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Original Article

Comparison of the Physical Characteristics of Support Stents for Cerebral Aneurysm Embolization

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Objective: There is a limited understanding of the characteristics of individual intracranial stents used for aneurysm treatment. We used an experimental model to evaluate the physical characteristics of support stents for aneurysm embolization.
Methods: Enterprise 2 VRD 4.0 × 39 mm, Neuroform Atlas 4.5 × 21 mm, and LVIS 4.5 × 32 mm stents were: 1) observed under light microscopy and subjected to measurements of 2) circumferential radial force, 3) strut tension, 4) stent compression, and 5) conformability upon bending.
Results: 1) Light microscopy showed a large structural difference between laser-cut (Enterprise 2 VRD, Neuroform Atlas) and braided (LVIS) stents. 2) Within the range of indicated blood vessel diameters, the radial force of Enterprise 2 VRD was higher than that of Neuroform Atlas. An extremely large force was required to decrease the LVIS diameter. 3) Neuroform Atlas easily deformed compared to Enterprise 2 VRD, while LVIS was extended with a smaller traction force than that required for Neuroform Atlas. 4) The compression strength was in the order of Enterprise 2 VRD >Neuroform Atlas >LVIS. 5) Enterprise 2 VRD showed a decreased cell area on the concave side, and Neuroform Atlas showed deformation with overlapping struts on the concave side. LVIS naturally adhered to the wall of the blood vessel model.
Conclusion: Laser-cut and braided stents showed different physical characteristics that were visualized and shown as numerical data. These findings improve the understanding of the proper use of these stents in clinical applications.

Keywords: physical characteristics, intracranial stent, cerebral aneurysm, coil embolization

Introduction

Several types of intracranial stent can be selected for aneurysm treatment, and this has made it possible to perform complex intravascular treatment of aneurysms.[1–3] Various methods of stent placement have also been reported.[4–8] However, the characteristics of individual stents are not fully understood, and thus, complications develop in some cases.[9] Therefore, we reproduced several situations that might occur in clinical practice, using an experimental system to compare the physical characteristics of support stents for cerebral aneurysm embolization: Enterprise 2 VRD (Cerenovus, Irvine, CA, USA), Neuroform Atlas (Stryker, Kalamazoo, MI, USA), and LVIS (MicroVention, Aliso Viejo, CA, USA), which are widely used in Japan. Here, we discuss the clinically appropriate usage and precautions required based on differences of characteristics among these stents.

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Materials and Methods

Three support stents for cerebral aneurysm embolization (Enterprise 2 VRD 4.0 × 39 mm, Neuroform Atlas 4.5 × 21 mm, and LVIS 4.5 × 32 mm) were examined in the study. These three stents are all widely used in Japan. Using two stents of each type for most tests, 1) observation under a light microscope, 2) measurement of circumferential radial force, 3) measurement of strut tension strength, 4) measurement of stent compression strength, and 5) evaluation of conformability by bending were performed. For LVIS, only one stent was used for 1) and 2), but two stents were used for 3), 4), and 5). The LVIS used in 1) and 2) was broken in 2). In 3) and later experiments, we used the broken

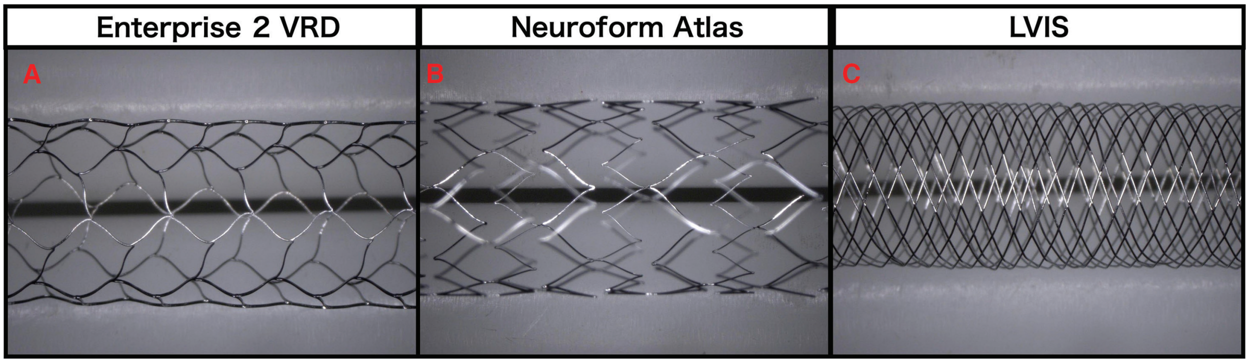

Fig. 1 **(A)** Enterprise 2 VRD 4.0 × 39 mm was observed under light microscopy. (**B**) Neuroform Atlas 4.5 × 21 mm was observed under light microscopy. (**C**) LVIS 4.5 × 32 mm was observed under light microscopy.

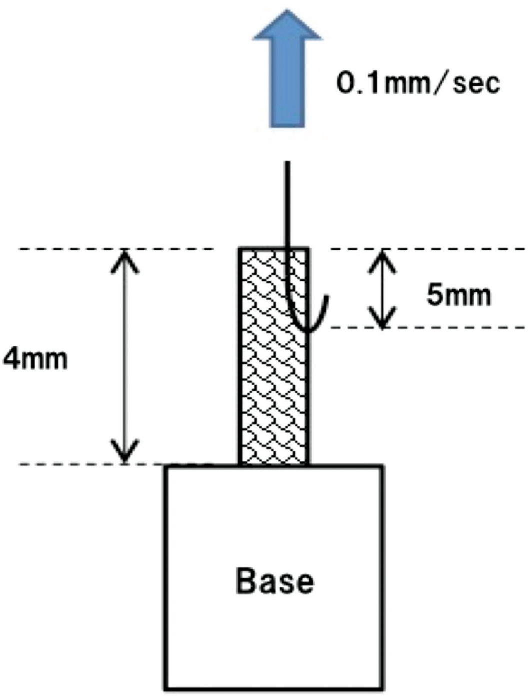

Fig. 2 Measurement of strut tension strength. Individual stents were fixed at a site 14 mm from the base. The site 5 mm from the top of the stent was pulled using a metal wire.

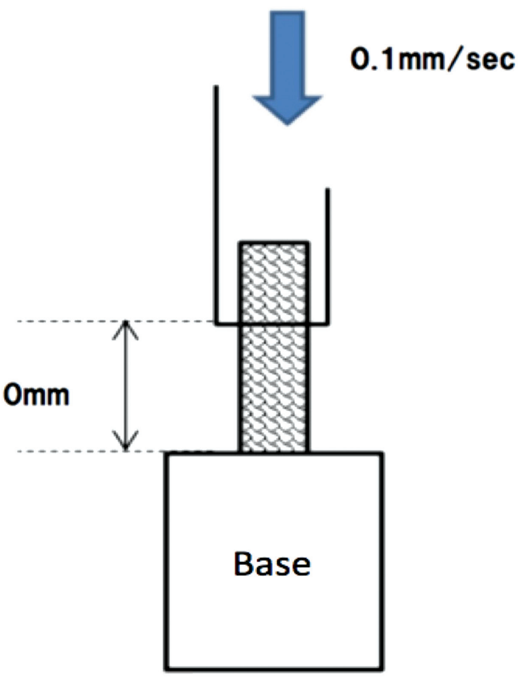

Fig. 3 Measurement of stent compression strength. The stent was compressed by fixing its end to the base and hooked by a metal wire at a site 10 mm from the base.

stent to obtain reference data, in addition to the new stents to obtain data for analysis.

1) Stents were observed using a light microscope (VHX-1000; Keyence, Osaka, Japan) (**Fig. 1**).

2) Circumferential radial force: The force caused by a decrease or increase in stent diameter was measured. First, the original diameter of 9 mm was decreased to 1.3 mm and maintained at this position for one second, before returning to 9 mm. The diameter was changed at a rate of 0.1 mm/s. Measurements were performed at 37 °C in air using a tensile testing machine (Model TTR2; Blockwise Engineering, Tempe, AZ, USA) and a J-Crimp station (Model RJ 124; Blockwise Engineering).

3) Strut tension strength: An expanded stent was fixed, and a metal wire (0.36 mm) was placed at a site 5 mm from the edge of the stent. The wire was pulled at 0.1 mm/s to deform the struts. Measurements were performed at 25 °C in air using a compact tabletop test device (EZ-SX; Shimadzu, Kyoto, Japan) (**Fig. 2**).

4) Stent compression strength: An expanded stent was fixed, and a metal wire (0.36 mm) was placed at a site 10 mm from the stent fixation site. The metal wire was moved at 0.1 mm/s to deform the stent. Measurements were performed at 25 °C in air using the EZ-SX device (**Fig. 3**).

5) Evaluation of conformability: A silicon tube was bent in the stent to observe interference of the struts.

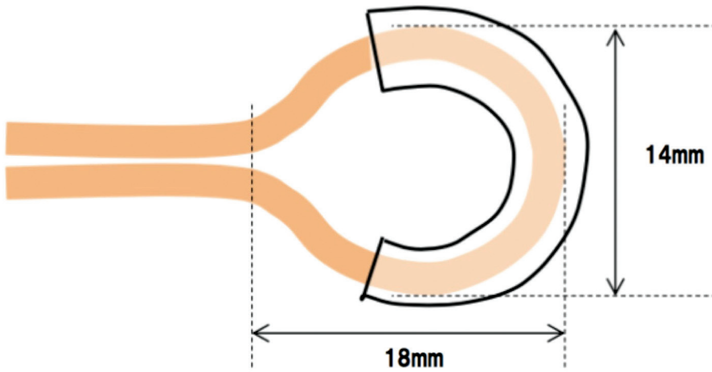

Fig. 4 Evaluation of conformability.

Table 1 Comparison of measured values for individual stents. The unit of the cell area is mm³ and that of other values is mm. Neuroform Atlas is composed of struts with 2 sizes

Stent	Stent size (mm)	Deployed diameter (mm)	Deployed length (mm)	Deployed stent edge length (mm)	Maximum cell length (mm)	Cell area (mm³)	Strut width (mm)
Enterprise 2 VRD	4 × 39	5.49	34.48	8.35	2.65	4.06	0.0462
Enterprise 2 VRD	4 × 39	5.02	34.85	8.41	2.56	4.33	0.0471
Neuroform Atlas	4.5 × 21	5.70	21.33	Proximal 7.60 Distal 6.01	3.81	5.46	0.0506, 0.0315
Neuroform Atlas	4.5 × 21	5.72	21.39	Proximal 7.64 Distal 6.18	3.77	5.48	0.0579, 0.0365
LVIS	4.5 × 32	4.91	26.88	7.36	1.69	0.53	0.0593

Measurements were made using a microscope (VHX-1000). The stents should have been in the tube lumen but they could not be put inside after the previous tests (1)–(4) (**Fig. 4**).

Results

1) Observation under a light microscope (**Table 1**): Two 4.0 × 39 mm Enterprise 2 VRD, two 4.5 × 21 mm Neuroform Atlas, and one 4.5 × 32-mm LVIS stents were observed structurally under a microscope. Enterprise 2 VRD, a closed-cell stent with 8 links in the circumferential direction, and Neuroform Atlas, an open-cell stent with 4 links in the circumferential direction, are categorized as laser-cut stents. LVIS, a braided stent, has no links in the circumferential direction. The indicated blood vessel diameter for the 4-mm Enterprise 2 VRD is 2.5–4 mm, but the diameters after the two stents were deployed were 5.49 and 5.02 mm, clearly suggesting variation between sizes of products. The indicated blood vessel diameter for the 4.5-mm Neuroform Atlas is 4–4.5 mm, and the two stent diameters after deployment were 5.70 and 5.72 mm, showing high conformity. The indicated blood vessel diameter for the 4.5-mm LVIS is 3–4.5 mm, and the stent diameter after deployment was 4.91 mm, which is almost the same as the upper limit of the indicated blood vessel diameter. We also measured the stent length, diameter of the stent edge (flare), maximum cell diameter, cell area, and strut width.

2) Circumferential radial force: Since it was difficult to obtain expensive stents, we used only available stents for measurements in this study. Values obtained by dividing raw data by stent length were used as the circumferential radial force (**Fig. 5**). The indicated blood vessel diameters for the 4-mm Enterprise 2 VRD, 4.5-mm Neuroform Atlas, and 4.5-mm LVIS are 2.5–4, 4–4.5, and 3–4.5 mm, respectively. In a comparison within these ranges, the radial force of Enterprise 2 VRD was higher than that of Neuroform Atlas. LVIS showed a totally different reaction, and a large force was required to decrease its diameter. The stent showed the highest radial force when its diameter was small, and an extremely low radial force at a diameter of 4.5 mm, the upper limit of the indicated blood vessel diameter.

3) Strut tension strength (**Fig. 6**): When tension (tractive power) in the direction of the strut long axis was added to a single strut, Neuroform Atlas was clearly deformed more than Enterprise 2 VRD. LVIS was extended with a smaller tractive power than that required for Neuroform Atlas, suggesting it had the lowest strut strength with

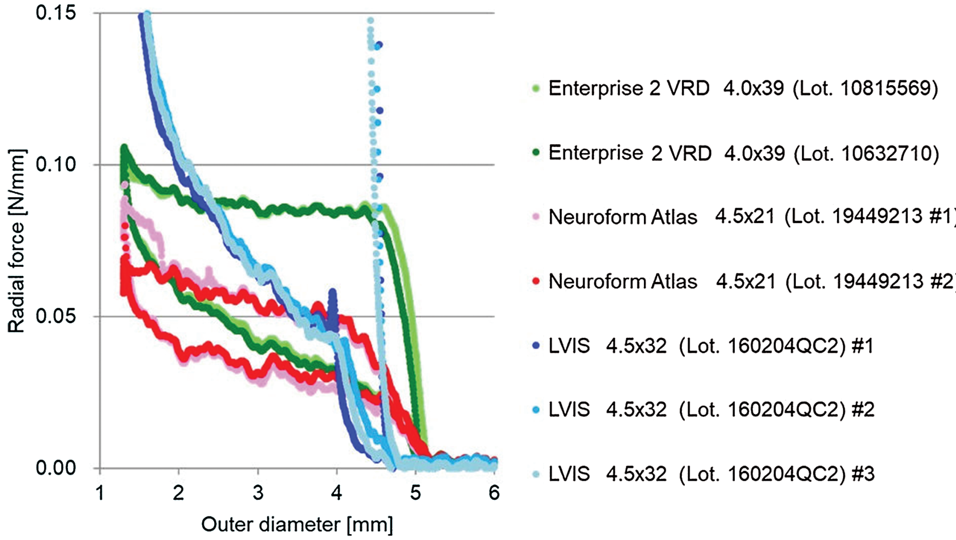

Fig. 5 Circumferential radial force. These are the data normalized using the stent length. The upper limit of the radial force is 0.15 N/mm.

tension. Data for the broken LVIS are shown for reference. After the tension test, it was visually confirmed that individual stents returned to their original appearance before the test (**Fig. 7**).

4) Stent compression strength (**Fig. 8**): Enterprise 2 VRD, LVIS, and Neuroform Atlas were bent by the application of forces of approximately 0.10–0.12, 0.05–0.07, and 0.015–0.018 N, respectively. In a comparison before bending, the compression strength of Enterprise 2 VRD was clearly higher than that of Neuroform Atlas, and that of LVIS was the lowest. Data for the broken LVIS are shown for reference. When the compression load was removed after the test, it was visually confirmed that the individual stents had returned to their original appearance (**Fig. 9**).

5) Evaluation of conformability: The stent was bent to mimic deployment in a curved blood vessel. Enterprise 2 VRD showed decreased and increased cell areas on the concave and convex sides of the bend, respectively. Neuroform Atlas showed stent deformation with overlapped struts on the concave side, in addition to severe fuzzing. LVIS showed decreased and increased cell areas on the concave and convex sides, respectively, as for Enterprise 2 VRD, but the stent adhered tightly to the wall of the model blood vessel in an extremely natural way (**Fig. 10**).

Discussion

Cho et al.,[10] Krischek et al.,[11] and King et al.[12] have discussed the characteristics of individual stents by comparing Neuroform, Enterprise, LVIS Jr., and LEO; Neuroform 3, Wingspan, Solitaire, Leo(+), and Enterprise; and Enterprise VRD and Neuroform EZ, respectively. In addition, various methods of stent assistance have been described[1] based on the stent comparison by Krischek et al. However, as far as we are aware, there are no reports on the Enterprise 2 VRD, Neuroform Atlas, and LVIS stents, which are widely used in Japan. We compared these stents using an experimental model. The cost was a limitation in our experiments, and therefore, we examined only a limited number of stents.

1) Observation under a microscope: For the laser-cut stents, Enterprise 2 VRD had higher physical strength than Neuroform Atlas, due to the 8 and 4 links in the circumferential direction in these respective stents.[12,13] The strut thickness was about the same in these stents. LVIS has no links in the circumferential direction, and its struts move more freely when pulled or compressed, but the movement of the stent when deployed in the blood vessel wall is not likely to occur.

2) Circumferential radial force: The radial force of Enterprise 2 VRD was higher than that of Neuroform Atlas. This is due to the higher number of links in the circumferential direction in Enterprise 2 VRD and the closed-cell structure. For LVIS, a large force was required to decrease its diameter. When increasing the diameter, LVIS showed the highest radial force at a small diameter, but the radial force was extremely low at a diameter of 4.5 mm, the upper limit of the indicated blood vessel diameter. LVIS had friction between wires constituting the stent at a decreased diameter, whereas such friction did not occur in laser-cut stents. These results suggest that LVIS has a higher radial

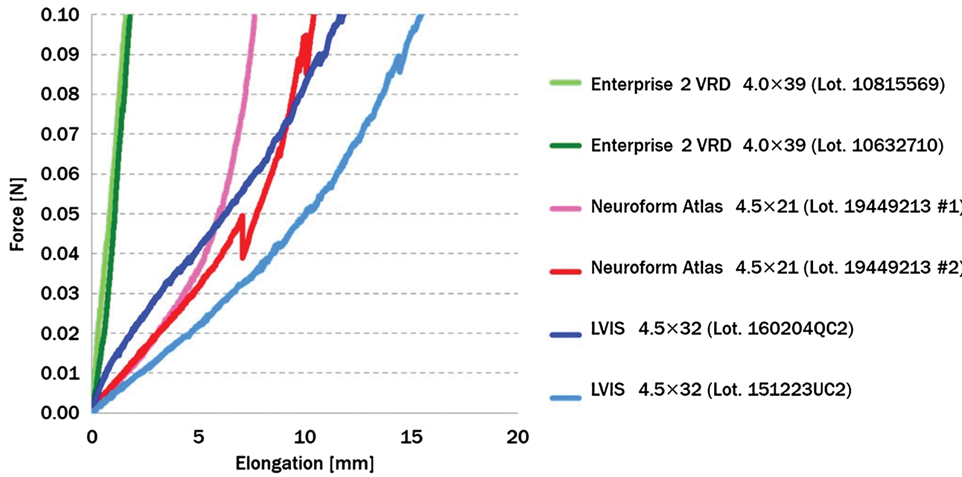

Fig. 6 Strut tension strength. The upper limit of the force is 0.10 N. Since LVIS 4.5 × 32 (Lot 160204QC2) was broken, data for this stent are shown for reference only.

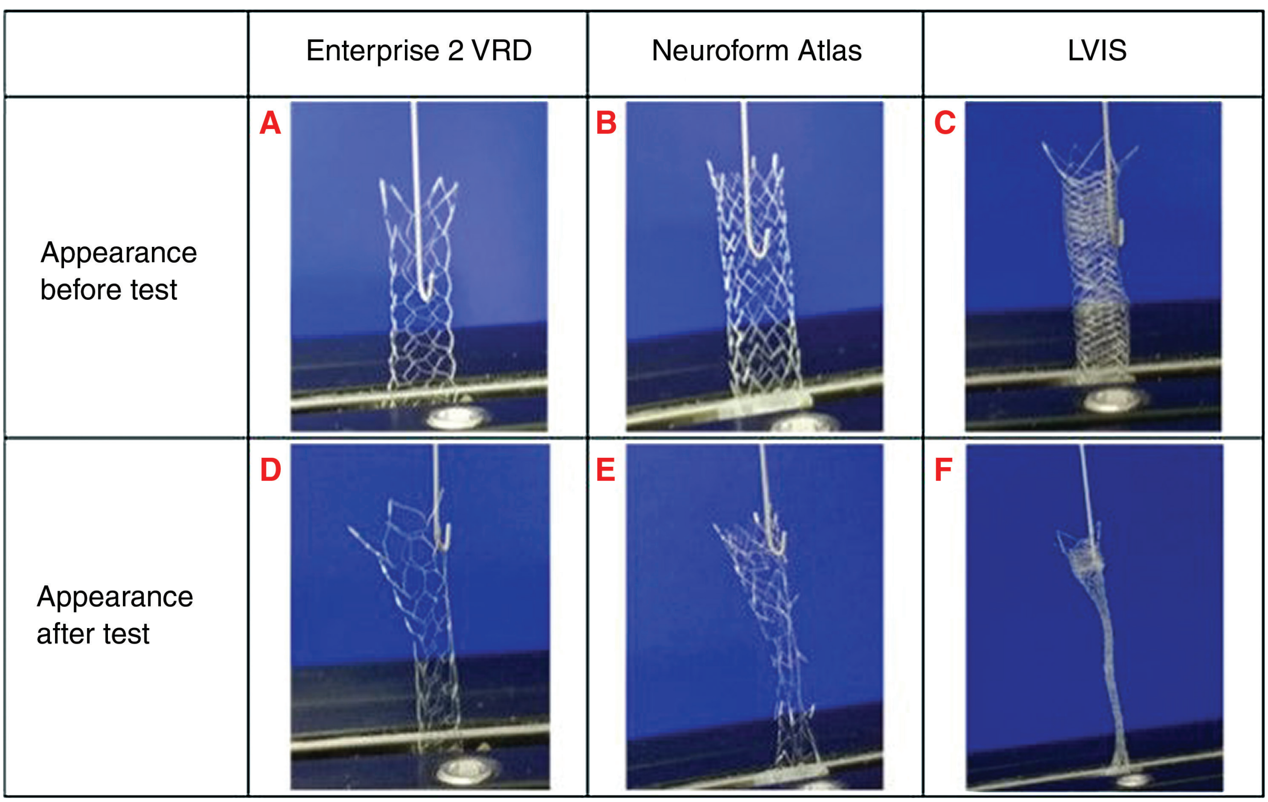

Fig. 7 (**A**) Appearance of Enterprise 2 VRD before the stent tension test. (**B**) Appearance of Neuroform Atlas before the stent tension test. (**C**) Appearance of LVIS before the stent tension test. (**D**) Appearance of Enterprise 2 VRD after the stent tension test. (**E**) Appearance of Neuroform Atlas after the stent tension test. (**F**) Appearance of LVIS after the stent tension test.

force than Enterprise 2 VRD and Neuroform Atlas. In a deployment with no limitations, the stent diameter of LVIS (4.91 mm) was only slightly larger than the largest indicated blood vessel diameter (4.5 mm). Therefore, care is required to deploy a stent for blood vessels with a diameter close to the upper limit of the indicated blood vessel diameter, although there may be differences between products.

3) Strut tension strength: The strength of Enterprise 2 VRD was clearly higher than that of Neuroform Atlas, due to the greater number of links in the circumferential direction, which gives Enterprise 2 VRD a higher structural strength. Since LVIS has no such links, only friction between wires occurred under tension. Therefore, LVIS was deformed in the direction of the axis more easily than

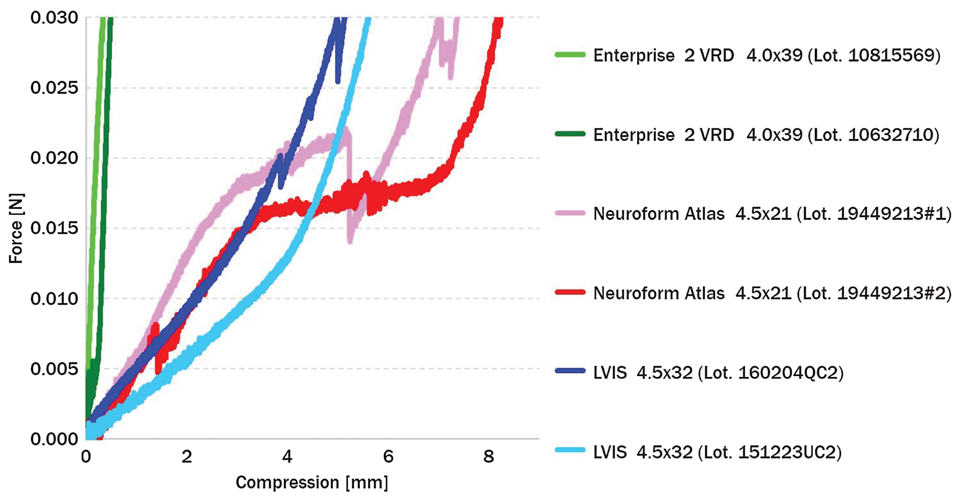

Fig. 8 Stent compression strength. The upper limit of the force is 0.030 N. The LVIS 4.5 × 32 (Lot 160204QC2) was broken, and data for this stent are shown for reference only.

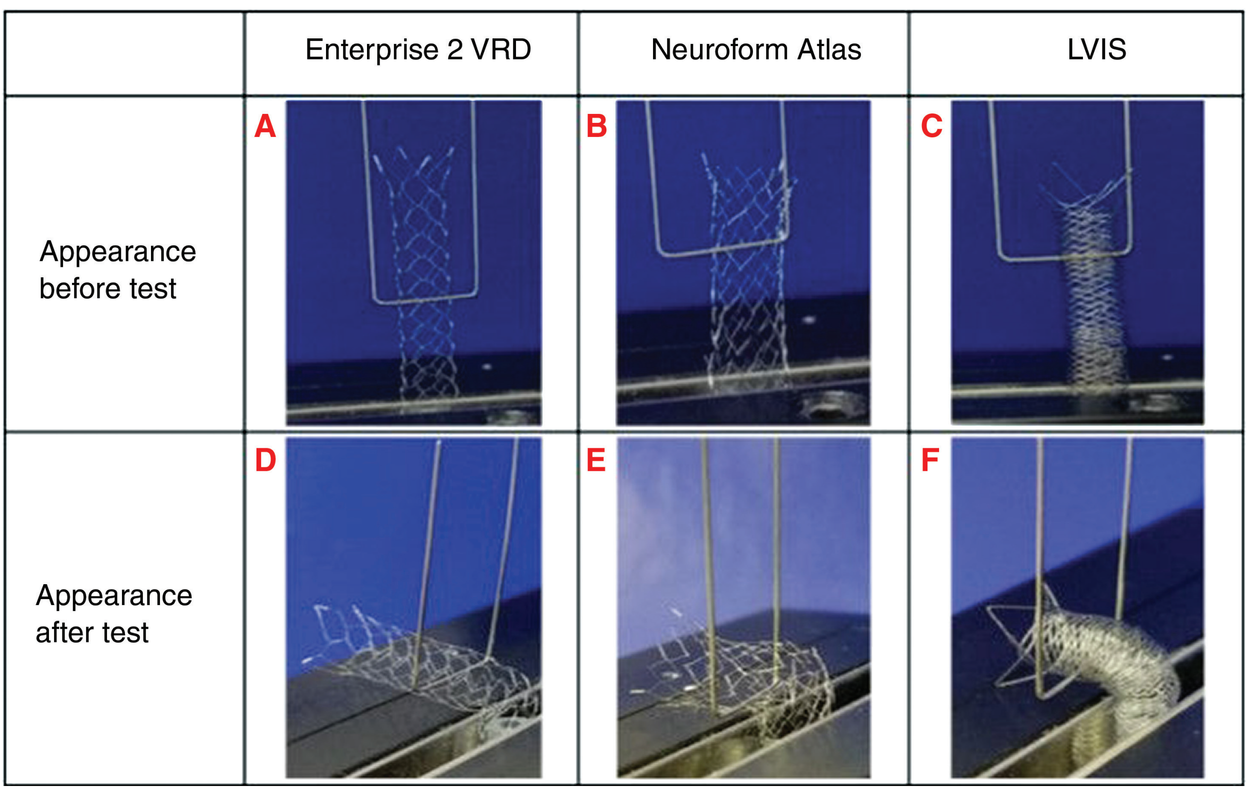

Fig. 9 (**A**) Appearance of Enterprise 2 VRD before the compression test. (**B**) Appearance of Neuroform Atlas before the compression test. (**C**) Appearance of LVIS before the compression test. (**D**) Appearance of Enterprise 2 VRD after the compression test. (**E**) Appearance of Neuroform Atlas after the compression test. (**F**) Appearance of LVIS after the compression test.

the laser-cut stents. On the other hand, since the movement of struts is limited by links in Enterprise 2 VRD and Neuroform Atlas, the decrease of their diameters is limited under tension. Although LVIS is apparently weak under tension, it is unlikely that devices used in combination, such as microcatheter and guidewires, will interfere with strut wires of the LVIS during coil embolization, and the clinical risks are likely to be small in actual practice.

4) Stent compression strength: The stent compression strength of Enterprise 2 VRD was also higher than that of Neuroform Atlas, due to the higher number of links in the circumferential direction. Regarding LVIS, since there

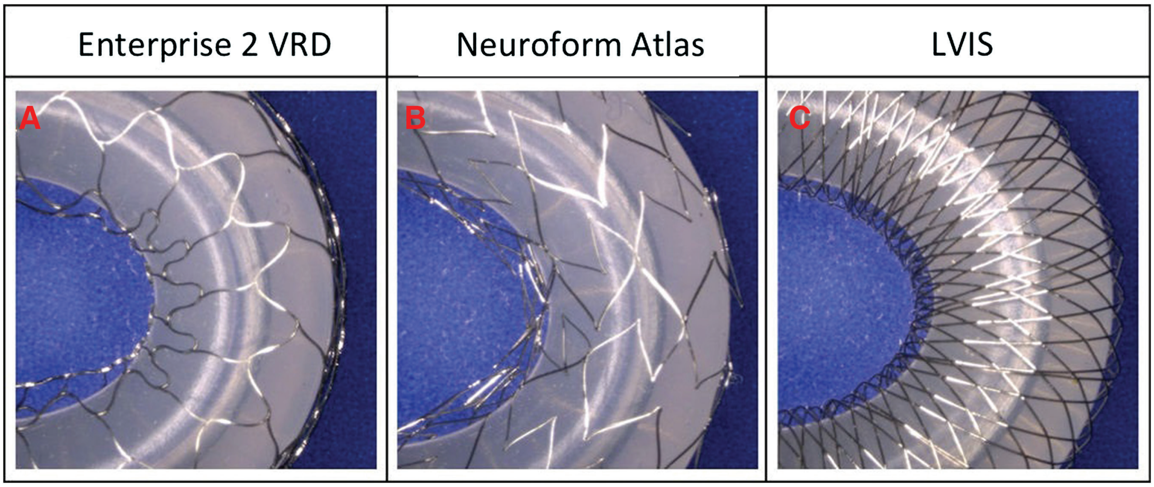

Fig. 10 (**A**) Enterprise 2 VRD was bent to evaluate its conformability. (**B**) Neuroform Atlas was bent to evaluate its conformability. (**C**) LVIS was bent to evaluate its conformability.

was only friction between wires in the early stage of stent compression, the force required for compression was extremely small. At a certain level of compression, the force required is increased because intervals between wires (opening area) were eliminated, and thus, the curve in steepened (**Fig. 8**).

5) Conformability: Since LVIS has almost no interference between struts, the stent adheres to the blood vessel wall in an extremely natural way. In contrast, a laser-cut stent has interference between struts and is highly resistant to bending. Enterprise 2 VRD, a closed-cell stent, has sufficient strength to maintain its form, but Neuroform Atlas, an open-cell stent, has difficulty in maintaining its form and its struts fuzzed.

Many reports on coronary artery stents in the cardiovascular field provide useful information on the strength of intracranial stents.[13–17] Based on these reports, the difference in strength between Enterprise 2 VRD and Neuroform Atlas was considered to be due to the stent design (number of links in the circumferential direction). The circumferential radial force, strut tension strength, and stent compression strength were all higher in Enterprise 2 VRD, with particularly large differences for the strut tension and stent compression strengths. The higher strengths for Enterprise 2 VRD lessen the risk of stent deformation during the operation of a microcatheter. However, the stent exerts a high force to maintain its form, causing a high possibility that blood vessels may straighten when the stent is deployed.[18–20] Therefore, attention to the running of blood vessels is required after stent placement. Regarding incomplete stent apposition to blood vessel walls, Enterprise 2 VRD is superior to Enterprise VRD and its adhesion to bent blood vessels is favorable.[21]

Neuroform Atlas can be deployed from a microcatheter with an inner diameter of 0.0165 inches, which is useful in peripheral vessels with a small diameter.[22–24] However, the lower strength compared to Enterprise 2 VRD make it more likely that the stent may be deformed in pulling by a microcatheter in the trans-cell technique or when a microcatheter is passed through the stent, and thus, careful technical attention is required for use of Neuroform Atlas.

In the Y-stent technique, Neuroform Atlas may not be deployed sufficiently through the cell of Enterprise 2 VRD. On the other hand, Enterprise 2 VRD may move or deform Neuroform Atlas when it is deployed through the cell of Neuroform Atlas.

Since the structure and usage of LVIS differ from those of a laser-cut stent, it was difficult to compare the test results in a simple manner. Although LVIS showed the highest radial force among the three types of stent when its diameter was close to the smallest indicated blood vessel diameter (3 mm in this study), the stent showed the lowest force when its diameter was close to the maximum diameter, as seen when the stent was deployed with no limitations. Among the three types of stents, the LVIS diameter was least easily changed. In contrast, in measurements of strut tension and stent compression strengths, the LVIS length expanded and contracted with an extremely low load, indicating that this stent was weakest in the long axis direction among the tested stents. This is due to the LVIS structure without connections between struts, which differs from a laser-cut stent. Although relatively complex techniques are required to deploy the stent, LVIS is widely used because of its high conformability.[25–27]

This study is useful because the characteristics of stents based on their structures were visualized and shown as numerical data. However, since it was difficult to obtain a sufficient number of stents because they are expensive, we had to compare stents with different indicated blood vessel diameters. Therefore, care is required with the interpretation of the results. In addition, since the LVIS broke during measurement of circumferential radial force, data for strut tension and stent compression strength for the broken stent are only shown for reference.

Conclusion

Laser-cut and braided stents showed different physical characteristics that were visualized and shown as numerical data. These findings improve the understanding of the proper use of these stents in clinical applications.

Disclosure Statement

None of the authors have a conflict of interest with regard to the contents of the study.

References

1) Kim BM, Kim DJ, Kim DI: Stent application for the treatment of cerebral aneurysms. *Neurointervention* 2011; 6: 53–70.
2) Piotin M, Blanc R, Spelle L, et al: Stent-assisted coiling of intracranial aneurysms: clinical and angiographic results in 216 consecutive aneurysms. *Stroke* 2010; 41: 110–115.
3) Chalouhi N, Jabbour P, Singhal S, et al: Stent-assisted coiling of intracranial aneurysms: predictors of complications, recanalization, and outcome in 508 cases. *Stroke* 2013; 44: 1348–1353.
4) Hong B, Patel NV, Gounis MJ, et al: Semi-jailing technique for coil embolization of complex, wide-necked intracranial aneurysms. *Neurosurgery* 2009; 65: 1131–1138; discussion 1138-1139.
5) Thorell WE, Chow MM, Woo HH, et al: Y-configured dual intracranial stent-assisted coil embolization for the treatment of wide-necked basilar tip aneurysms. *Neurosurgery* 2005; 56: 1035–1040; discussion 1035-1040.
6) Spiotta AM, Gupta R, Fiorella D, et al: Mid-term results of endovascular coiling of wide-necked aneurysms using double stents in a Y configuration. *Neurosurgery* 2011; 69: 421–429.
7) Yang TH, Wong HF, Yang MS, et al: "Waffle cone" technique for intra/extra-aneurysmal stent placement for the treatment of complex and wide-necked bifurcation aneurysm. *Interv Neuroradiol* 2008; 14: 49–52.
8) Menendez JY, Harrigan MR: X-configuration stent-assisted coiling. *World Neurosurg* 2010; 74: 143–144.
9) Johnson AK, Munich SA, Tan LA, et al: Complication analysis in nitinol stent-assisted embolization of 486 intracranial aneurysms. *J Neurosurg* 2015; 123: 453–459.
10) Cho SH, Jo WI, Jo YE, et al: Bench-top Comparison of physical properties of 4 commercially-available self-expanding intracranial stents. *Neurointervention* 2017; 12: 31–39.
11) Krischek O, Miloslavski E, Fischer S, et al: A comparison of functional and physical properties of self-expanding intracranial stents [Neuroform3, Wingspan, Solitaire, Leo(+), Enterprise]. *Minim Invas Neurosurg* 2011; 54: 21–28.
12) King B, Vaziri S, Singla A, et al: Clinical and angiographic outcomes after stent-assisted coiling of cerebral aneurysms with Enterprise and Neuroform stents: a comparative analysis of the literature. *J Neurointerv Surg* 2015; 7: 905–909.
13) Ormiston JA, Webber B, Webster MW: Stent longitudinal integrity bench insights into a clinical problem. *JACC Cardiovasc Interv* 2011; 4: 1310–1317.
14) Choudhury TR, Al-Saigh S, Burley S, et al: Longitudinal deformation bench testing using a coronary artery model: a new standard? *Open Heart* 2017; 4: e000537.
15) Abdel-Wahab M, Sulimov DS, Kassner G, et al: Longitudinal deformation of contemporary coronary stents: an integrated analysis of clinical experience and observations from the bench. *J Interv Cardiol* 2012; 25: 576–585.
16) Arnous S, Shakhshir N, Wiper A, et al: Incidence and mechanisms of longitudinal stent deformation associated with Biomatrix, Resolute, Element, and Xience stents: angiographic and case-by-case review of 1,800 PCIs. *Catheter Cardiovasc Interv* 2015; 86: 1002–1011.
17) Ormiston JA, Dixon SR, Webster MW, et al: Stent longitudinal flexibility: a comparison of 13 stent designs before and after balloon expansion. *Catheter Cardiovasc Interv* 2000; 50: 120–124.
18) Takemoto K, Tateshima S, Rastogi S, et al: Disappearance of a small intracranial aneurysm as a result of vessel straightening and in-stent stenosis following use of an Enterprise vascular reconstruction device. *J Neurointerv Surg* 2014; 6: e4.
19) Gao B, Baharoglu MI, Cohen AD, et al: Stent-assisted coiling of intracranial bifurcation aneurysms leads to immediate and delayed intracranial vascular angle remodeling. *AJNR Am J Neuroradiol* 2012; 33: 649–654.
20) Kono K, Shintani A, Terada T: Hemodynamic effects of stent struts versus straightening of vessels in stent-assisted

coil embolization for sidewall cerebral aneurysms. *PLoS One* 2014; 9: e108033.

21) Chihara H, Ishii A, Kikuchi T, et al: Deployment technique that takes advantage of the characteristics of Enterprise VRD2: an in vitro study. *J Neurointerv Surg* 2017; 9: 969–973.
22) Ten Brinck MFM, de Vries J, Bartels RHMA, et al: NeuroForm Atlas stent-assisted coiling: preliminary results. *Neurosurgery* 2019; 84: 179–189.
23) Cay F, Peker A, Arat A: Stent-assisted coiling of cerebral aneurysms with the Neuroform Atlas stent. *Interv Neruoradiol* 2018; 24: 263–269.
24) Ulfert C, Pham M, Sonnberger M, et al: The Neuroform Atlas stent to assist coil embolization of intracranial aneurysms: a multicentre experience. *J Neurointerv Surg* 2018; 10: 1192–1196.
25) Iosif C, Piotin M, Saleme S, et al: Safety and effectiveness of the Low Profile Visualized Intraluminal Support (LVIS and LVIS Jr) devices in the endovascular treatment of intracranial aneurysms: results of the TRAIL multicenter observational study. *J Neurointerv Surg* 2018; 10: 675–681.
26) Feng Z, Fang Y, Xu Y, et al: The safety and efficacy of low profile visualized intraluminal support (LVIS) stents in assisting coil embolization of intracranial saccular aneurysms: a single center experience. *J Neurointerv Surg* 2016; 8: 1192–1196.
27) Zhang X, Zhong J, Gao H, et al: Endovascular treatment of intracranial aneurysms with the LVIS device: a systematic review. *J Neurointerv Surg* 2017; 9: 553–557.