on fluoroscopic image analysis (top view). (B) Comparison of the coil distribution in the aneurysm model based on fluoroscopic image analysis (side view). (C) Comparison of the center-centroid distance and the center-centroid distance—gravity direction of the three types of coils in fluoroscopic images for each coil secondary diameter. *Center-Centroid distance: The distance between the center of the aneurysm model and the centroid of the coil mass. **Center-Centroid distance—gravity direction: Value obtained by extracting only the gravity component from Center-Centroid distance.

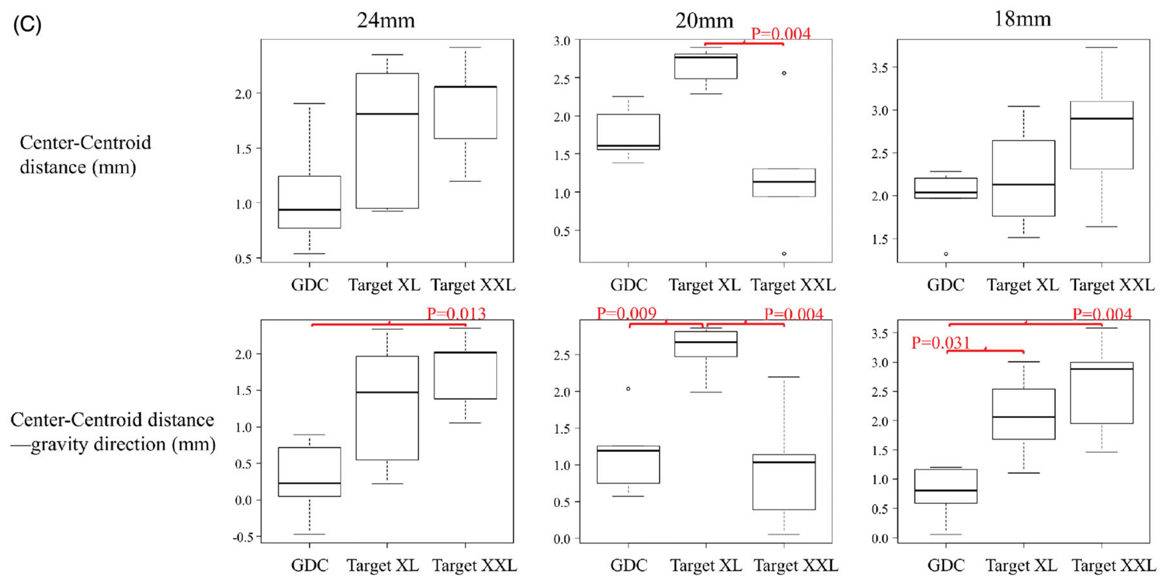

Figure 3. (Continued).

vessel wall than the Target coils. In addition, even though the VER of the GDC was smaller than that of the other coils, the repulsive force of the GDC was the greatest, indicating that it had excellent shape retention and blood pressure resistance.

We first analyzed the distribution of various coils deployed in the aneurysm silicon model. Contrary to the GDC, Target XL and XXL did not align with the aneurysm wall and tended to be biased in the gravity direction. Ito et al. also reported an analysis of coil distribution under fluoroscopy, but it was performed only from one direction [10]. In our study, the coil distribution was evaluated three-dimensionally, including the gravity direction, and the quantitative analysis results clearly showed that the centroid of Target XL and XXL was biased toward the gravity direction.

Contrarily, although the GDC was shorter than the other coils, there was no significant difference in its coil area and roundness among the observation directions. The displacement of its center of gravity was smaller than that of the other coils, and it was found to expand evenly along the vessel wall. *In vivo*, the coil blood pressure resistance is important, and it is reasonable that coils that align with the aneurysm wall, such as GDC coils, be used for framing. Therefore, the blood pressure resistance of each coil was verified by measuring the actual force exerted on the wall. The vertical force exerted by the coil against the vessel wall is an indicator of its fit performance, shape retention, and blood pressure resistance at the aneurysm neck. The force comprises various factors, such as coil volume, stiffness, and embolization uniformity. Among these, coil stiffness is considered to play a major role. As shown by White et al. [11] and Rui et al. [12], when the coil is regarded as a spring, the coil stiffness, or spring constant K, can be expressed by the following formula:

$$K = \frac{D_1^4 G}{8 D_2^3 n};\ \text{stiffness}\ \propto \frac{D_1^4}{D_2^3}$$

Coil stiffness is determined by the stock wire diameter (D1), primary diameter (D2), material (G, modulus of elasticity), and coil pitch (n). The purpose of this study is to compare and verify the difference in force exerted by coils on the aneurysm wall due to differences in stock wire diameter and primary diameter. Therefore, we chose three types of coils from a single manufacturer that have the same material, coil pitch, and three-dimensional structure, and whose stock wire diameter and primary diameter are easily comparable. In the cylindrical model with uniform coil embolization, the cylinder VER of the GDC was the lowest at 14%. However, the repulsive force was the greatest for the GDC (stock wire diameter, 0.004; primary diameter, 0.015), followed by Target XL (0.003, 0.014) and Target XXL (0.003, 0.017). The fact that Target XL and XXL have the same stock wire diameter and that Target XXL with a smaller primary diameter had a smaller repulsive force is consistent with the stiffness formula, whereas the fact that the GDC had the greatest repulsive force demonstrates that a larger stock wire diameter has a greater effect than a smaller primary diameter.

This is also consistent with the results of the formula above, where the cubic of the primary diameter

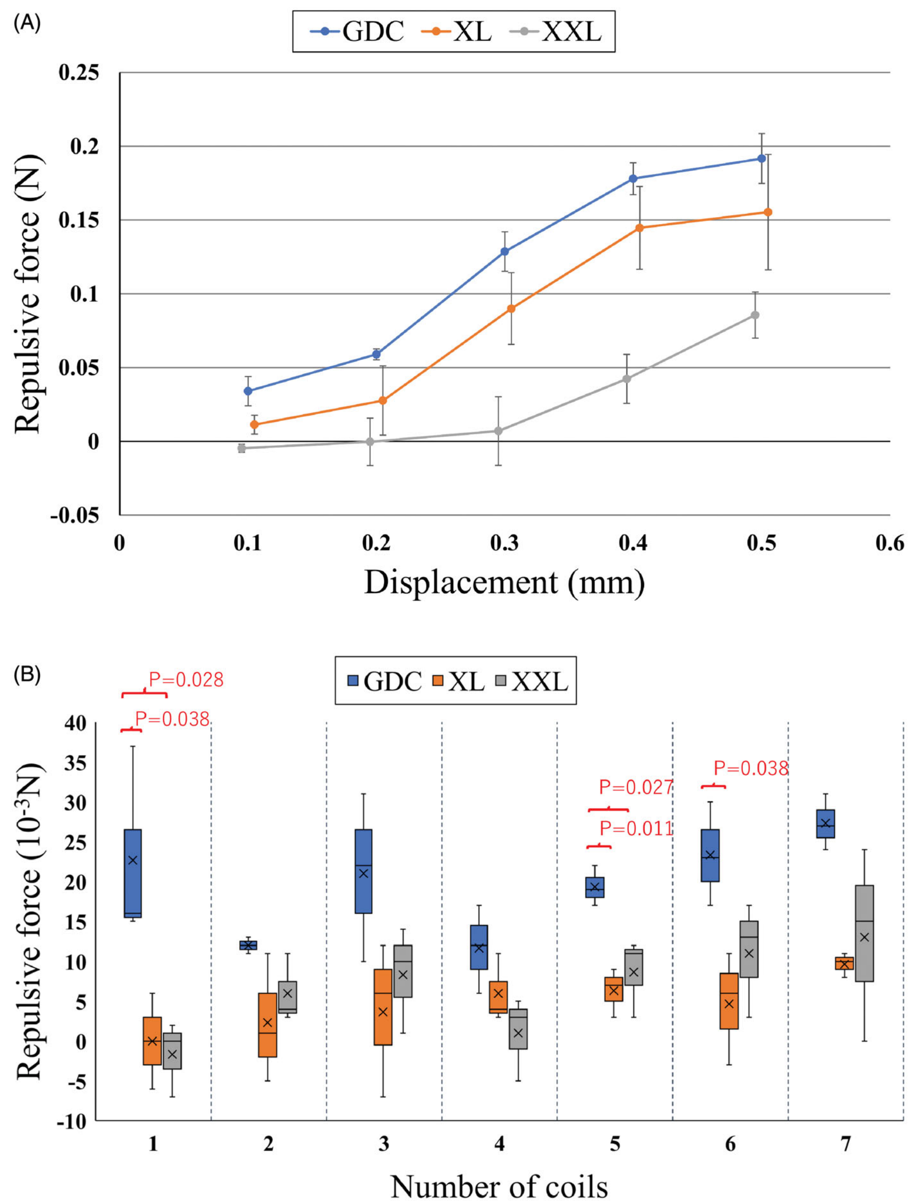

Figure 4. (A) Comparison of the repulsive force by coil type in the cylindrical model. (B) Comparison of repulsive force by coil type in the aneurysm model (0.5 mm compression).

is the denominator and the fourth power of the stock wire diameter is the numerator. Even in the aneurysm model where embolization coils were non-uniformly placed, the repulsive force of the GDC was always greater than that of Target XL and XXL, regardless of the number of coils. As shown in Table 2, the cumulative VER of the GDC is smaller than that of the other coils for any number of embolization coils, and it can be inferred that the repulsive force results would be similar even if the number of coils stacked is more than seven. Our results indicate that the repulsive force is defined more by the coil stiffness than by the VER, which is consistent with the report by Fujimura et al. that stiffer coils are more likely to enter the outside of the aneurysm dome and help prevent recurrence [13]. Hence, when considering the blood pressure resistance of coils, it would be more appropriate to consider the coil stiffness rather than the VER. Additionally, it can be inferred that Target XL and XXL are biased toward the gravity direction due to their low stiffness and low shape retention. For such coils with a small stock wire diameter, it is necessary to use a high coil fill factor.

Several retrospective studies have demonstrated an inverse correlation between aneurysm recurrence and VER in the intracranial region [14,15], and VERs of $>$ 20% to 25% have been reported to prevent compaction [16,17]. Moreover, achieving the same level of

VER in large-volume visceral aneurysms has been reported to prevent recurrence [18]. However, the larger the volume, the more coils are required for embolization, which not only increases medical costs, but also makes it difficult to achieve a high VER [19,20]. Therefore, to prevent recurrence even with a small number of coils, the characteristics of the first framing coil to be filled are more important. In this study, we showed that the VER does not directly increase the blood pressure resistance, but the coil stiffness, which is defined by the stock and primary wire diameters, may affect the resistance.

Nonetheless, when the VER is low, an embolization effect that assures blockade of blood flow in the aneurysm may be necessary. The biological response in the aneurysm, particularly fibrosis, has such an effect, but its completion is at the late stage of embolization. In our study, giant cell infiltration as a foreign body reaction filled the mass relatively early after embolization, but this also requires time [21]. Thus, it is necessary for the coil to be continuously stable from the hyperacute phase after embolization, which will serve as a foundation for the subsequent biological response. For this reason, it is important that the frame coil does not experience coil compression. In other words, coils that have a large repulsive force resistant to blood pressure align along the aneurysm wall and retain their coil shape after embolization are considered to be important as frame coils.

There are some limitations of this study. We did not consider the coil friction on the model wall. Additionally, in the aneurysm model compression test, we only measured at a single point on the wall and did not directly measure the repulsive force of the entire aneurysm wall and thus, the aneurysm neck. Since measurement error is likely to occur in complex shape models and coils tend to be distributed non-uniformly, we used only spherical models. However, because many aneurysms are irregular in shape in the clinical environment, there are limitations to conclusions obtained from spherical models alone. The measurement method that can be verified even if the shape of the aneurysm model is changed will be considered moving forward. Furthermore, since aneurysm filling was performed manually, the coil insertion speed was not necessarily constant, which may have resulted in nonuniform coil distribution in the aneurysm compression test. However, even if the coils are inserted at a constant speed, the catheter tip cannot be fixed and perfectly uniform distribution is impossible. By embolizing coils as densely as possible in the cylindrical model, this nonuniform coil distribution was eliminated. Finally, this study is only a physical study and has limited clinical applicability. However, we also performed embolization using 3 D coils, bioactive coils, and fibered coils with good results (29 consecutive masses, 0% recurrence from 2012 to the present). Based on the results of this physical experiment and biological experiment [21], we plan to report on the usefulness of combined embolization with 3 D coils, bioactive coils, and fibered coils in the future.

Conclusion

GDC coils with a larger stock wire diameter and a smaller primary diameter unfolded evenly along the wall and had a greater repulsive force. Coil stiffness contributes to coil stability and shape retention, indicating the possibility of preventing recurrence by selecting a frame coil with a focus on coil stiffness. In the future, it is necessary to compare the results of aneurysm coiling using framing coils with different stiffness in clinical practice.

Disclosure statement

No potential competing interest was reported by the authors.

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