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Remodeling of Abdominal Aortic Angulation and Curvature After Endovascular Aneurysm Repair in Patients With vs Without Late Type Ia Endoleak or Endograft Migration

Richte C. L. Schuurmann, PhD[1], Rogier Kropman, MD, PhD[2], Kenneth Ouriel, MD[3], William D. Jordan Jr, MD[4], Bart E. Muhs, MD, PhD[5], Yannick 't Mannetje, MD, PhD[6], Michel M. P. J. Reijnen, MD, PhD[7], Bram Fioole, MD, PhD[8], Çağdaş Ünlü, MD, PhD[9], Peter Brummel, MD[10], and Jean-Paul P. M. de Vries, MD, PhD[1]

Abstract

Purpose: To investigate aortic remodeling of the supra- and infrarenal aorta from preoperative to 1 month and midterm follow-up after endovascular aneurysm repair (EVAR) by analyzing changes in angulation and curvature in patients with vs without late type Ia endoleak or device migration. **Materials and Methods:** From a multicenter database, 35 patients (mean age 76±5 years; 31 men) were identified with late (>1 year) type Ia endoleak or endograft migration (≥10 mm) and defined as the complication group. The control group consisted of 53 patients (mean age 75±7 years; 48 men) with >1-year computed tomography angiography (CTA) follow-up and no evidence of endoleaks. Suprarenal and infrarenal angles were measured on centerline reconstructions of the preoperative, 1-month, and midterm CTA scans. The value and location relative to baseline of maximum suprarenal and infrarenal curvature were determined semiautomatically using dedicated software. Changes were determined at 1 month compared with the preoperative CTA and at midterm compared with 1 month. **Results:** Preoperative suprarenal angulation was significantly greater in the complication group compared to the controls (34°±18° vs 24°±17°, p=0.008). It decreased significantly at 1 month in the complication group (29°±16°, p=0.011) and at midterm follow-up in the controls (20°±19°, p<0.001). Preoperative infrarenal angulation was not significantly different (57°±15° vs 49°±24°, p=0.114). This measurement increased significantly through midterm follow-up in the complication group (63°±23°, p<0.001) but remained stable in the controls (46°±22°). Preoperative suprarenal curvature was not significantly different (38±22 m^{-1} vs 29±25 m^{-1}, p=0.115). This variable increased significantly through midterm follow-up in the complication group (44±22 m^{-1}) but remained constant in the controls (28±22 m^{-1}). Preoperative infrarenal curvature was significantly greater in the complication group (77±29 m^{-1} vs 65±28 m^{-1}, p=0.047) and decreased significantly in both groups during midterm follow-up (50±17 m^{-1} vs 41±19 m^{-1} p=0.033). The location of the maximum curvature with regard to baseline shifted significantly distally in the complication group (54±43 to 72±41 mm, p<0.001), while it remained stable in the controls (46±33 to 48±31 mm). **Conclusion:** At midterm follow-up, significant differences in supra- and infrarenal angulation and curvature were observed between patients with vs without type Ia endoleak or migration. The location of the maximum curvature shifted distally in patients with complications. The aortic morphology is more stable during midterm follow-up in the patients without endoleaks.

Keywords

abdominal aortic aneurysm, angulation, curvature, endograft, endoleak, endovascular aneurysm repair, migration, morphology, stent-graft

Introduction

Endovascular aneurysm repair (EVAR) is the preferred option for treatment of patients with an infrarenal abdominal aortic aneurysm (AAA). Endograft deployment in challenging aortic anatomy may increase the risk for endograft-related complications, such as type Ia endoleak and device migration.[1–4] Implantation of a noncompliant endograft in an aorta may stretch the anatomy, which can induce tension on the endograft in the proximal and distal seal zones.[5]

Traditionally, bending of the juxtarenal aorta is defined by angulation (Figure 1A). This variable is commonly used in the literature to describe the aortic geometry and is included in the indications for use of commercially available endografts. Angulation, however, simplifies the complex 3-dimensional (3D) anatomy by triangulation and does not incorporate the multiple forces on the aortic geometry. Aortic curvature, which is the inverse of the radius of a circle that fits over the centerline at a certain location, can be calculated mathematically over the entire aortic trajectory (Figure 1B). The location of the maximum curvature relative to the baseline, which is defined as the lower border of the origin of the lowest renal artery, is determined mathematically. Aortic curvature has been described in previous publications and has been associated with intraoperative as well as late type Ia endoleak and endograft migration (≥10 mm).[3,6,7]

The capacity of the endograft main body to adapt to the geometry of the aorta is the result of the material properties of the implanted endograft and the elasticity of the aorta. Both the endograft and the aortic wall bend relative to the material's resistance to the applied lateral force and end up in equilibrium as long as the materials are in an elastic state. The lateral forces of the stent on the aorta increase in aortas with larger curvature, so the hypothesis is that aortic straightening can occur in angulated aortas after endograft implantation. This can induce morphologic remodeling of the aorta, which has also been observed in previous studies.[8–10] The aortic curves proximal and distal of the main body of the endograft may also increase to compensate for local straightening. Because of the changing and increased forces, these patients may be at increased risk for device migration and subsequent type Ia endoleak.

This study describes aortic remodeling of the supra- and infrarenal aorta from preoperative to 1 month and midterm follow-up after EVAR by analyzing changes in angulation and curvature in patients with vs without late type Ia endoleak or device migration.

Materials and Methods

Study Protocol

This is a multicenter, retrospective, observational, anatomy-based study of remodeling of the supra- and infrarenal aorta. Experienced observers who followed a predefined protocol made diameter and angle measurements on computed tomography angiography (CTA) scans using a 3mensio vascular workstation (version 10.0; Pie Medical Imaging BV, Maastricht, the Netherlands). Interobserver variability of the measurements has been assessed in a previous publication.[11] Neck diameter measurements were measured with 0.0-mm precision (1.96 times the standard deviation of 0.9 mm) and neck length with 0.6-mm precision (1.96 times the standard deviation of 8.0 mm). Investigational review board approval was obtained with exemption from patient consent for review of deidentified CT datasets.

Measurements included semiautomatic construction of a single centerline through the mid-lumen of the aorta from the level of the celiac trunk to the aortic bifurcation. On the postoperative CT scans, the centerline followed the center of the flow lumen of the endograft main body. The centerline was drawn between both endograft limbs distal to the flow divider.

Suprarenal angulation was measured on the centerline as the angle between the flow direction in the suprarenal aorta and the aortic neck. Infrarenal angulation was measured as the angle between the flow direction in the aortic neck and the aneurysm sac. This method has also been

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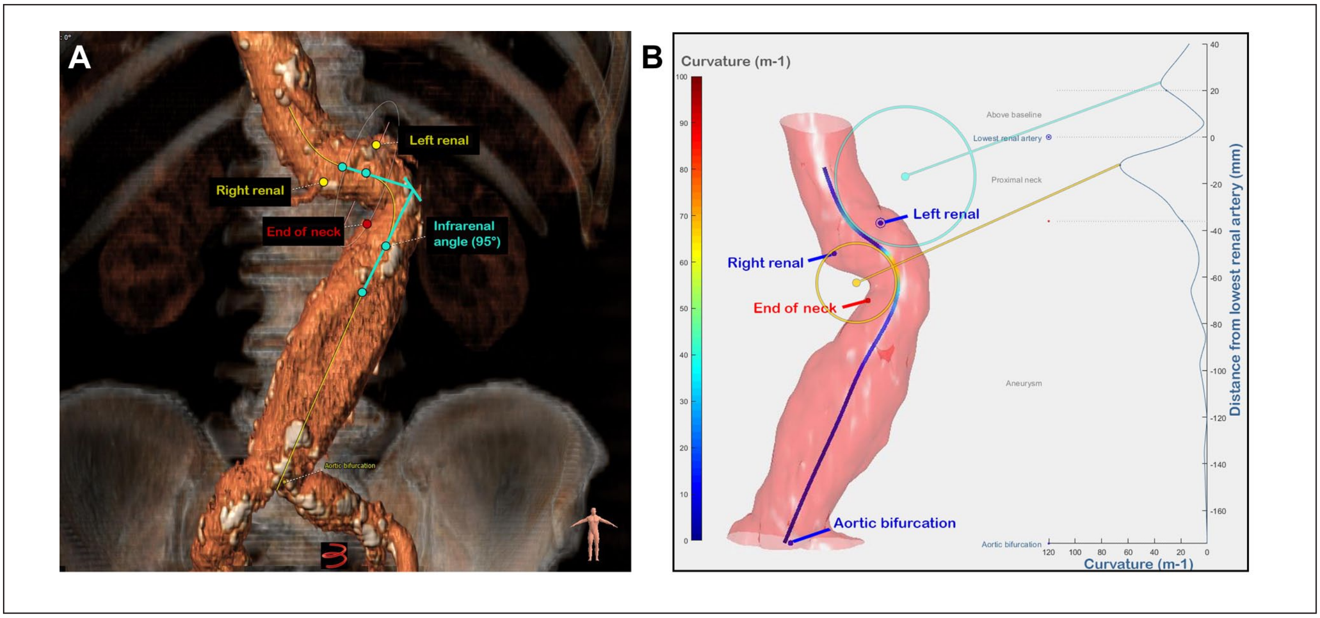

Figure 1. Preoperative anatomy shown on a computed tomography angiography reconstruction from a patient scheduled for elective endovascular aneurysm repair. (A) Infrarenal angulation by flow direction (95°), measured on the aortic centerline in a 3mensio vascular workstation. (B) Aortic curvature mathematically calculated over the aortic centerline. Maximum curvature is 68 m^{-1}, located in the aortic neck at 12 mm below the lowest renal artery (baseline).

described in previous publications.[6,12] Aortic curvature has been described and validated in a previous publication[6] and has been associated with increased risk of intraoperative type Ia endoleak and late (>1 year) type Ia endoleak and device migration (≥10 mm).[3,7]

The maximum suprarenal curvature is automatically calculated using Vascular Image Analysis Prototype software (Endovascular Diagnostics BV, Utrecht, the Netherlands) over the trajectory 0 to 5 cm proximal of the lowest renal artery (baseline). Infrarenal curvature is defined over the entire trajectory of the infrarenal aorta. The units of curvature are inverse meters (m^{-1}). Curvature was calculated by numeric computation over the Cartesian coordinates of the centerline using Equation 1. The distance between the maximum infrarenal curvature and baseline were automatically defined by the software.

Aortic neck length was measured as the centerline length between the lowest renal artery baseline and the first slice that exceeded 10% of the baseline neck diameter. The preoperative aortic neck diameter was measured as the average of 2 orthogonal diameters from adventitia to adventitia. The aneurysm diameter was measured as the maximum of 2 orthogonal diameters over the length of the aneurysm sac.

$$\kappa = \frac{\sqrt{(z''y' - y''z')^2 + (x''z' - z''x')^2 + (y''x' - x''y')^2}}{(x'^2 + y'^2 + z'^2)^{3/2}} \qquad (1)$$

Study Population

The study population has previously been used to define the prognostic value for type Ia endoleak and device migration of preoperative anatomical characteristics, including curvature[3] and endograft apposition in the aortic neck.[13] Inclusion criteria were the elective treatment of an infrarenal aortic aneurysm and the availability of a preoperative CTA scan, an early postoperative CTA scan (within 100 days after the procedure), and a second postoperative CTA scan at least 12 months after the procedure. Exclusion criteria were the use of adjuncts for proximal fixation, such as cuffs, endoanchors, or chimney stent-grafts; deliberate low positioning of the endograft not directly under the lowest renal artery; devices without regular means of seal or fixation in the neck (including Ovation and Aorfix); and a type Ia, Ib, or III endoleak on the early postoperative (30-day) CTA scan.

The database of 150 elective EVAR patients from 3 high-volume EVAR centers [Yale School of Medicine (New Haven, CT, USA), University of Alabama, (Birmingham, AL, USA), and St Antonius Hospital (Nieuwegein, the Netherlands)] that was used as a matched control cohort for the Aortic Securement System Global Registry (ANCHOR; *ClinicalTrials.gov* identifier NCT01534819) was available for this study. Of these patients, 85 had a pre-EVAR CTA scan, a 30-day CTA scan, and a late postoperative CTA scan. Adjuncts for fixation, such as bare metal stents, extension cuffs, or chimney stent-grafts, were used in 8 patients. Five patients were excluded because the endograft was deliberately deployed lower than directly distal to the lowest renal artery. Eight patients were treated with devices having different means of fixation (6 Ovation and 2 Aorfix) and were excluded. Four patients who had a type Ia endoleak on the 30-day CT scan, 1 patient who had a type Ib endoleak, and 1 patient who had a type III endoleak were also excluded from the analysis. Of the 58 remaining patients, 3 had a late type Ia endoleak and 2 were diagnosed with endograft migration (>10 mm), leaving 53 patients (mean age 75±7 years; 48 men) without evidence of device-related complications during follow-up to serve as a control group.

Since events were rare in the population, the 5-patient complication group was enriched with 30 patients who underwent reintervention for type Ia endoleak (n=25) or migration (n=5) at 6 high-volume Dutch EVAR centers; only patients who met the selection criteria were selected. Thus, the complication group comprised 35 patients (mean age 76±5 years; 31 men) with late (>1 year) type Ia endoleak or endograft migration (≥10 mm).

The previously mentioned publication[3] describing the predictive value for type Ia endoleak and device migration of preoperative anatomical characteristics had 80 control patients, which included also those without midterm CTA follow-up.[3] Angulation was measured differently in the current study (flow-direction method) compared with the previous publication (fixed landmark method). The difference between these methods has been described in detail before.[6] With the fixed landmark method the angle is measured between fixed points on the centerline; a cranial or caudal shift of the angle would result in a change of the measured angulation, even if the maximum angle remains unchanged. The flow direction method better appreciates angles that are located between the landmarks and is therefore unaffected by a spatial shift of the angle. The flow direction method was better suited for a study such as this that compared angulation over time. The values in this manuscript may therefore deviate from the previously mentioned publication.[3]

Implanted endografts were Endurant (Medtronic Cardiovascular, Santa Rosa, CA, USA; n=45), Talent (Medtronic Cardiovascular; n=18), Zenith (Cook Medical, Bloomington, IN, USA; n=14), Excluder (W.L. Gore & Associates, Flagstaff, AZ, USA; n=9), AFX (Endologix, Inc, Irvine, CA, USA; n=1), and Powerlink (Endologix, Inc; n=1). The distribution of endografts between patients with vs without complications is provided in Table 1.

Table 1. Distribution of Endografts Between Patients With and Without Complications.[a]

Endograft	Type Ia Endoleak/Migration		Total
	No	Yes	
AFX	1 (2)	0 (0)	1 (1)
Endurant	32 (60)	13 (37)	45 (51)
Excluder	8 (15)	1 (3)	9 (10)
Powerlink	1 (2)	0 (0)	1 (1)
Talent	2 (4)	16 (46)	18 (20)
Zenith	9 (17)	5 (14)	14 (16)
Total	53	35	88

[a]Data are given as the number (percentage).

Outcomes and Statistics

The suprarenal and infrarenal angulation and curvature were measured on the preoperative CTA, 1-month CTA, and midterm CTA. Changes in suprarenal and infrarenal angulation and curvature were determined between the 1-month CTA and the preoperative CTA and between the midterm CTA and the 1-month CTA. The locations of the maximum supra- and infrarenal curvature relative to the lowest renal artery baseline were also compared between the 1-month CTA and the preoperative CTA and between the midterm CTA and the 1-month CTA. Differences in angulation, curvature, and location of the maximum curvature were assessed with the paired *t* test. The complication group was compared with the control group, and differences between the groups were assessed with the independent *t* test.

Normality of the data was tested with the Kolmogorov-Smirnov test and inspection of the Q-Q plots. Normally distributed data are presented as means ± standard deviation, while variables with skewed distributions are summarized as the median and interquartile range (IQR Q1, Q3). Repeated measures were used to assess aortic remodeling on the 1-month and midterm CTA scans. Separate lines are displayed for the complication and control groups with 95% confidence interval (CI). P values were considered significant when the 2-tailed α was <0.05. Statistical analysis was performed with SPSS software (version 25; IBM Corporation, Armonk, NY, USA).

Results

The preoperative CTA was acquired 1 month (IQR 0, 2) before the index procedure for both the control and complication groups (p=0.875). The first postoperative CTA was acquired 1 month (IQR 1, 1) post-EVAR for the control group and at 1 month (IQR 1, 2) for the complication group (p=0.138). The midterm CTA was made at 19 months (IQR 13, 31) for the control group, which was the last available CTA scan. In the complication group the midterm CTA was the last scan without evidence of complications (type Ia endoleak or device migration >10 mm). This scan was obtained 13 months (IQR 3, 25) post-implantation, which was significantly shorter than for the controls (p=0.030).

The mean preoperative neck diameters were similar, 23±4 mm for the control group and 25±3 mm for

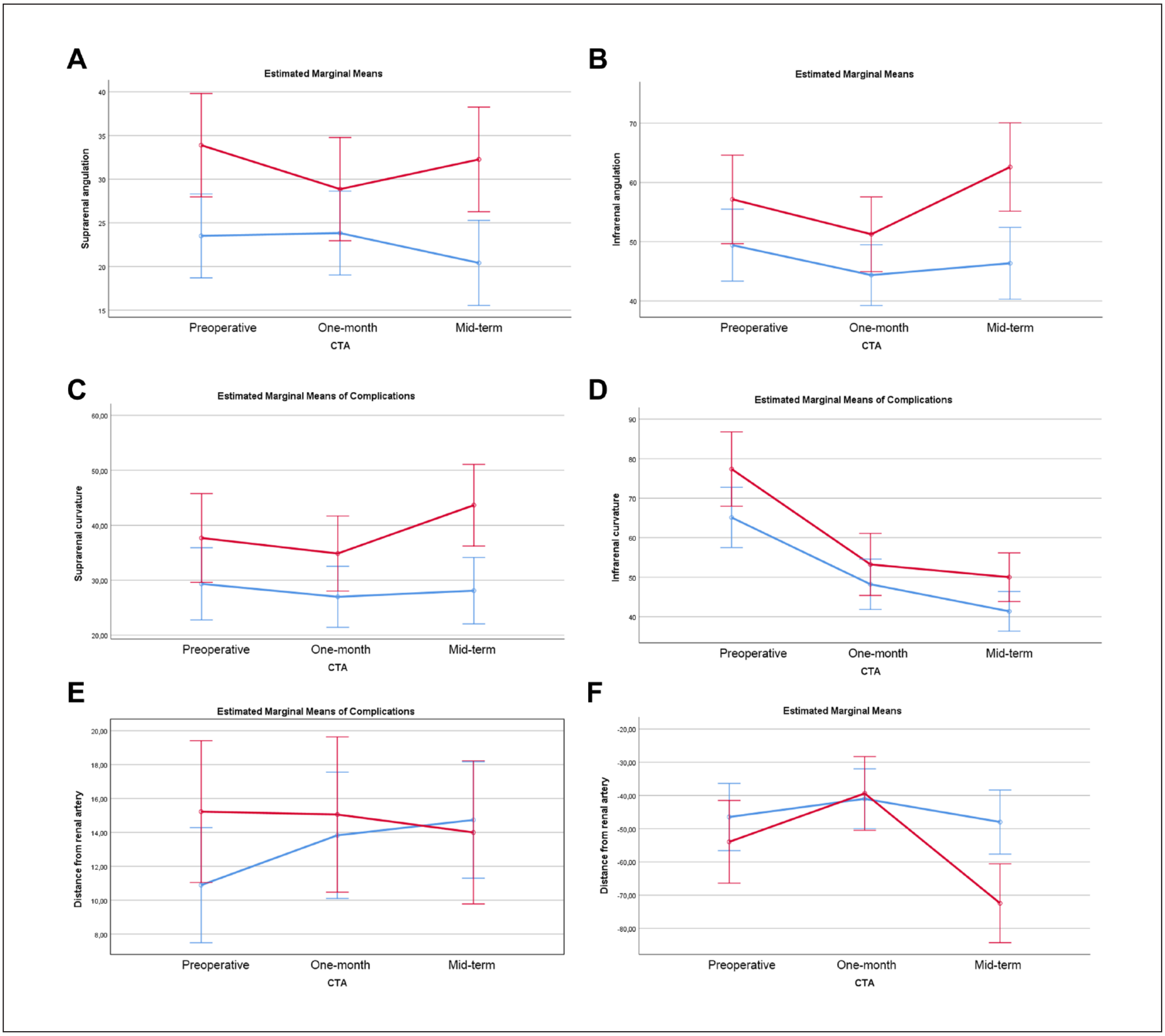

Figure 2. Repeated measures of angulation and maximum curvature for patients with type Ia endoleak or device migration (red) and controls (blue). (A) Suprarenal angulation, (B) infrarenal angulation, (C) maximum suprarenal curvature, (D) maximum infrarenal curvature, (E) distance between maximum suprarenal curvature and renal artery baseline, and (F) distance between maximum infrarenal curvature and renal artery baseline.

the complication group (p=0.059), while the neck lengths differed significantly (25±13 mm in the control group and 19±14 mm in the complication group, p=0.031). The preoperative aneurysm diameter was 54±9 mm for the control group and 64±12 mm for the complication group, which was significantly different ($p<0.001$).

Aortic Remodeling

Suprarenal and infrarenal angulation, measured as the change in flow direction, and curvature are displayed in Figure 2 and Table 2. In the complication group, the preoperative suprarenal angle was significantly larger compared to the controls (34°±18° vs 24°±17°, respectively; p=0.008). The infrarenal angle was not significantly larger (57°±19° vs 49°±24°, respectively; p=0.114). The preoperative suprarenal curvature was not significantly larger in the complication group compared with the controls (38±22 m^{-1} vs 29±25 m^{-1}, respectively; p=0.115). The preoperative infrarenal curvature was significantly larger in the complication group compared with the controls (77±29 m^{-1} vs 65±28 m^{-1}, respectively; p=0.047).

Table 2. Pre- and Post-EVAR Angulation and Maximum Curvature in the Type Ia Endoleak/Migration Patients (Complication Group) vs Controls.[a]

	Pre-EVAR CTA	p[b]	One-Month CTA	p[b]	p[c]	Midterm CTA	p[b]	p[d]
Suprarenal angle, deg	28±18		26±18			25±19		
Controls	24±17	0.008	24±18	0.192	0.874	20±19	0.003	<0.001
Complication group	34±18		29±16		0.011	32±16		0.070
Maximum suprarenal curvature, m^{-1}	33±24		30±21			34±23		
Controls	29±25	0.115	27±19	0.079	0.346	28±22	0.002	0.559
Complication group	38±22		35±22		0.561	44±22		0.037
Distance between maximum suprarenal curvature and baseline,[e] mm	13±13		14±14			14±13		
Controls	11±12	0.113	14±14	0.681	0.169	15±13	0.789	0.669
Complication group	15±12		15±13		0.937	14±11		0.689
Infrarenal angle, deg	52±22		47±19			53±23		
Controls	49±24	0.114	44±20	0.095	0.067	46±22	0.001	0.173
Complication group	57±19		51±18		0.013	63±23		<0.001
Maximum infrarenal curvature, m^{-1}	70±28		50±23			45±19		
Controls	65±28	0.047	48±23	0.327	<0.001	41±19	0.033	0.018
Complication group	77±29		53±23		<0.001	50±17		0.317
Distance between maximum infrarenal curvature and baseline,[e] mm	49±37		40±33			58±37		
Controls	46±33	0.357	41±35	0.821	0.251	48±31	0.002	0.122
Complication group	54±43		39±30		0.073	72±41		<0.001

Abbreviation: EVAR, endovascular aneurysm repair.
[a]Data are presented as the mean ± standard deviation.
[b]Difference between complication group and control group.
[c]Change in angulation/curvature compared to the pre-EVAR CTA scan.
[d]Change in angulation/curvature compared to the 1-month CTA scan.
[e]Centerline distance of the maximum curvature location from the lowest renal artery baseline.

The suprarenal angle did not change at 1 month in the control group (from 24°±17° to 24°±18°; p=0.874) but decreased significantly during midterm follow-up to 20°±19° (p<0.001). In the complication group the suprarenal angle did not change significantly during follow-up.

The infrarenal angle did not change significantly during follow-up in the control group. In the complication group, the infrarenal angle decreased significantly from 57°±19° to 51°±18° at 1-month follow-up (p=0.013). During midterm follow-up, the angle had increased again significantly to 63°±23° (p<0.001).

The suprarenal curvature did not change significantly during follow-up in the control group, and the location of the suprarenal curvature remained unchanged. In the complication group, the suprarenal curvature was stable at 1 month (from 38±22 m^{-1} to 35±22 m^{-1}, p=0.561) but increased significantly during midterm follow-up to 44±22 m^{-1} (p=0.037). The location of the suprarenal curvature did not change in the complication group (15±12, 15±13, and 14±11 mm measured from baseline).

The infrarenal curvature decreased significantly at 1 month in the control group from 70±28 m^{-1} to 50±23 m^{-1} (p<0.001) and continued to decrease during midterm follow-up to 41±19 m^{-1} (p=0.018). The location of the maximum curvature remained unchanged (46±33, 41±35, and 48±31 mm measured from baseline). In the complication group, the infrarenal curvature decreased significantly from 77±29 to 53±23 m^{-1} at 1 month (p<0.001). During midterm follow-up, the infrarenal curvature remained at 50±17 m^{-1} (p=0.317). The location of the maximum curvature relative to the lowest renal artery, however, shifted upward during the first month from 54±43 to 39±30 mm (p=0.073) but shifted downward to 72±41 mm during midterm follow-up (p<0.001).

The location of the preoperative maximum infrarenal curvature was in the aortic neck in 42% of the control patients and 37% of the patients with complications. This was within the length of the main body (<5 cm below baseline) in 57% of the control patients and 54% of the patients with complications. After endograft implantation, the maximum infrarenal curvature was located in the aortic neck in 60% and 54% and within the main body in 77% and 77% of the control and complication groups, respectively. During midterm follow-up, the maximum curvature was within the aortic neck in 34% and 23% and within the main body in 53% and 29% of the control and the complication groups, respectively.

The aortic remodeling is depicted in Figure 3 with the mean and 95% CIs for angulation and curvature in the

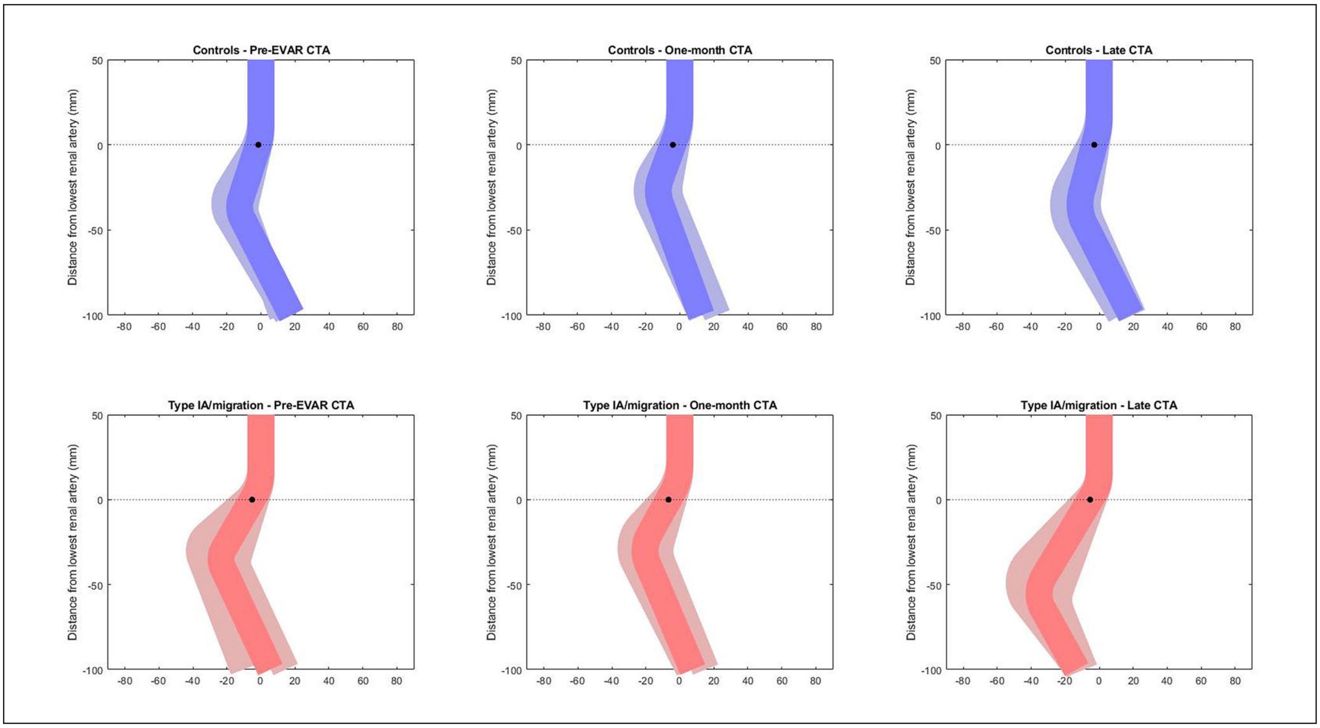

Figure 3. Projections of aortic remodeling for patients with type Ia endoleak or device migration (red) and controls (blue). The solid trajectory displays the mean values, whereas the light area covers the 95% confidence interval. The renal artery baseline is visualized by the black dot and the horizontal dotted line. The supra- and infrarenal angles are projected on the average location of the maximum curvature of each group. CTA, computed tomography angiography; EVAR, endovascular aneurysm repair.

complication and control groups. The aortic remodeling is depicted per endograft model in Figure 4. Nine patients were treated with a device without suprarenal fixation (Excluder). These patients had significantly smaller preoperative suprarenal angles compared to the patients treated with other devices (p=0.032). Therefore comparison of the suprarenal angle between patients with supra- and infrarenal fixation is not possible. Patients who were treated with a Zenith endograft had significantly greater decrease in infrarenal angulation after device implantation compared to the other devices ($-15° \pm 17°$ vs $-4° \pm 17°$, respectively; p=0.032). Curvature decrease was not significantly different between patients treated with a Zenith endograft or other devices (p=0.891).

At 30 days, the aneurysm diameter had grown non-significantly (0.2 ± 1.9 mm) in the control group and nonsignificantly (0.9 ± 1.6 mm) in the complication group. At midterm, the aneurysm had shrunk significantly (-7.3 ± 8.3 mm) in the control group but had grown nonsignificantly (1.5 ± 8.4 mm) in the complication group. The difference between both groups at midterm was significant ($p<0.001$).

Discussion

Angulation and curvature of the stented aorta decrease significantly after endograft implantation, and the trajectory straightens further during midterm follow-up. The most substantial changes occur with the infrarenal curvature, both in patients with and without late proximal seal–related complications. This suggests that most endografts are unable to fully accommodate to the aortic anatomy, so the anatomy has to adapt to the implanted endograft. The endograft continues to apply force onto the aortic wall, and the aortic wall slowly adjusts to reduce these forces. This effect is more prominent with greater initial curvature and with stiffer devices such as the Zenith. Remodeling of the aortic angles has previously been observed in patients treated with Zenith Flex, Excluder, and Incraft.[8,14] In this study, the Zenith endograft also straightened the infrarenal trajectory significantly more than the other endografts, which is in accordance with earlier findings. Other devices that may be better able to conform to severe curvature such as the Anaconda, Aorfix, and the Conformable Excluder were not included in this study. Comparing these devices with the devices with variable stiffness in this study would be an interesting subject for future research. The suprarenal aorta was relatively unaffected by endograft implantation, despite 90% of the patients being treated with devices with suprarenal fixation. The suprarenal part of the aorta may be fixed in position, restricted by surrounding tissues and branches and thus less prone to adapt to the implanted device.

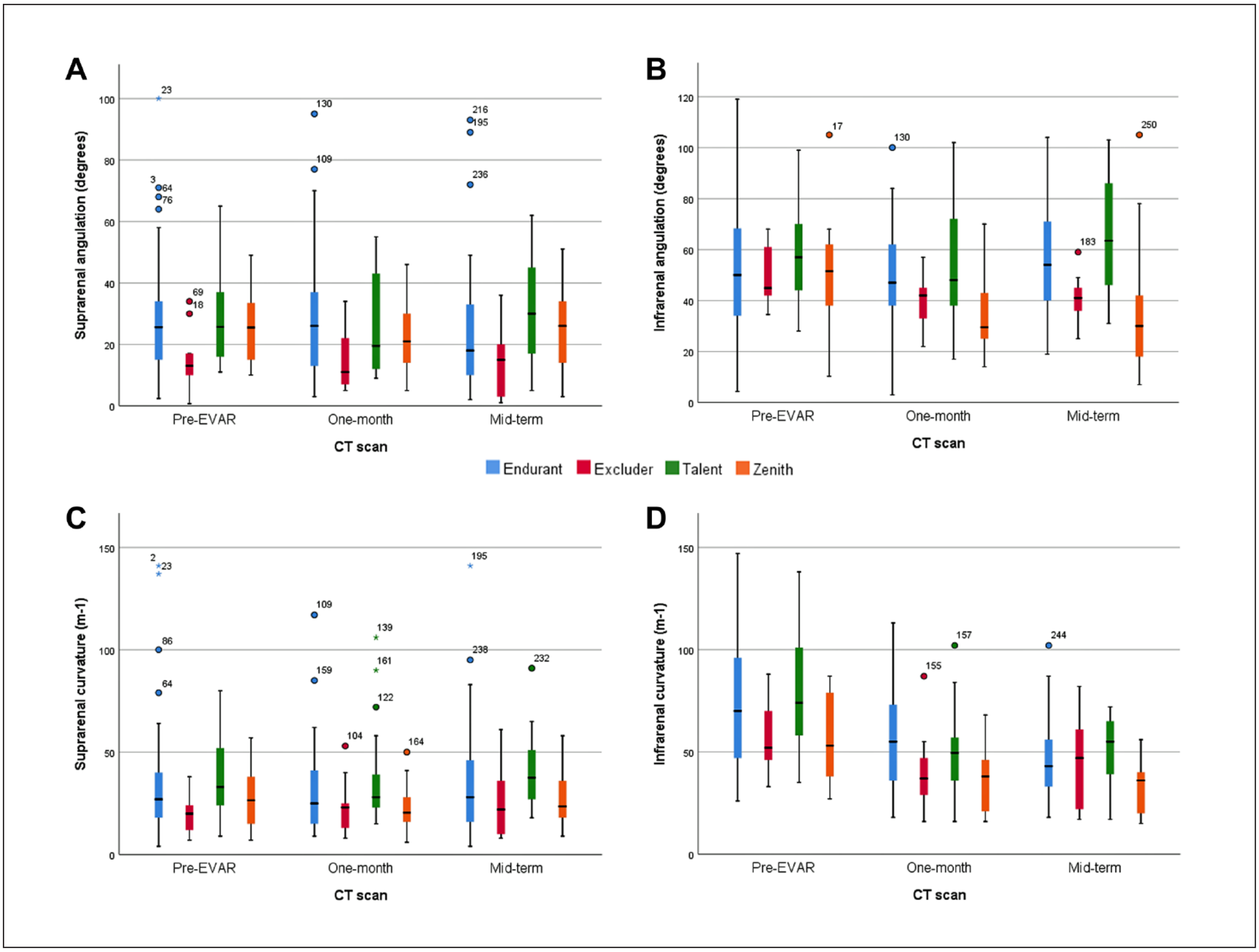

Figure 4. Remodeling of suprarenal and infrarenal angulation and maximum curvature for Endurant (n=45), Excluder (n=9), Talent (n=18), and Zenith (n=14) endografts. Patients with and without complications have been combined. (A) Suprarenal angulation, (B) infrarenal angulation, (C) maximum suprarenal curvature, and (D) maximum infrarenal curvature. CT, computed tomography; EVAR, endovascular aneurysm repair.

There were several differences between patients with and without later type Ia endoleak and device migration. Patients with these complications had significantly greater preoperative suprarenal angulation and infrarenal curvature, while the neck diameter of both groups was comparable. Preoperative infrarenal angulation and suprarenal curvature were not significantly different. The aneurysm diameter was significantly larger in the complication group, which may have allowed for more straightening in the aneurysm sac in these patients.

The predictive values of preoperative aortic angulation and curvature for type Ia endoleak and device migration have also previously been described,[3] and a relevant cutoff for infrarenal curvature has now been defined at 75 m^{-1}. This threshold might, however, differ among various endograft designs. In the current publication the suprarenal angle was measured as the change in flow direction between the suprarenal and infrarenal aortic neck and the infrarenal angle was measured as the change in flow direction between the infrarenal aortic neck and the aneurysm sac. This method differs from that used in the previous publication, where the angles were measured from specific landmarks. In this study significant differences of the preoperative suprarenal angle were observed between the complication group and control group, which were not observed in the previous publication.[3] This may be the consequence of the different methods as well as different inclusion criteria for the control groups. Another study that investigated long-term outcomes of EVAR in severely angulated anatomy found that angulation (both supra- and infrarenal) increased the risk of type Ia endoleak,[15] which confirms that angulation is an important factor to take into account during EVAR planning and surveillance. That study did not include supra- and infrarenal curvature.

The aortic trajectory straightens after endograft implantation. At 1 month, these changes were quite similar for both groups and most prominent in the infrarenal aorta. During midterm follow-up, however, suprarenal angulation and curvature and infrarenal angulation increased significantly in the complication group compared to the 1-month CTA. The location of the angle also shifted distally in the complication group, while it remained the same in the controls. This may be the result of displacement of the endograft and geometrical remodeling of the aorta.

The aortic remodeling after endograft implantation is the result of the combined hemodynamic and mechanical forces acting on the configuration. Previous research has shown that higher angulation and curvature increase drag forces on the endograft, which may account for the increased risk for type Ia endoleak and migration in patients with greater suprarenal angulation.[16,17] These studies further suggest that decreased curvature of the stented trajectory is beneficial for the reduction of drag forces on the graft, which may help stiff devices resist migration.

The findings of this study can be useful for the manipulation of preoperative anatomical models that serve as input for simulation of endograft implantation. It shows how the angles and curves can be expected to change and shift after endograft implantation. Accounting for geometrical remodeling of the compliant aortic trajectory could improve predictive simulation models for EVAR procedures. Second, 3D segmentations, which are used in overlay technology, could be manipulated to better fit the actual postimplantation geometry by correcting for postimplantation remodeling.

Limitations

First, only CT imaging data and study outcome data were available. Patient demographics and comorbidities were not assessed but may be confounders. Second, this imaging study included only patients with late (>1 year) type Ia endoleak or device migration. The results may therefore not apply to intraoperative or early (<1 year) complications.

Third, in the complication group, angulation and curvature were measured on the CT scan prior to the scan on which the type Ia endoleak or migration (>10 mm) was diagnosed. Changes of the aortic trajectory may progress even further after onset of the complications.

Fourth, the midterm follow-up of the control group was significantly longer than for the complication group. Some of the patients in the complication group were also treated in an earlier time period (between 2005 and 2012) compared to the control patients (between 2009 and 2012). Some patients in the control group may yet suffer a complication during future surveillance, which could affect the difference between the groups that was found in this study.

Fifth, the comparison of a random control group to selected patients with evident complications may have induced a selection bias. A large part of the patients in the control group originated from the USA, while the complication group mainly originated from Dutch centers. Some of the anatomical characteristics differed significantly between the groups. Differences between these populations may have affected the results.

Sixth, the study included various types of endografts, making the groups heterogeneous, and the distribution of devices was not equal between both groups. The complication group included significantly more Talent devices, whereas the control group included significantly more Endurant and Excluder models. Therefore, the results of the present study may not reflect outcomes for all the endografts as there are differences in conformability. Also, differences between supra- and infrarenal fixation could not be assessed. In addition, devices such as the Anaconda, Aorfix, and Conformable Excluder might be better able to conform to severe aortic curvature. Finally, diameter change of the aortic neck was not assessed in this study.

Conclusion

The aorta straightens until the endograft and the aortic wall are in an elastic equilibrium. This equilibrium may shift over time as the aortic wall adapts to reduce the applied forces. Therefore, aortic remodeling of the supra- and infrarenal trajectory can affect the outcome after endograft implantation. At midterm follow-up, significant differences in supra- and infrarenal angulation and curvature were observed between patients with type Ia endoleak or migration and controls without either. The location of the maximum curvature shifted downward to below the main body in most patients with complications. The aortic morphology was more stable during midterm follow-up in the patients without late complications. A prospective study is necessary to confirm the current results.

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