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Experimental study of coil delivery wire insertion force in intracranial aneurysm embolization: force discrepancy generated inside the microcatheter through that coil delivery wire passes

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ABSTRACT

In endovascular coil embolization for intracranial aneurysms, as coils are filled in the aneurysm and the stage of procedure is advanced, the force to push forward the coil delivery wire (insertion force) increases. However, the coil insertion force that interventionist's felt at his fingertips does not directly reflect the stress of the aneurysm and is affected by the resistance generated inside the microcatheter through that the wire passes. The authors evaluated this force discrepancy by subtracting the loading force at the tip of delivery wire from the insertion force of delivery wire and examined the relationship among them. Experiments were performed with the device that applies a constant loading force to the delivery wire tip with the coil removed. A force gauge was connected to the end-tip of the delivery wire to measure the insertion force. The force was measured by changing delivery wire in different coil brands and the conditions of microcatheter (straight or bent position). The results demonstrated that force discrepancy generated inside the microcatheter increased as the loading force increased in a linear relationship. Different coil delivery wires produced differences in the way that force discrepancy changed, thus reflecting the properties of each wire. Microcatheters with more curvature were associated with a higher force discrepancy. In conclusions, as the loading force increases, the force discrepancy increases, and it means that the coil insertion force that the interventionist feels at his fingertips also increases. This force discrepancy is impacted by the delivery wire properties and microcatheter curvature.

Keywords: intracranial aneurysm, embolization, coil delivery wire, microcatheter, insertion force

INTRODUCTION

Endovascular coil embolization for intracranial aneurysms has notably increased as a treatment alternative to microsurgical clipping and is an essential procedure. Coil embolization of

intracranial aneurysms is a technique consisting of inserting detachable coils into the aneurysmal sac through the microcatheter. As the coils are filled in the aneurysm and the stage of the embolization is advanced, the force to push forward the coil delivery wire (coil insertion force) increases. However, this coil insertion force at interventionist's fingertips does not directly reflect the stress of the aneurysm and it is also affected by the force discrepancy generated inside the microcatheter through that the coil delivery wire passes. To date, the relationships among stress on the aneurysm, coil insertion force at the fingertips of the interventionist, and force discrepancy that generated inside the microcatheter have not been elucidated, and thus, the purpose of this research is to assess the relationships among them.

The authors analyzed the force discrepancy generated inside the microcatheter by finding the difference between the loading force at the tip of delivery wire and the delivery wire insertion force, and we evaluated the discrepancy and its relationship with the degree of the loading force. Furthermore, we measured the force discrepancy under various conditions by changing coil delivery wire in different coil brands and conditions of the microcatheter to examine the underlying factors.

MATERIALS AND METHODS

Figure 1 and 2 show the schemas and photographs of the experimental system, respectively. We conducted the experiment using coil delivery wires with the coil at the tip removed. We inserted the delivery wire into the inner lumen of the microcatheter and advanced it forward mechanically at a constant speed. A 40 [mm] length pin gauge was inserted for 20 [mm] at the tip of the microcatheter. We produced a state where a constant force (loading force) can be applied even while the delivery wire is advancing forward by applying a rotational resistance to the pin gauge with a roller (Fig.2A). Loading force simulated the stress on the aneurysm in the actual procedure. The intensity of the loading force was adjusted manually to tighten a roller and measured by the force gauge (DSN-2N: IMADA Co., Ltd, Toyohashi, Japan) (Fig.2C). Furthermore, a force gauge was connected to the proximal end of the delivery wire as well to measure the insertion force of the delivery wire. This force gauge was placed on the automatic sliding stage and the insertion speed was controlled (Fig.2B). The loading force of the delivery wire was varied and simultaneously measured the insertion force. Data of the force was collected while the delivery wire advanced forward for 10 [mm].

The force discrepancy that occurred as the delivery wire passed through the microcatheter was found by subtracting the loading force from the wire insertion force with the following equation: [wire insertion force = loading force + force discrepancy generated inside the microcatheter]. That is, [force discrepancy generated inside the microcatheter = wire insertion force - loading force]. Statistical analysis was not appropriate and omitted in this article because of small sample size. Whereas, the formulas of the regression line ($y = a + bx$) of each group were presented, respectively.

Experiment 1

The wire insertion force was measured by changing the loading force while the microcatheter was placed in the straight course. The purpose of this experiment was to find the difference between each coil delivery wire by placing the microcatheter linearly to minimize its influence on the delivery wire that occurred inside a bent microcatheter. The four types of coil delivery wire used were as follows: GDC (Stryker Neurovascular, Fremont, CA, USA), ED Coil (Kaneka Medics, Osaka, Japan), Orbit Galaxy Coil (Codman & Shurtleff, Inc., Raynham, MA, USA), Micrus

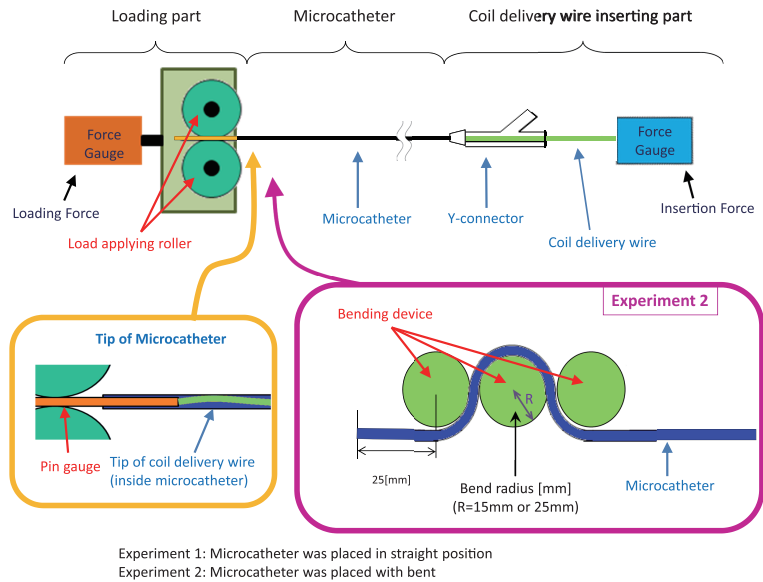Study of coil delivery wire insertion force

Fig. 1 A schema of the experimental system.

A coil delivery wire without the coil at the tip was inserted into the inner lumen of the microcatheter and was advanced forward. Rotational resistance (loading force) was applied to the tip of wire with a roller. Loading force was measured by a force gauge and the other force gauge was also connected to the proximal tip of the delivery wire to measure its insertion force.

In Experiment 1, the microcatheter was placed in a straight position. In Experiment 2, three bending devices were used to produce a state in which the microcatheter was bent. The bend radius (R) of the bending devices was set at 15 and 25 [mm].
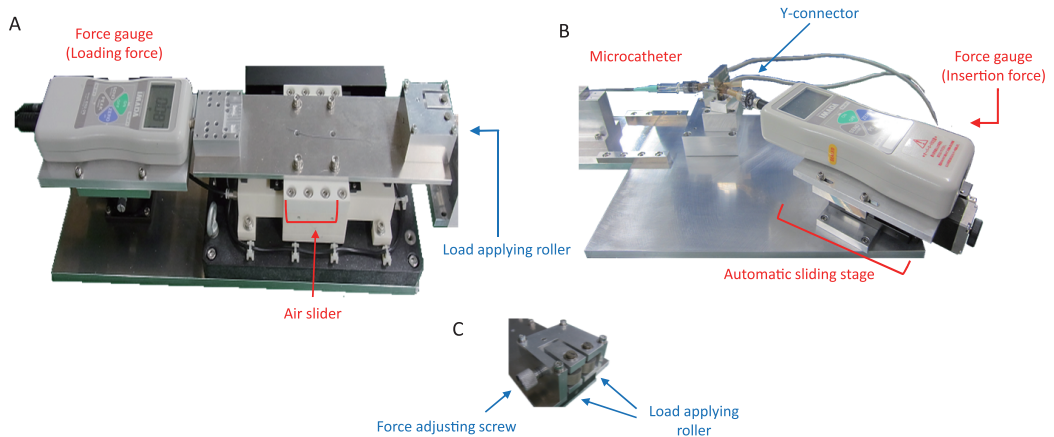

Fig. 2 Photographs of the experimental system.

Fig. 2A: the photograph shows the load applying roller and force gauge. The air slider prevents other load except for the one from the roller even as the wire advances forward.

Fig. 2B: Wire insertion force was measured by connecting the force gauge to the proximal end of the delivery wire extending from the Y-connector connected to the microcatheter hub. The wire insertion speed was controlled by the automatic sliding stage.

Fig. 2C: This is the load applying roller. The intensity of the loading force was set to tighten a roller with the force adjusting screw.

Coil (Codman & Shurtleff, Inc.). For the microcatheter, Excelsior SL-10 (Stryker Neurovascular) was used. The lumen of the microcatheter was filled with saline solution. The insertion speed of the delivery wire was set at 1 [mm/s], 4 [mm/s], and 10 [mm/s].

Experiment 2

The wire insertion force was measured by changing the loading force between the straight position of the distal of the microcatheter and the bent position with a given bending radius. This experiment assessed the impact of the curvature of the microcatheter on the force discrepancy generated inside the microcatheter. As shown in Figure1, three cylindrical bending devices were used to produce a state in which the microcatheter was bent. The radiuses of the bending devices were set at 15 [mm] and 25 [mm]. The insertion speed of the delivery wire was set at 1 [mm/s]. GDC, ED Coil, and Target Coil (Stryker Neurovascular) were used for this experiment. The microcatheter used was Excelsior SL-10.

RESULTS

Experiment 1

With all types of coil delivery wire, the more the loading force became larger, the higher became the force discrepancy inside the microcatheter. Regression lines were obtained and a positive correlation was found between the loading force and the force discrepancy. The relationship between the loading force and the force discrepancy demonstrated some differences among the coil delivery wires (Fig.3).

GDC and ED Coil showed relatively similar tendencies but were different from Orbit Galaxy Coil and Micrus Coil. Compared to GDC and ED Coil, Orbit Galaxy Coil and Micrus Coil had a slightly higher force discrepancy. Compared to the other three types, Orbit Galaxy Coil had a little greater linear slope, and its force discrepancy increased more easily as the loading force increased.

With regards to the relationship between the loading force and the force discrepancy, each coil delivery wire presented small difference depending on the delivery wire insertion speed, but its impact was limited.

Experiment 2

Figure 4 and 5 show the results according to the microcatheter condition and the type of coil delivery wire, respectively. As seen in Experiment 1, the force discrepancy inside the microcatheter increased as the loading force increased, and a positive correlation was found between them. In a comparison when the microcatheter was placed in a straight or bent position, the force discrepancy was higher in the bent position. Furthermore, the smaller the radius of the curvature (i.e., the more catheter was bent), the higher was the force discrepancy (Fig.4).

Among the delivery wires, GDC and ED Coil showed relatively similar trends to each other but were different from Target Coil (Fig.5). Force discrepancy was measured even when the loading force was 0 [N] with Target Coil, and it was also higher when the radius of the curvature was smaller. While the linear slope of GDC and ED Coil changed depending on the radius of the curvature, there was only a slight change in the slope for Target Coil.
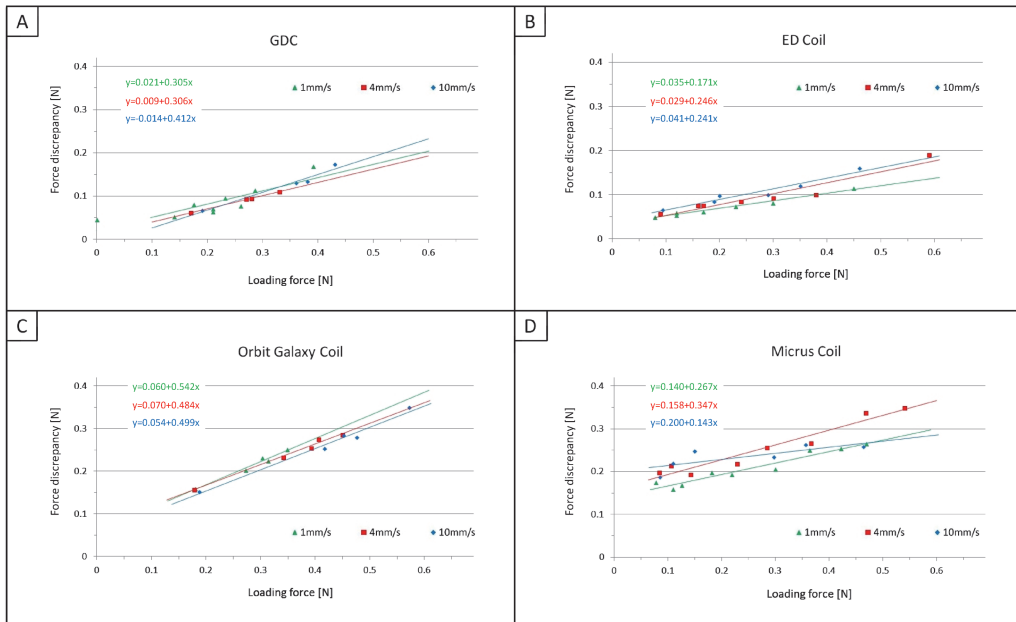
Fig. 3 The results of Experiment 1 with the microcatheter placed in the straight position.
The relationship between the loading force and the force discrepancy generated inside the microcatheter were presented according to the coil brand (A: GDC, B: ED Coil, C: Orbit Galaxy Coil, D: Micrus Coil). As the loading force increases, the force discrepancy increased linearly. GDC and ED Coil showed relatively similar trends to each another, but they were different from Orbit Galaxy Coil and Micrus Coil. There was no obvious difference among the delivery wire insertion speeds.
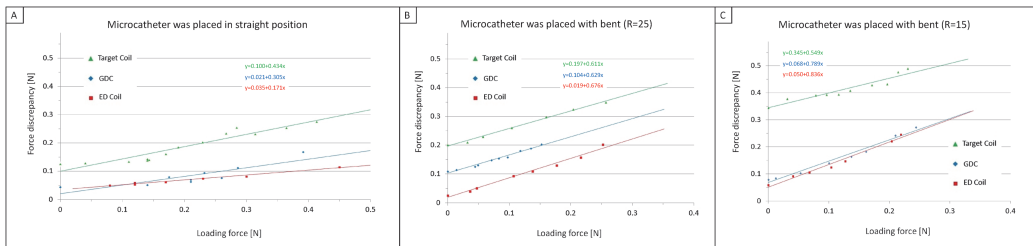

Fig. 4 The results of Experiment 2 by microcatheter positions.
A: a microcatheter is positioned linearly. B: a microcatheter is bent (R=25), C: a microcatheter is bent (R=15). In each case, the force discrepancy increased as the loading force increased. Target Coil presented a higher force discrepancy than GDC and ED Coil. GDC and ED Coil showed relatively similar results.
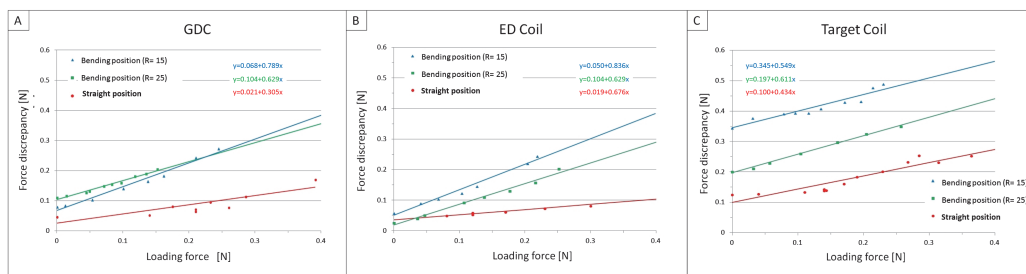
Fig. 5 The results of Experiment 2 by each coil brand (A: GDC, B: ED Coil, C: Target Coil).
The force discrepancy increased linearly as the loading force increased. The force discrepancy also tended to increase when the wire was bent more. With Target Coil, a force discrepancy occurred only by inserting the wire into a bent microcatheter. GDC and ED Coil showed relatively similar results, which were different from Target Coil. The slope of the regression line changed depending on the radius of the curvature with GDC and ED Coil, but the change of the slope was small with Target Coil.

DISCUSSION

Evaluation of the force discrepancy generated inside the microcatheter

Intracranial aneurysm coil embolization is a technique in which coils are inserted inside aneurysmal sac through a microcatheter. When the coils are filled in the aneurysm, the force to push forward the coil delivery wire increases. The increase of coil insertion force was felt by the feedback that interventionists experienced at their fingertips via the delivery wire. By law of action and reaction, the stress that the coil exerts on the aneurysm at the tip of microcatheter is equal to the reaction force of the coil delivery wire. However, since the interventionist inserts the coil via the delivery wire inserted through an approximately 150 cm-long microcatheter, the coil insertion force felt at the hand does not directly reflect the load on the aneurysm. Lamano et al reported that they have measured the coil insertion force stressing on the aneurysm wall by using silicone aneurysm,[1] and Matsubara et al and their group reported that they have measured the coil insertion force that the operator felt at his fingertips by a Y-connector sensor connected to the hub of the microcatheter.[2,3] However, the former assessed only the force at the front-tip of the microcatheter and delivery wire, and the latter only assessed the force measured at the end-tip of them. Thus, the difference in coil insertion forces between the front and end tips of the delivery wire (i.e., inside the microcatheter) was still not assessed. Therefore, the present research analyzed the force discrepancy by finding the difference between the loading force of the delivery wire tip and the delivery wire insertion force. All experimental results demonstrated that the larger the loading force, the greater became the force discrepancy generated in the microcatheter. Friction force occurring as the coil delivery wire passes through the microcatheter may be the main factor generating the force discrepancy although it is difficult to estimate to what extent delivery wire contacts inside the microcatheter and produces the friction. In addition, other factors such as delivery wire's physical property might also influence. Then, measurement results of the force discrepancy by changing conditions, such as type of coil delivery wires and microcatheter positions, showed that some of the causes underlying the differences in force discrepancy were types of coil delivery wire and microcatheter bending.

Influence by the coil delivery wire

Depending on the coil brand, coil detachment system or structure of the delivery wire are different. Moreover, there are differences in physical and mechanical properties among coil

delivery wires. Previous studies have researched on the properties of the coil itself[4-8]; whereas very few have examined the details of delivery wire structure.[9] Since the coil delivery wire is transitioned by a proximal portion of the wire which is firm to increase pushability and gradual flexibility towards the tip, and there is a connection portions midway where the wire rigidity changes. The delivery wire is predominantly made of stainless steel, but there are variations in the superficial coating which affects the coefficient of friction. We believe that these differences in various characteristics manifested in the results between coil delivery wires.

The results of Experiment 1 demonstrated the difference in the way that force discrepancy changed among each delivery wire. Experiment 2 also presented the difference in coil brands. Additionally, Experiment 2 showed the characteristic findings of Target Coil. A force discrepancy was generated without loading force just by inserting the delivery wire to the bent microcatheter, which we believed were due to static friction. On the other hand, the change in the force discrepancy associated with loading force (i.e., slope of the regression line) was almost constant in Target Coil, in contrast to the other coils. This result seemed to reflect the characteristics of Target Coil. In our experience, delivery wire of Target Coil empirically tends to be pushed with constant feedback feeling at the fingertips. Koyama et al assessed structural differences in the supple tip part of the delivery wire by using various coils.[9] They reported that since the structure and the elasticity of the tip of delivery wire differs among coil brands, understanding these characteristics are essential to perform safe treatment. In our research as well, we found that the force discrepancy generated in the microcatheter differs depending on the coil brand; thus, it is helpful to understand each of their characteristics in performing coil embolization.

Influence by the rigidity of coil delivery wire

Rigidities of an object are classified in flexural rigidity, axial rigidity, torsional rigidity, and shearing rigidity. Since there are no torsional manoeuvers of the wire in coil embolization, flexural and axial rigidity of the wire are involved in the procedure. In the present study, we created a condition in which the wire tip does not get stuck and could advance forward, which reduced the effects of axial rigidity which deforms the wire longitudinally. The soft tip and transition part of the delivery wire are less rigid and easily deformed. Hence, the flexural rigidity of the wire might be mainly involved in producing the discrepancy inside the microcatheter. However, in actual coil embolization, sometimes the coil does not advance smoothly into the aneurysm and stagnates at the tip. In this situation, the wire deformation in the axial direction (axial rigidity) may also have an effect, thereby further increasing the force discrepancy inside the microcatheter.

Influence by the microcatheter condition (degree of bending)

In Experiment 2, the microcatheter was placed in a straight and bent position and we found that the force discrepancy was higher the more bent the microcatheter was. From a physics perspective, in analyzing this phenomenon that occurs by bending the catheter, we can assume that it was due to the friction caused by increased contact between the delivery wire and catheter luminal wall due to bending of the microcatheter. By increasing the bend of the catheter, the friction of the delivery wire inside the microcatheter increases, thereby increasing the resistance further.

In contrast, in Experiment 1, the force discrepancy increased as the loading force increased, even though the microcatheter was placed in a straight position. Although microcatheter was positioned linearly to minimize the friction between the delivery wire and the inner lumen, parts with low flexural rigidity such as the tip or the transitions of the delivery wire might deform and droop when the loading force was increased. This mechanism is the presumed one of the cause of the generation of discrepancy. However, in the present research, the interior of the

microcatheter could not be observed; therefore, we could not perform detailed analysis of the exact location and degree of the friction occurring inside the microcatheter, and remains to be examined in future studies.

Influence by the coil delivery wire insertion speed

In Experiment 1, the force discrepancy was barely affected by the coil delivery wire insertion speed. Previous papers on coil insertion force reported differences in insertion force generation patterns according to the insertion speed; however, it is mainly affected by coil behavior that changes according to the insertion speed.[1,2,10,11] The insertion force increases more easily when the coil insertion speed is high because of the coil bouncing against the aneurysm wall, whereas a slow speed also increases the insertion speed because of statistical friction occurring from stagnant coil movement. Only when the insertion speed is adequate will the coil move smoothly without increasing the insertion force. In this study, the wire could advance forward simply because the coil was removed, and there might be no obvious differences due to speed.

Significance of this research in clinical practice

In clinical practice, a strong resistance feeling is occasionally experienced to insert the coil delivery wire at times especially in the final stage of coil embolization. Likewise, a resistance feeling at the fingertips is more likely to occur at coil insertion when the microcatheter is more curved. The results of this research revealed that the force discrepancy in passing the delivery wire through the microcatheter increased as the loading force increased and it was affected by the degree of microcatheter bend. These findings explained why the gap between the coil insertion force at the fingertips and the stress directly on the aneurysm widened as the coil embolization progressed. The results of the present research seemed to adequately reflect actual clinical experiences at the process of the coil embolization. Although it is highly possible that the stress at the tip is not high despite the feeling of a strong resistance feeling at the fingertips in the final stage of the coil embolization, a similar resistance felt in the early stage of the embolization must be treated with caution.

CONCLUSIONS

As the loading force increases, the force discrepancy generated inside the microcatheter through that the coil delivery wire passes increases. This result means that when the stress at the tip of delivery wire increases, the coil insertion force that the interventionist feels at his fingertips also increases. This force discrepancy is impacted by the delivery wire properties and microcatheter curvature. In order to perform a safe coil embolization for intracranial aneurysms, it is important to understand that the force discrepancy generated in the microcatheter increases according to the stress on the lesion.

ACKNOWLEDGEMENTS

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