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Severe Tortuosity of the Distal Descending Thoracic Aorta Affects the Accuracy of Distal Deployment During a Thoracic Endovascular Aortic Repair

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Abstract

Purpose: An accurate distal deployment is essential for successful thoracic endovascular aortic repair (TEVAR) of a paradiaphragmatic aortic aneurysm. This study aimed to investigate the anatomical and intraoperative factors that affect the accuracy of distal deployment during TEVAR. **Methods:** We conducted a retrospective review of preoperative and postoperative computed tomography scans of 426 patients undergoing TEVAR at our institution between October 2008 and May 2021, of which the stent-graft was attempted to be deployed just above the celiac axis or the superior mesenteric artery in 56 patients. Based on the anatomical factors related to the malposition (deployed $>$10 mm away from the target vessel) and the greater curve to the straight-line ratio (G/S ratio), the patients were categorized as severe tortuosity (n=21) and mild tortuosity (n=35) groups to compare the operative and clinical outcomes. **Result:** Stent-graft malpositioning occurred in 21 cases. Among all anatomical variables, only the G/S ratio was significantly larger in the malpositioned cases (p=0.049). A cutoff G/S ratio value of 1.15 was determined using the receiver operating curve analysis. In the severe tortuosity group, the distal end of the stent-graft was significantly farther (median: 10.0 [interquartile range (IQR): 2.5–19.5] mm vs 3.0 [0–8.0] mm; p=0.015) from the target vessel, and the tilt angle of the stent-graft's distal edge was larger (median: 21.4 [IQR: 15.8–24.5] vs 9.5 [5.5–12.5] degree; p$<$0.01) than that in the mild tortuosity group. Both groups were comparable for the incidence of a primary type Ib endoleak (p=0.454), a secondary type Ib endoleak (p=1.0), and the rate of distal reintervention (p=0.276). **Conclusion:** Severe tortuosity in the distal descending thoracic aorta is associated with a malpositioned and tilted distal end of the stent-graft.

Clinical Impact

Thoracic endovascular aortic repair (TEVAR) for paradiaphragmatic thoracic aortic aneurysms requires accurate distal landing. In this paper, a retrospective CT analysis revealed that the greater curve to the straight-line ratio (G/S ratio) was associated to affects the malposition of the stent graft, defined as being deployed more than 10 mm away from the target vessel. Further, a comparative analysis based on the G/S ratio demonstrated that severe aortic tortuosity was associated with a more distal and tilted deployment of the stent graft.

Keywords

thoracic endovascular aortic repair, thoracic aortic aneurysms, aortic tortuosity

Introduction

Thoracic endovascular aortic repair (TEVAR) is widely used for the treatment of descending thoracic aortic aneurysms (TAA). An accurate deployment of the stent-graft is necessary for proper sealing of the aneurysmal region to prevent endoleak and migration and improve the long-term results. Several authors have deliberated an accurate

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proximal deployment owing to the possibility of serious complications.[1,2] We reported the relationship between anatomical and device-related factors and a proximal bird beak configuration.[3] On the other hand, only a few studies have reported an accurate distal deployment despite its significance for treating TAA near the level of the diaphragm. Although we often experience the stent-graft being deployed apart from the aimed position, the underlying reasons leading to an inaccurate distal deployment remain indeterminate. Accordingly, the purpose of this study was to assess the influence of anatomical and procedural variables on the accuracy of distal deployment during TEVAR.

Materials and Methods

Patient Population

We reviewed the surgical records of 426 patients undergoing consecutive TEVARs at our institution between October 2008 and May 2021. In 56 of these patients, the stent-graft was attempted to be deployed just above the target vessel, like the celiac axis, the superior mesenteric artery, or the celiacomesenteric trunk. Basically, one 20 mm landing zone was needed to comply with the instructions for use. Patient demographics, baseline information, and procedural details were collected retrospectively. The implanted stent-grafts were commercially available devices, such as TAG (W. L. Gore & Assoc., Flagstaff, Ariz., USA), Zenith TX2 or Alpha Thoracic (Cook Medical Inc., Bloomington, Ind., USA), Talent or Valiant (Medtronic Vascular, Santa Rosa, Calif, USA), or Relay Plus (Bolton Medical Inc., International Parkway Sunrise, Fla., USA). Patients were excluded from the review if there was a lack of adequate preoperative or postoperative computed tomography (CT) angiography data or a history of prior open repair of thoracoabdominal aortic aneurysm. The ethics committee of the Nagoya University Hospital approved the study and waived the need for patient consent.

All the patients underwent CT angiography before discharge; at 3, 6, and 12 months; and annually thereafter, if permitted by renal function.

The preoperative and postoperative CT angiography were reviewed to analyze the preoperative anatomical values and postoperative procedural outcomes. Patients were divided into 2 groups based on the aortic tortuosity, and early and late outcomes were compared between the 2 groups.

Image Analysis and Definition

The CT angiography data were analyzed using a 3-dimensional (3D) workstation (Aquarius workstation; Tera Recon Inc., San Mateo, Calif, USA). The anatomical values were measured in the preoperative CT analysis. The aortic

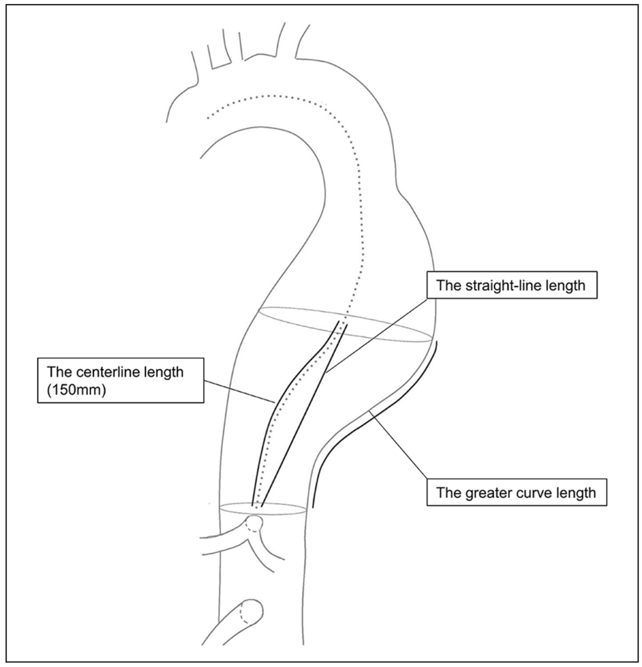

Figure 1. Variables related to the tortuosity of the aorta—the centerline length, the straight-line length, and the greater curve length—were measured in the section 150 mm above the target vessel.

centerline and the perpendicular plane were set automatically and adjusted manually. The diameter of the vessel or aneurysm was measured in the perpendicular plane, and the straight-line length was measured regardless of the vessel route. The greater curve line was extracted automatically by the 3D workstation.

Taper rate is defined as the rate of dilation 10 mm above the target vessel. Aortic tortuosity was calculated using the centerline to straight-line ratio (C/S ratio) or the greater curve to straight-line ratio (G/S ratio) in the section from the target vessel to 150 mm above in the centerline (Figure 1). To evaluate the association between the aortic bending point and the target vessel, a 15° bending point was measured, which was defined as a distance from the target vessel to the point where the perpendicular plane changes 15° from the plane just above the target vessel. The postoperative CTs before discharge were analyzed to evaluate the procedural outcomes. The distance from the target vessel to the stent-graft was determined as the minimum distance from the upper edge of the target vessel ostium to the nearest point of the stent-graft's distal edge; the measurement was obtained from a multiplanar reconstruction. In addition, the tilt angle of the distal edge was analyzed in the reconstructed image (Figure 2).

Malposition, as an indicator of inaccurate distal landing, was defined as being deployed $>$10 mm away from the target vessel as visualized in the postoperative CT or the requirement

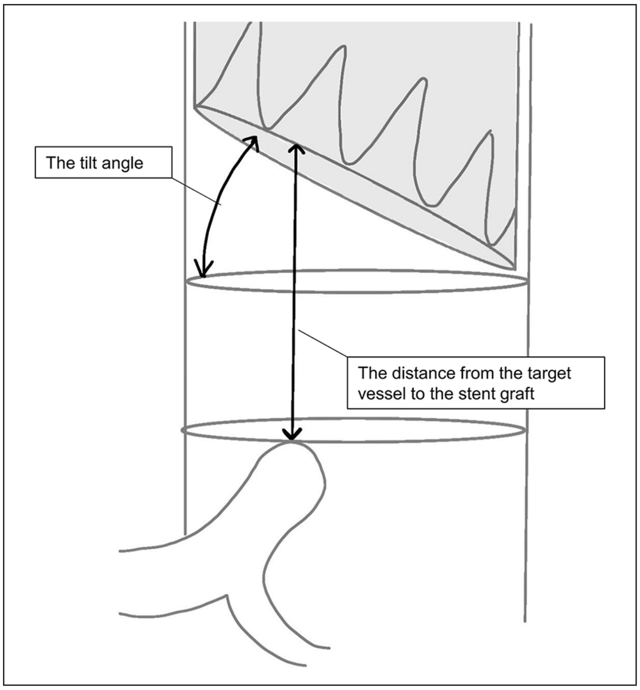

Figure 2. The distance from the target vessel to the stent-graft was determined as the minimum distance from the upper edge of the target vessel ostium to the nearest point of the stent-graft distal edge. It was measured in a multiplanar reconstruction. The tilt angle was defined as the angle (in degrees) between the distal plane of the stent-graft and the perpendicular plane.

of intraoperative distal extension that was not planned before the surgery. An endoleak first observed within 30 days after the surgery was defined as a primary endoleak, and that detected more than 30 days after the surgery was defined as a secondary endoleak.[4] The reappearance of an endoleak either after spontaneous resolution or after an intervention that was considered successful was defined as a recurrent endoleak.[4]

Statiscal Analysis

Continuous data were reported as medians and interquartile ranges (IQRs), whereas categorical variables were described as frequency and percentages. The cases in which the surgeon attempted to deploy the stent-graft just above the vessel were analyzed. The groups with accurate and inaccurate landing and the groups with severe tortuosity and mild tortuosity were compared using the Student's *t* test (if normally distributed) or the Mann-Whitney U test (if not normally distributed) for analyzing continuous variables, whereas the chi-square (χ^2) or Fisher's exact test was used for analyzing categorical variables. The multiple comparison correction was not performed. A Kaplan-Meier analysis was used to calculate freedom from type Ib endoleak or distal reintervention, which was compared between groups using the log-rank test. A p value of <0.05 was considered significant for all analyses. Furthermore, the receiver operating characteristic curve (ROC) analysis was performed to determine the cutoff value for aortic tortuosity, based on which the study cohort was divided into 2 groups. All statistical analyses were performed using SPSS Statistics version 28.0 (IBM Corp., Armonk, NY, USA).

Results

Patient Characteristics and Procedural Details

A total of 426 patients who underwent TEVAR during the study period were reviewed, and in 56 cases, the surgeon attempted to deploy the stent-graft just above the target vessel. Out of all these patients, malpositioning of the stent-graft occurred in 21 patients. Baseline demographic characteristics of the patients were comparable between the group with malposition and the group with the accurate landing of the stent-graft (Table 1). However, there were significant differences in the frequency of hypertension (p=0.003) and dyslipidemia (p=0.027), while the history of aortic repair was similar between the 2 groups. The aortic pathologies found in the study patients included degenerative aneurysm (n=40, 71.4%), dissecting aneurysm (n=15, 26.8%), and penetrating atherosclerotic ulcer (n=1, 1.8%).

Furthermore, no statistically significant difference was observed in the perioperative procedural details, such as the type of stent-graft, the number of stent-grafts implanted, the length and diameter of the stent-graft, the order of deployment (from proximal or distal), proximal landing, and the target vessel between the groups with malposition and the group with accurate landing (Table 2).

Preoperative Anatomical Variables

Table 3 presents the results for the anatomical variables measured from the preoperative CT. The median aneurysm diameter was 63 mm (IQR: 57–70 mm). The median distance of the 15° bending point was 34 mm (IQR: 22–51 mm) above the target vessels, and the median taper rate was 4.1% (IQR: 0%–8.7%). None of these variables were significantly different between the malpositioned and the accurate landing groups. In addition, there was no statistically significant difference between the 2 groups in terms of the C/S ratio (malpositioned stent-graft: 1.040 [IQR: 1.030–1.080] vs accurate landing of stent-graft: 1.070 [IQR: 1.035–1.135]; p=0.078). Only the G/S ratio was significantly higher in the malpositioned stent-graft group than that in the group with accurate landing (1.118 [IQR: 1.068–1.162] vs 1.161 [IQR: 1.086–1.251]; p=0.049).

Next, using the ROC analysis, the cutoff value for the G/S ratio was determined as 1.15 (area under the curve=0.659, sensitivity=0.571, specificity=0.743).

Table 1. Patient Characteristics.

Characteristics	Total (n=56)	Accurate (n=35)	Malposition (n=21)	p Value
Age (years)	76 (71–80)	76 (71–80)	74 (70.5–80)	0.273
Male sex	43 (76.8)	28 (80.0)	15 (71.4)	0.337
Hypertension	48 (85.7)	34 (97.1)	14 (66.7)	**0.003**
Dyslipidaemia	18 (32.1)	15 (42.9)	3 (14.3)	**0.027**
Diabetes	5 (8.9)	2 (5.7)	3 (14.3)	0.267
Haemodialysis	1 (1.8)	0 (0)	1 (4.8)	0.375
CAD	15 (26.8)	10 (28.6)	5 (23.8)	0.697
CVD	8 (14.3)	4 (11.4)	4 (19.1)	0.34
History of aortic repair				0.352
TAR	4 (7.1)	2 (5.7)	2 (9.5)	
TAR+ET	4 (7.1)	1 (2.9)	3 (14.3)	
TEVAR	2 (3.6)	1 (2.9)	1 (4.8)	
Etiology				0.132
Atherosclerotic	40 (71.4)	23 (65.7)	17 (81.0)	
Dissecting	15 (26.8)	12 (34.3)	3 (14.3)	
Other	1 (1.8)	0 (0)	1 (4.8)	
Emergent	6 (10.7)	4 (11.4)	2 (9.5)	0.599

Data are presented as n (%) or median (interquartile range) unless stated otherwise. Bold values indicate statistical significance ($p<0.05$).
Abbreviations: CAD, coronary artery disease; CVD, cerebral vascular disease; ET, elephant trunk; TAR, total arch replacement; TEVAR, thoracic endovascular aortic repair.

Table 2. Procedural Details.

Procedural details	Total (n=56)	Accurate (n=35)	Malposition (n=21)	p Value
Device				0.726
TAG	19 (33.9)	12 (34.3)	7 (33.3)	
Valiant	13 (23.2)	9 (25.7)	4 (19.1)	
RELAY	3 (5.4)	1 (2.9)	2 (9.5)	
Zenith TX2	16 (28.6)	9 (25.7)	7 (33.3)	
Zenith Alpha	3 (5.4)	2 (5.7)	1 (4.8)	
Talent	2 (3.6)	2 (5.7)	0 (0)	
Number of devices				0.907
1	20 (35.7)	13 (37.1)	7 (33.3)	
2	34 (60.7)	21 (60.0)	13 (61.9)	
3	2 (3.6)	1 (2.9)	1 (4.8)	
First deployment				0.225
Proximal	12 (21.4)	5 (14.3)	7 (33.3)	
Distal	24 (42.9)	17 (48.6)	7 (33.3)	
Single stent-graft	20 (35.7)	13 (37.1)	7 (33.3)	
Proximal landing				0.115
Native	39 (69.6)	27 (77.1)	12 (57.1)	
Graft	17 (30.4)	8 (22.9)	9 (42.9)	
Target vessel				0.688
CA	35 (62.5)	21 (60.0)	14 (66.7)	
SMA	20 (35.7)	13 (37.1)	7 (33.3)	
Celiacomesenteric trunk	1 (1.8)	1 (2.86)	0 (0)	
Distal diameter of stent-graft, mm	34 (31–36)	34 (31–34)	34 (31–37.5)	0.339
Length of distal stent-graft, mm	150 (130–200)	150 (147–200)	150 (106.5–193)	0.190
Over sizing rate, %	36 (22–41)	36 (26–39)	38 (18–42)	0.623
Operative time, minutes	114 (95.25–155.75)	114 (95–155)	113 (95.5–166.5)	0.826
Bleeding, g	59.5 (30–171.75)	45 (25–160)	108 (33–250)	0.195
Contrast agent, mL	85 (60–140)	80 (60–140)	110 (60–200)	0.201

Data are presented as n (%) or median (interquartile range) unless stated otherwise.
Abbreviations: CA, celiac axis; SMA, superior mesenteric artery.

Table 3. Anatomical Variables Measured in the Preoperative Computed Tomography.

Anatomical variables	Total (n=56)	Accurate (n=35)	Malposition (n=21)	p Value
Aneurysm diameter, mm	63 (57–70)	60 (54–68)	65 (59.5–74)	0.175
Target vessel, bending point (15°), mm	34 (22–51)	33 (21.5–52.5)	35.5 (24.5–51.5)	0.861
Taper rate (%)	4.1 (0–8.7)	4.0 (0–7.4)	5.6 (0–11.1)	0.178
Centerline to straight-line ratio (150 mm)	1.055 (1.030–1.175)	1.040 (1.030–1.080)	1.070 (1.035–1.135)	0.078
Greater curve to straight-line ratio (150 mm)	1.121 (1.076–1.197)	1.118 (1.068–1.162)	1.161 (1.086–1.251)	**0.049**

Data are presented as n (%) or median (interquartile range) unless stated otherwise. Bold values indicate statistical significance ($p<0.05$).

Table 4. Operative and Clinical Outcomes Between Severe and Mild Tortuosity Groups.

Outcomes	Total (n=56)	Severe (n=21)	Mild (n=35)	p Value
Distance from target vessel to stent-graft, mm	3.85 (0–11.0)	10 (2.5–19.5)	3.0 (0–8.0)	**0.015**
Tilt of stent-graft, degree	11.6 (6.2–20.6)	21.4 (15.8–24.5)	9.5 (5.5–12.5)	<**0.001**
Unplanned distal extension	4 (7.1)	2 (9.5)	2 (5.7)	0.592
Postoperative EL				0.413
Ib	9 (16.1)	4 (19.0)	5 (14.3)	
II	4 (7.1)	2 (9.5)	2 (5.7)	
III	4 (7.1)	0 (0)	4 (11.4)	
Primary type Ib EL	9 (16.1)	4 (19.0)	5 (14.3)	0.717
Secondary type Ib EL	4 (7.1)	1 (4.8)	3 (8.6)	1.0
Recurrent type Ib EL	2 (3.6)	0 (0)	2 (5.7)	0.523
Type Ib EL at the final follow-up	1 (1.7)	0 (0)	1 (2.8)	1.0
Reintervention to the distal	5 (8.9)	3 (14.3)	2 (5.7)	0.276
Type Ib EL or reintervention to the distal	12 (21.4)	6 (28.6)	6 (17.1)	0.248

Data are presented as n (%) or mean±standard deviation (SD) unless stated otherwise. Bold values indicate statistical significance ($p<0.05$).
Abbreviation: EL, endoleak.

Accordingly, 21 patients were categorized into the severe tortuosity group (G/S ratio≧1.15), and 35 patients into the mild tortuosity group (G/S ratio<1.15).

Early Outcomes

The early postoperative outcomes using CT data were analyzed to compare the severe and mild tortuosity groups (Table 4). In the severe tortuosity group, the distal end of the stent-graft was significantly farther from the target vessel than in the mild tortuosity group (median: 10.0 [IQR: 2.5–19.5] mm vs 3.0 [IQR: 0–8.0] mm; p=0.015). The tilt angle of the distal edge of the stent-graft was also larger in the severe tortuosity group (21.4° [IQR: 15.8°–24.5°] vs 9.5° [IQR: 5.5°–12.5°]; p<0.01). An unplanned intraoperative distal extension was required in 2 patients each in both groups (severe tortuosity group: 9.5%; mild tortuosity group: 5.7%; p=0.592).

A primary type Ib endoleak was observed in 4 patients (19.0%) in the severe tortuosity group and 5 patients (14.3%) in the mild tortuosity group (p=0.413). In 5 cases, the endoleak disappeared spontaneously, but distal reintervention was required in 3 cases. In 1 patient, the endoleak persisted because the patient refused additional treatment.

Late Outcomes

The median follow-up period was 39.0 (IQR: 16.0–55.0) months. No statistically significant differences were observed between the severe and mild tortuosity groups regarding a secondary type Ib endoleak (n=1, 4.8%, vs n=3, 8.6%; p=1.0), the recurrent type Ib endoleak (n=0 vs n=2, 5.7%; p=0.523), and reintervention to the distal (n=3, 14.3%, vs n=2, 5.7%) during the follow-up period. In addition, the 2 groups were comparable regarding the rate of cases developing a type Ib endoleak or distal extension (n=6, 28.6%, vs n=6, 17.1%; p=0.248). The Kaplan-Meier analysis of freedom from the type Ib endoleak or distal extension also did not reveal significant between-group differences (p=0.264) (Figure 3).

Discussion

We observed that in the case of severe aortic tortuosity, as defined by the G/S ratio, the distal end of the stent-graft was deployed farther from the target vessel and tilted from the perpendicular plane. This is the first report demonstrating the relationship between the anatomical factors and the accuracy of the deployment of a stent-graft in TEVAR.

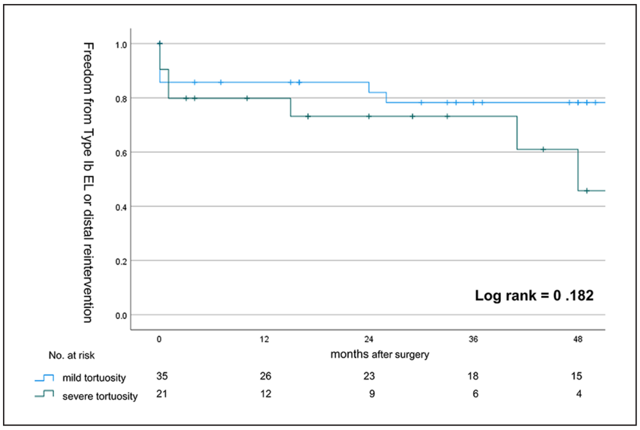

Figure 3. Kaplan-Meier curves of freedom from type Ib endoleak or distal extension. The log-rank test revealed no significant difference between patients with mild and severe tortuosity. EL, endoleak.

TEVAR is a widely performed, less-invasive durable treatment option for repairing the descending thoracic aorta.[5,6] Furthermore, intentional coverage of the celiac artery enables to expand the indication for paradiaphragmatic TEVAR.[7] We reported that celiac artery coverage allowed a 20 mm extension in the length of the distal seal.[8] These cases with the distally deployed stent-graft also require extreme accuracy in the deployment. Although the importance of aortic morphology has been described in several articles, most of them focus on the proximal landing zone, ie, the length of the landing zone, the diameter, and the tortuosity of the aortic arch.[1–3,9,10] Only a few studies focused on the distal aortic morphology and the distal landing zone.[11,12]

Ueda et al[13] reported on the relationship between aortic tortuosity and endoleak. They used a computer-based curvature analysis, calculated the tortuosity index for each section of the aorta, and concluded that the cohort with an endoleak had a higher tortuosity index of the aorta. In a similar study, Nakatamari et al[11] reported a discriminant analysis predicting endoleak using the same tortuosity index. However, it is difficult to apply these computational methods to clinical cases because their technical complexities require mathematical calculations. However, a systematic review about type Ib endoleak, performed by Belvroy et al,[14] concluded that the tortuosity index relates negatively to the type Ib endoleak, and the aforementioned article by Nakatamari et al[11] was cited as evidence.

DuBois et al[15] proposed a "compromised distal landing zone," characterized by large diameter, cross-sectional thrombus, mural calcification, and greater tortuosity index. Accordingly, aortic tortuosity has been reported as one of the risk factors that worsen clinical outcomes. However, few studies have discussed the effect of aortic tortuosity on the accuracy of the deployment. Berezowski et al[16] performed *in vitro* deployment experiments on 3D-printed models of a "straight aorta" with insignificant aortic tortuosity and a "crooked aorta" with significant aortic tortuosity, which was based on the ratio of the incremental curve length of the centerline to the linear distance; the authors concluded that the distal aortic tortuosity forms an important impediment while covering the distal landing zone's entire circumference with a stent-graft. In a subsequent article, the authors found that the cohort with inaccurate distal landing was more likely to have a type Ib endoleak.[12]

In this study, we assessed the section at 150 mm above the target vessel, considering the length of commonly used stent-grafts. We also assessed the C/S ratio and the G/S ratio, considering that stent-grafts are deployed along the greater curvatures. The fact that the G/S ratio in the 150 mm section was significantly different between the 2 groups (malpositioned stent-graft and that with accurately landing grafts) suggests the importance of considering not only the centerline but also the greater curve when examining the preoperative CT. The G/S ratio is a relatively simple variable and is available on most 3D workstations without complicated calculations.

We also examined the relationship between inaccuracy in deployment and other variables. In cases where the target vessel and bending point were close to each other, we presumed worse outcomes due to the difficulty in adjustment during distal deployment. However, there was no significant difference. Unlike previous reports, there was no significant difference in devices and proximal landing when using another stent-graft.[16] The frequency of hypertension and dyslipidemia was significantly higher in the malposition group inexplicably.

Focusing on tortuosity, which is the only variable related to the accuracy of deployment, we also conducted a comparative study by categorizing the patients into severe tortuosity and mild tortuosity groups. We observed that the stent-graft was located significantly farther from the target vessel and tilted in the severe tortuosity group, suggesting that the extent of tortuosity hampered the accurate deployment of the stent-graft. The G/S ratio is an effective index to predict the difficulty of accurate deployment. The mid-to-long-term clinical outcomes, such as type Ib endoleak and reintervention to the distal section, did not differ significantly. In this study, the patients after the initial surgery have only a short distance for extension in the distal segment. Although it is not staticsally significant, reintervention with the distal extension, combined with other outcomes, tended to have a higher frequency in the severe tortuosity group. Therefore, it can be deduced that inaccurate landing causes insufficient sealing and increases the risk of worse outcomes. Further studies involving more patients are needed.

There were certain limitations to this study. First, this was a single-center retrospective study that included a small number of patients. Second, multiple surgeons performed the surgery, which may have resulted in technical differences that affected the operative outcomes. Furthermore, there may be device-related differences as a variety of stent-grafts were implanted.

Conclusion

The G/S ratio was the only anatomical variable that related to the malposition of the stent-graft, and severe tortuosity of the descending aorta may serve as an important predicting factor for inaccurate distal deployment.

Declaration of Conflicting Interests

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