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ORIGINAL ARTICLE

Aortic morphometry at endograft position as assessed by 3D image analysis affects risk of type I endoleak formation after TEVAR

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Abstract
Purpose The purpose of this study was to identify morphologic factors affecting type I endoleak formation and bird-beak configuration after thoracic endovascular aortic repair (TEVAR).
Methods Computed tomography (CT) data of 57 patients (40 males; median age, 66 years) undergoing TEVAR for thoracic aortic aneurysm (34 TAA, 19 TAAA) or penetrating aortic ulcer (n=4) between 2001 and 2010 were retrospectively reviewed. In 28 patients, the Gore TAG® stent-graft was used, followed by the Medtronic Valiant® in 16 cases, the Medtronic Talent® in 8, and the Cook Zenith® in 5 cases. Proximal landing zone (PLZ) was in zone 1 in 13, zone 2 in 13, zone 3 in 23, and zone 4 in 8 patients. In 14 patients (25 %), the procedure was urgent or emergent. In each case, pre- and postoperative CT angiography was analyzed using a dedicated image processing workstation and complimentary in-house developed software based on a 3D cylindrical intensity model to calculate aortic arch angulation and conicity of the landing zones (LZ).
Results Primary type Ia endoleak rate was 12 % (7/57) and subsequent re-intervention rate was 86 % (6/7). Left subclavian artery (LSA) coverage (p=0.036) and conicity of the PLZ (5.9 vs. 2.6 mm; p=0.016) were significantly associated with an increased type Ia endoleak rate. Bird-beak configuration was observed in 16 patients (28 %) and was associated with a smaller radius of the aortic arch curvature (42 vs. 65 mm; p=0.049). Type Ia endoleak was not associated with a bird-beak configuration (p=0.388). Primary type Ib endoleak rate was 7 % (4/57) and subsequent re-intervention rate was 100 %. Conicity of the distal LZ was associated with an increased type Ib endoleak rate (8.3 vs. 2.6 mm; p=0.038).
Conclusions CT-based 3D aortic morphometry helps to identify risk factors of type I endoleak formation and bird-beak configuration during TEVAR. These factors were LSA coverage and conicity within the landing zones for type I endoleak formation and steep aortic angulation for bird-beak configuration.

Keywords Aortic morphometry · Type I endoleak · TEVAR · Risk · Bird beak

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Thoracic endovascular aortic repair (TEVAR) has been shown to reduce perioperative mortality and morbidity compared to open surgical repair of the thoracic aorta [1–3]. Other than in open surgery, prerequisite for technical and clinical success in TEVAR is adequate proximal and distal fixation of the stent-grafts. Especially in pathologies involving the aortic arch, adequate stent-graft fixation can be very challenging since there is a number of anatomic factors, such as the presence of side branches, that can lead to an incomplete apposition of the stent-graft to the aortic wall, called "bird-beak" configuration and to endoleak formation [4–7]. Endoleaks, especially those occurring at the proximal (PLZ) or distal landing zone (DLZ), are the "Achilles heel" of TEVAR since they are often difficult to predict and often result in re-interventions or even treatment failure [4–7]. 3D quantification of the aortic arch morphology can be very helpful for preoperative planning in challenging TEVAR cases. The purpose of this study was to assess whether geometric parameters, such as aortic arch angulation and conicity within the landing zones, derived from 3D image analysis determine the risk of bird-beak configuration, type I endoleak formation, and thus technical failure of TEVAR.

Methods

Study population

This is a retrospective study of patients who underwent TEVAR for thoracic aneurysm disease (thoracic or thoracoabdominal aortic aneurysm, TAA or TAAA) or penetrating aortic ulcer (PAU) between 2001 and 2010. Patients undergoing TEVAR for dissection, intramural hematoma, traumatic aortic transection, etc., were excluded from this analysis for reasons of homogeneity of the study population in terms of aortic arch geometry and because of differing mechanisms of endoleak formation between dissections and aneurysms [5, 6].

Further inclusion criteria for this analysis were availability of preoperative and postoperative computed tomography angiography (CTA) with slice thicknesses smaller than 2 mm. A technical exclusion criterion was given by unsuccessful image analysis in few cases, e.g., due to insufficient image contrast.

Fifty-seven patients (40 males) met the above criteria and were included in this analysis. Patients had a median age of 66 years (range, 40–86 years) at presentation. Vascular pathologies included 34 TAA, 19 TAAA, and 4 PAU (Table 1). Maximum diameters of the aortic pathologies were at median 66.5 mm (range, 45–98.98 mm).

Demographic, procedural, and outcome data of these patients were collected prospectively in a dedicated TEVAR database. In 28 cases, the Gore TAG® stent-graft device was implanted, followed by the Medtronic Valiant® in 16 cases, the Medtronic Talent® in 8, and the Cook Zenith® in 5 patients.

Landing zones and LSA revascularization

For elective cases (n=43), a PLZ of ≥20 mm length was required. In emergent cases (n=14), however, a ≥15 mm proximal "neck" was accepted. The PLZ were categorized according to the reporting standards for thoracic endovascular aortic repair [8]. There were no patients in this series with proximal fixation in zone 0. Patients requiring zone 1 deployment (n=13) underwent right-to-left carotid-carotid bypass procedures using an 8-mm Dacron graft.

Table 1 Patient demographics, pathology, and procedural details (n=57)

Age	Median (range)	66 (40–86)
Gender	Male/female	40:17
Aortic pathology	TAA	34 (60 %)
	TAAA	19 (33 %)
	PAU	4 (7 %)
Diameter of pathology	Median (range)	66.5 (45–98.8)
Urgency	Elective	43 (75 %)
	Urgent/emergent	14 (25 %)
Ishimaru zone	0	0
	1	13 (23 %)
	2	13 (23 %)
	3	23 (40 %)
	4	8 (14 %)
AICA/rapid pacing		49 (86 %)
Stent-grafts	Gore TAG®	28 (49 %)
	Medtronic Valiant®	16 (28 %)
	Medtronic Talent®	8 (14 %)
	Cook Zenith®	5 (9 %)
Length of covered aorta (mm)	Median (range)	213 (82–322)

TAA thoracic aortic aneurysm, *TAAA* thoracoabdominal aortic aneurysm, *PAU* penetrating aortic ulcer, *AICA* adenosine-induced cardiac arrest

In 13 patients, proximal fixation was in zone 2. Indications for primary left subclavian artery (LSA) revascularization included long-segment aortic coverage and prior or concomitant infrarenal aortic replacement [9]. In addition, a hypoplastic right vertebral artery, a patent left internal mammary artery graft, and a functioning dialysis fistula in the left arm were also indications to perform primary revascularization. Debranching procedures and TEVAR were performed in two stages in elective cases.

Twenty-three patients required proximal stent-graft fixation in zone 3 and eight patients in zone 4. The distal landing zone was zone 4 in 19 patients, zone 5 in 32 patients, zone 6 in 1 patient, and zone 9 in 5 patients. Patients with zone 9 fixation underwent prior retrograde visceral artery debranching.

Oversizing of the endoprothesis was intended to be 10–20 %. Adenosine-induced cardiac arrest (AICA) and since March 2009 rapid pacing were used for exact stent-graft placement in zones 1–3.

Computer aided measurements

Pre- and postoperative CTA were analyzed using a dedicated image processing workstation (Aquarius Intuition v4.4, TeraRecon, CA, USA) [10].

Beginning with the postoperative CTA, the distance between the proximal covered end of the stent-graft and the ostium of the LSA as well as the distance between the distal covered end of the stent-graft and the ostium of the coeliac trunk (TRC) were measured along the centerline of the aorta (Fig. 1a). These positions were used to determine measurement positions for analysis of preoperative CTAs. Whatever anchorage zone, absolute value of length is taken into account. If the proximal end of the endograft appeared not to be orthogonal to the aortic lumen, mean distance between proximal markers was chosen.

To quantify aortic conicity within the LZ, the maximal aortic lumen diameter at six positions was defined: at the postoperative position of proximal/distal stent-graft marker (transposed from the postoperative to the preoperative dataset) and 1 cm proximal as well as 1 cm distal to the future position of the respective markers (Fig. 1b).

In this order, the conicity of the aorta at the PLZ and DLZ, each with the corresponding oversizing of stent-graft in relation to the aortic diameter at PLZ/DLZ, was measured. Furthermore, proximal apposition of the stent-graft in the inner curve of the aortic arch was documented focusing on the presence of a bird-beak configuration (Fig. 2).

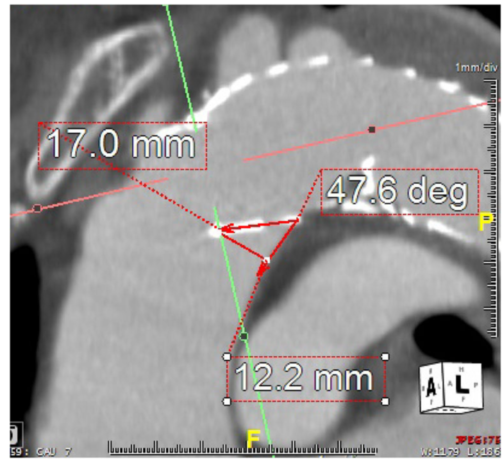

Fig. 2 Bird-beak configuration of the proximal end of the stent-graft. Incomplete apposition of the proximal end of the stent-graft to the inner curve of the aortic arch (distance to the inner curve, 12 mm; protruding edge, 17 mm; angle of the bird-beak, 47°)

3D cylindrical intensity model

To analyze the aortic arch curvature and its correlation to complications such as endoleaks, an in-house developed three-dimensional (3D) model-based approach was used [11, 12]. In this automatic approach, a 3D cylindrical intensity model is utilized that represents the intensity profile of an ideal 3D-cylinder,

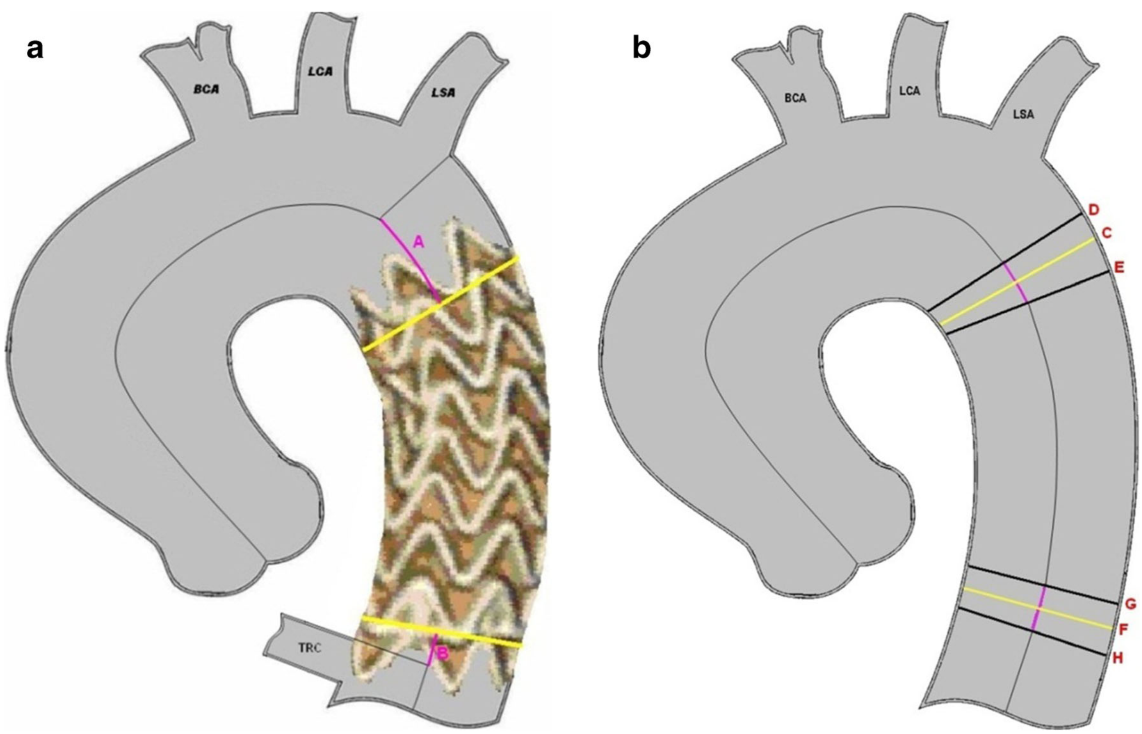

Fig. 1 **a** Distance measurements between the proximal end of the stent-graft and the ostium of the left subclavian artery (LSA) (*A*), as well as between the distal end of the stent-graft and the ostium of the coeliac trunk (TRC) (*B*) based on the first postoperative CT angiography. *BCA* brachiocephalic artery, *LCA* left carotid artery. **b** The maximal aortic lumen diameter at six positions was defined: at the postoperative position of proximal (*C*)/distal (*F*) stent-graft marker (transposed from the postoperative to the preoperative dataset) and 1 cm proximal (*D*/*G*) as well as 1 cm distal (*E*/*H*) to the future position of the respective markers

which is smoothed by a 3D Gaussian function to model the image blur that is generated during CT imaging. The model is directly fitted to the 3D image data through an incremental process based on a Kalman filter [11]. As a result, we obtain the 3D centerline positions and 3D contour of a vessel as well as local vessel diameters along the centerline (Fig. 3). Moreover, the centerline of the vessel was investigated with regard to its bending in 3D space. To quantify the local curvature of the centerline at a particular position of the aorta, we fit cubic polynomials to the 3D centerline within a certain range (in our case ±30 mm with a spacing of 1 mm, see Fig. 3). The local centerline curvature is analytically computed using first- and second-order partial derivatives of the fitted polynomials [12], and the radius of curvature is given by the inverse of the curvature. In this study, we determined the radius of aortic arch curvature at the position of the proximal stent-graft marker. This model-based approach has been validated before using phantom models [11, 12].

Definitions and statistics

Endoleaks were categorized as previously described by White et al. [13]. An endoleak occurring at the PLZ is classified as type Ia, while an endoleak at the DLZ is an Ib endoleak. Primary endoleaks were defined as apparent on intraoperative control angiography or primary postoperative CTA control (≤30 days) [8].

Bird-beak configuration is defined as a lack of apposition of the proximal stent-graft to aortic wall along the lesser curve [5].

Conicity within the landing zones was defined as the difference of the maximum aortic diameter 1 cm proximal and 1 cm distal to the postoperative position of proximal/distal stent-graft marker (transposed from the postoperative to the preoperative dataset).

Statistical analysis was performed with SigmaPlot 12.5 (Systat Software, Inc.). For statistical evaluation, Fisher's exact test and the non-parametric Mann-Whitney U test (rank sum test) were used. Two-sided p values were computed, and a difference was considered statistically significant at $p \leq 0.05$. Values are expressed as mean±standard deviation.

Primary endpoints of this study were the incidence of primary type Ia and Ib endoleaks, and secondary endpoint was the incidence of bird-beak configuration.

Results

Analysis of CTA data was successful for all 57 patients.

Endoleak type Ia

The incidence of primary type Ia endoleak was 12 % (7/57) (Table 2).

Conicity of the PLZ in patients with a type Ia endoleak (5.9 mm) was stronger compared to patients without type Ia endoleak (2.6 mm; $p=0.016$).

In six of the seven patients (85.7 %) with an endoleak type Ia, the LSA was overstented. This was the case in 34 % of the patients without type Ia endoleak ($n=50$) ($p=0.036$). Distance between proximal stent-graft marker and LSA origin was 17 mm in patients with LSA coverage and type Ia endoleak ($n=6$) and 25 mm in patients with LSA coverage without type Ia endoleak ($n=17$) ($p=0.151$).

The mean oversizing at the position of the proximal stent-graft marker was 4.7 % in the patients with type Ia endoleak ($n=7$), half than the 9.7 % in the patients without endoleak ($p=0.402$). Maximum aortic diameter at the position of the

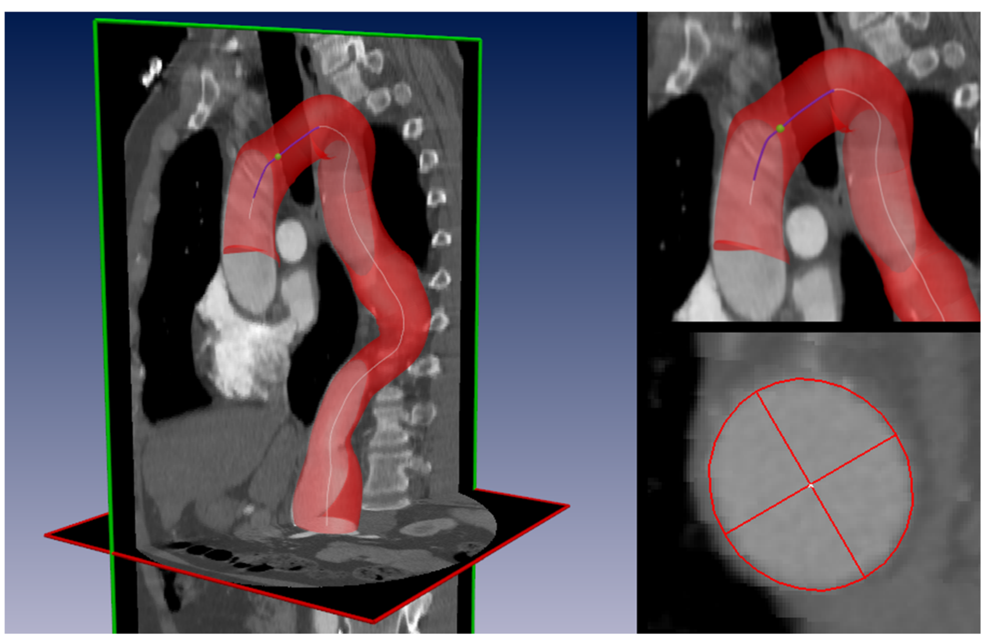

Fig. 3 3D model-based segmentation result of the aorta with two orthogonal 2D sections of the original preoperative CTA data set (*left*), an enlargement of the aortic arch (*top right*), and a 2D orthogonal section with local diameters (*bottom right*): shown are the 3D contour (*red*), 3D centerline (*white*), transferred centerline position of the proximal stent-graft marker from the postoperative image (*green*), as well as the centerline range (*blue*, ±30 mm) used for computing the curvature of the aorta at the position of the proximal stent-graft marker

Table 2 Aortic geometry and endoleaks/bird-beak configuration

Variable	No. or mean	Median (min-max)	p
Endoleak type Ia	7/57 (12 %)		
Conicity of PLZ			
Type Ia endoleak	5.9 mm	4.9 mm (0.7–12.8)	0.016
No endoleak	2.6 mm	2.1 mm (0.1–14.2)	
LSA coverage			
Type Ia endoleak	6/7 (85.7 %)	n.a.	0.036
No endoleak	17/50 (34 %)		
Stent-graft oversizing			
Type Ia endoleak	4.7 %	4.2 %	0.402
No endoleak	9.7 %	10.1 %	
Radius of aortic curvature			
Type Ia endoleak	54.1 mm	51.9 mm (31.7–95.6)	0.554
No endoleak	59.6 mm	44.2 mm (16.3–261.3)	
Endoleak type Ib	4/57 (7 %)		
Conicity of DLZ			
Type Ib endoleak	8.3 mm	8.15 mm (5.2–8.2)	0.006
No endoleak	2.6 mm	2.0 mm (0.0–7.9)	
Stent-graft oversizing			
Type Ib endoleak	0.2 %	4.0 %	0.014
No endoleak	20.1 %	16.4 %	
Bird-beak configuration	16/57 (28 %)		
Radius of aortic curvature			
Bird-beak	41.5 mm	40.8 mm (16.3–95.6)	0.049
No bird-beak	65.5 mm	46.2 mm (21.4–261.3)	
Distance to LSA			
Bird-beak	13.3 mm	9.0 mm (1.2–39.8)	0.036
No bird-beak	49.6 mm	36.5 mm (1.3–167.0)	
Stent-graft oversizing			
Bird-beak	6.9 %	9.6 %	0.729
No bird-beak	10.0 %	9.4 %	

PLZ proximal landing zone, *DLZ* distal landing zone, *LSA* left subclavian artery, *n.a.* not applicable

proximal marker was on average 38.1±11.3 mm in patients with an endoleak type Ia, higher than in patients without endoleak (32.7±6.7 mm) (p=0.096).

In patients with type Ia endoleak, the average radius of curvature was 54.1±20.8 mm vs. 59.6±47.2 mm in patients without endoleak (p=0.554).

Six of the seven patients (85.7 %) with endoleak type Ia underwent re-intervention during follow-up, while in patients without endoleak, the mean re-intervention rate was 24 % (n=12) (p=0.003).

Endoleak type Ib

Primary type Ib endoleak rate was 7 % (4/57) in this series (Table 2).

Conicity of the DLZ was stronger in the patients with type Ib endoleak (8.3 mm) than in the patients without endoleak (2.6 mm; p=0.006).

In patients with type Ib endoleak, mean oversizing was 0.2 % compared to 20.1 % oversizing in patients without endoleak (p=0.014). Mean maximum aortic diameter at the DLZ was 35.9±7.0 mm in patients with type Ib endoleak vs. 29.9±6.2 mm in patients without endoleak (p=0.038).

All four patients with an endoleak type Ib received re-intervention and endoleak seal during follow-up.

Bird-beak configuration

Sixteen of the fifty-seven patients (28 %) presented a bird-beak configuration after TEVAR (Table 2). No stent-graft collapse was observed.

Among the 16 patients with a bird-beak configuration, three patients (18.8 %) were found with primary type Ia endoleak, 9.8 % in patients without bird-beak (p=0.388).

Mean radius of aortic arch curvature at position of proximal stent-graft marker was 41.5±19.4 mm among patients with a bird-beak configuration (at median 40.8 mm). In patients without bird-beak (n=41), aortic radius of curvature was 65.5±49.6 mm (at median 46.2 mm) (p=0.049).

Mean distance from the proximal stent-graft marker to the LSA was 13.3±12.6 mm in patients with bird-beak configuration (median distance 9.0 mm) vs. 49.6±43.0 mm in patients without bird-beak (median distance 36.5 mm) (p=0.036).

Mean stent-graft oversizing was 6.9 % in patients with bird-beak vs. 10.0 % in patients without bird-beak (p=0.729).

Discussion

Our results highlight different morphological aspects that can result in technical failure of TEVAR. Technical success is defined as successful deployment of the endograft with secure proximal and distal fixation and with absence of either a type I or III endoleak [8].

In the literature, there are numerous factors associated with an increased risk of primary type Ia endoleak formation. An incomplete apposition of the proximal end of the stent-graft at the inner curve of the aortic arch, a so-called bird-beak configuration, is reported to be one of them and was associated with an increased risk for a proximal type I endoleak also in this series without reaching statistical significance though [5, 14, 15]. A bird-beak sign of the stent-graft is more often observed in patients with aortic pathology requiring proximal fixation in zones 2 and 3 and also in patients with a steep aortic arch, such as trauma patients [16]. But even in aneurysm patients, as seen in this analysis, the radius of the aortic arch can strongly vary, and so, we observed a significant correlation between a smaller radius/steeper aortic arch and the presence of a bird-beak sign in these patients. Such patients benefit from stent-grafts that are designed to conform to the aortic arch, such as the Gore Conformable TAG Endoprosthesis and the Zenith Pro-Form TX2 and so more seldom show a bird-beak sign [17, 18].

Furthermore, due to aortic arch angulation, anchoring in zone 2 can result in an improper apposition of the proximal endograft within the ostium of the LSA and lead to proximal type I, type II, or even combined types I and II endoleaks [19]. As reported before, proximal type I endoleaks were significantly associated with LSA coverage [6]. Also, in this analysis, LSA coverage was significantly associated with bird-beak configuration and type Ia endoleak. Next-generation devices with a side branch for the LSA, like the Valiant Mona LSA, specially tailored for zone 2 anchorage could provide a more adequate seal in this challenging location and are currently under clinical investigation.

A third morphological factor, besides angulation and the presence of side branches like the LSA, that can influence technical success of TEVAR, is the conicity/tapering of the LZ [16]. As seen in this analysis, distinct conicity within the LZ was predictive of the presence of postoperative type Ia+b endoleaks. Moreover, patients showing primary proximal and distal type I endoleaks were found to have significantly less oversizing of their stent-grafts. Thus, in cases with distinct tapering of the LZ, adequate oversizing of at least 15 % seems crucial in order to prevent endoleaks. On the other hand, excessive oversizing, with or without bird-beak sign, can lead to stent-graft infolding or collapse [20]. Careful selection of device sizes is essential and can be challenging, especially in long-segment pathologies. In addition, a more comprehensive preoperative planning regarding nature and dimensions of the LZ as described above can be very helpful, and stent-grafts that accommodate a wide range of aortic diameters are beneficial in this regard.

This study has several limitations. First, although the key results achieved significance, the number of subjects in each group was relatively small. Furthermore, the study included patients that were treated with different devices. The risk of endoleak formation may be different for each device since differences in device designs result in different shapes and degrees of apposition and sealing. Third, the measured endograft positions may not completely match the deployment location due to potential vessel deformity.

Conclusions

In conclusion, CTA-based aortic morphometry helps to identify risk factors of type I endoleak formation and bird-beak configuration prior TEVAR. These factors are LSA coverage and conicity within the landing zones for type I endoleak formation and steep aortic angulation for bird-beak configuration. These factors should be especially appreciated during patient and stent-graft selection as well as procedure planning.

Conflicts of interest None.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. For this type of study, formal consent is not required.

Informed consent Informed consent was obtained from all individual participants included in the study.

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