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Clinical outcome and morphologic determinants of mural thrombus in abdominal aortic endografts

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Objective: Endograft mural thrombus has been associated with stent graft or limb thrombosis after endovascular aneurysm repair (EVAR). This study aimed to identify clinical and morphologic determinants of endograft mural thrombus accumulation and its influence on thromboembolic events after EVAR.
Methods: A prospectively maintained database of patients treated by EVAR at a tertiary institution from 2000 to 2012 was analyzed. Patients treated for degenerative infrarenal abdominal aortic aneurysms and with available imaging for thrombus analysis were considered. All measurements were performed on three-dimensional center-lumen line computed tomography angiography (CTA) reconstructions. Patients with thrombus accumulation within the endograft's main body with a thickness >2 mm and an extension >25% of the main body's circumference were included in the study group and compared with a control group that included all remaining patients. Clinical and morphologic variables were assessed for association with significant thrombus accumulation within the endograft's main body by multivariate regression analysis. Estimates for freedom from thromboembolic events were obtained by Kaplan-Meier plots.
Results: Sixty-eight patients (16.4%) presented with endograft mural thrombus. Median follow-up time was 3.54 years (interquartile range, 1.99-5.47 years). In-graft mural thrombus was identified on 30-day CTA in 22 patients (32.4% of the study group), on 6-month CTA in 8 patients (11.8%), and on 1-year CTA in 17 patients (25%). Intraprosthetic thrombus progressively accumulated during the study period in 40 patients of the study group (55.8%). Overall, 17 patients (4.1%) presented with endograft or limb occlusions, 3 (4.4%) in the thrombus group and 14 (4.1%) in the control group (*P* = .89). Thirty-one patients (7.5%) received an aortouni-iliac (AUI) endograft. Two endograft occlusions were identified among AUI devices (6.5%; overall, 0.5%). None of these patients showed thrombotic deposits in the main body, nor were any outflow abnormalities identified on the immediately preceding CTA. Estimated freedom from thromboembolic events at 5 years was 95% in both groups (*P* = .97). Endograft thrombus accumulation was associated with >25% proximal aneurysm neck thrombus coverage at baseline (odds ratio [OR], 1.9; 95% confidence interval [CI], 1.1-3.3), neck length ≤15 mm (OR, 2.4; 95% CI, 1.3-4.2), proximal neck diameter ≥30 mm (OR, 2.4; 95% CI, 1.3-4.6), AUI (OR, 2.2; 95% CI, 1.8-5.5), or polyester-covered stent grafts (OR, 4.0; 95% CI, 2.2-7.3) and with main component "barrel-like" configuration (OR, 6.9; 95% CI, 1.7-28.3).
Conclusions: Mural thrombus formation within the main body of the endograft is related to different endograft configurations, main body geometry, and device fabric but appears to have no association with the occurrence of thromboembolic events over time. (J Vasc Surg 2015;61:1391-8.)

The surgical management of abdominal aortic aneurysms (AAAs) has progressively shifted toward endovascular aneurysm repair (EVAR) as the primary treatment[1] for moderate- and high-risk patients. Limb thrombosis and

endograft occlusion are infrequent but potentially devastating complications that have limited the clinical success of EVAR[2,3] and have been associated with preceding endograft mural thrombus accumulation.[4,5] However, the evidence for this is scarce and potentially biased.

Endograft mural thrombus formation has been detected as early as 1 week after endograft deployment, and its course is still not completely understood.[4] Optimal management of asymptomatic thrombotic formation within abdominal aortic stent grafts has not been determined; although most experts defend conservative surveillance,[6] oral anticoagulation therapy has also been reported.[7] There is a clear need for further evidence to support either conduct.

Our hypothesis was that thrombus accumulation within the main body of the endograft is not associated with the occurrence of thromboembolic events.

METHODS

We designed a retrospective case-control study based on a prospectively maintained observational database of
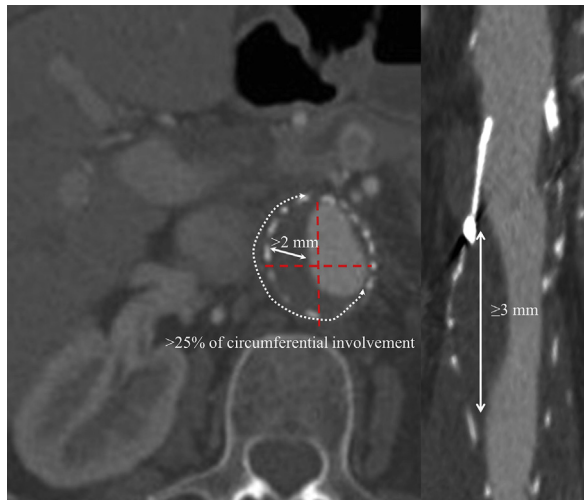
Fig 1. Study case selection: Inclusion criteria.

all patients undergoing EVAR in a high-volume center in The Netherlands. The study complies with the Helsinki statement on research ethics, and no informed consent was required according to institutional guidelines on research ethics.

Patients. From 2000 to 2012, EVAR was performed in 473 patients with AAAs at the Erasmus University Medical Center, Rotterdam, The Netherlands. The type of repair offered was individualized according to anatomic features, health status, and history of previous abdominal surgery (hostile abdomen). The patient's preference was accounted for before informed consent was obtained. Patients with previous aortic surgery or without degenerative AAAs (ie, with isolated iliac aneurysms, mycotic aneurysms, and anastomotic or traumatic pseudoaneurysms) as well as patients for whom a postoperative computed tomography angiography (CTA) image could not be obtained were not included.

Patients presenting with in-graft thrombus with a thickness >2 mm and an extension of >25% of the main body's circumference on at least three consecutive 1-mm slices in any postoperative CTA scan were included in the thrombus group (Fig 1). For case selection, all postoperative CTA images were analyzed with center-lumen line reconstruction. The remaining patients formed the control group. Patients who received a stent graft other than the ones deployed in the thrombus group were also excluded from the study for homogeneity (two patients with Powerlink [Endologix, Irvine, Calif] stent grafts).

Postoperative surveillance. Institutional follow-up protocols have changed significantly during the time of the study. From the initial practice, which consisted of contrast-enhanced CTA at 1 month, 6 months, 12 months, and yearly thereafter, the 6-month CTA evaluation has been reserved only for patients with a high risk of complications. In addition and according to the treating physician's expectation, selected patients with an expected lower risk of complications or with renal function impairment have been alternatively followed up with color duplex ultrasound or noncontrasted CT.

Data management. Baseline clinical, anatomic, and intraoperative data were acquired at the time of surgery. All subsequent long-term follow-up data were prospectively obtained on outpatient visits or from the patient's record on regular consultation.

Image analysis and measurements. All measurements (diameters, lengths, angles, cross-sectional area, and volumes) were performed with semiautomatically generated center-lumen line reconstructions on a workstation with dedicated reconstruction software (3mensio Vascular 4.2; Medical Imaging B.V., Bilthoven, The Netherlands) and according to previous validated methodology.[8] All long-term imaging data were obtained by a single observer with experience in image analysis (N.O.).

A centered ellipse was assumed as the most approximate form to represent the cross-sectional area of the main body. For cross-sectional area calculation, the largest and lesser diameters were measured, and the respective radius was determined. Cross-sectional area was calculated as follows: Area = rA*rB*π (in which rA is the largest radius and rB the lesser radius, and π value was rounded to six decimal digits). For lumen reduction determination, the difference between the cross-sectional areas of the main body and the patent lumen was calculated at the point of maximum thrombus accumulation.

Definitions. Reporting was done in accordance with the guidelines of the Society for Vascular Surgery/ American Association for Vascular Surgery Ad Hoc Committee for Standardized Reporting Practices in Vascular Surgery.[9] Cardiac status was defined and scored according to the Society for Vascular Surgery/American Association for Vascular Surgery medical comorbidity grading system.[10]

Thromboembolic events were defined as the composite of endograft occlusion, iliac limb occlusion, thromboembolic acute limb ischemia, and blue toe syndrome. Oversizing was determined from the ratio between the implanted main body diameter and the reference neck diameter in the first 15 mm of the infrarenal aneurysm neck. Neck length was defined as the distance between the distal point of the lowermost renal artery ostium and the beginning of the aneurysm.

Variation of the main body cross-sectional area was defined in percentage from the ratio between the maximum cross-sectional area assumed by the main body of the endoprosthesis and the minimum main body cross-sectional area identified in the first 10 mm of the stent graft.

End points. The primary end point of this study was freedom from thromboembolic events. In addition, clinical and morphologic variables were explored for association with significant thrombus accumulation within the endograft.

Statistical analysis. Categorical variables are presented as count and percentage and were compared by the Pearson χ^2 test. Continuous variables are presented as mean and standard deviation or median and interquartile range. Differences between groups were analyzed by the Mann-Whitney U test for independent nonparametric data and the Student t-test

Table I. Univariate analysis for in-graft thrombus accumulation

Demographic variables	Thrombus (n = 68)	No thrombus (n = 346)	P value	OR (95% CI)
Age ≥70 years	34 (50.0)	231 (66.8)	.008	0.50 (0.29-0.84)
Male gender	59 (86.8)	312 (90.2)	.400	—
Previous history of or continuous smoking at time of implantation[a]	49 (77.8)	221 (69.1)	.166	—
Cardiac status ≥2[b]	14 (20.6)	62 (17.9)	.563	—
Hypertension	48 (70.6)	217 (62.7)	.338	—
Cancer[c]	11 (20.0)	56 (18.7)	.816	—
ASA class 3/4	34 (50.0)	165 (47.7)	.738	—
Single antiplatelet therapy at time of implantation	61 (88.7)	289 (83.5)	.215	
Dual antiplatelet therapy at time of implantation	1 (1.5)	6 (1.7)		
Oral anticoagulation at time of implantation[d]	7 (10.3)	50 (15.4)	.278	0.63 (0.27-1.46)
Elective EVAR	56 (82.4)	270 (78)	.426	—
AAA Ø, mm	61 (54.0-74.3)	60 (55.0-72.3)	.497	—
AAA volume, mL	190.0 (150.8-369.0)	188.0 (143.0-281.0)	.595	—
Aneurysm growth ≥5 mm	10 (14.7)	50 (14.6)	.978	
Neck thrombus >25%	26 (38.2)	94 (27.2)	.016	1.98 (1.21-3.24)
Neck calcification >25%	19 (27.9)	65 (18.9)	.089	1.67 (0.93-3.04)
Proximal neck length ≤15 mm	21 (30.9)	55 (15.9)	.004	2.36 (1.31-4.26)
Proximal neck Ø ≥30 mm	15 (22.1)	42 (12.1)	.030	2.05 (1.06-3.96)
α Angle, degrees	20.0 (10.25-36.8)	21.0 (12.0-34.8)	.782	—
β Angle, degrees	34.0 (19.3-53.3)	35.0 (23.0-53.8)	.141	—
AUI graft configuration	10 (14.7)	21 (6.1)	.014	2.66 (1.19-5.94)
Main body diameter ≥31 mm	32 (54.2)	104 (33.1)	.002	2.39 (1.36-4.20)
Endograft fabric, polyester	49 (72.1)	186 (53.8)	.005	2.22 (1.25-3.92)
Ratio between cross-sectional areas of main body and limbs ≥2.3	42 (61.8)	136 (39.4)	.001	1.93 (1.14-3.29)
Main body cross-sectional area variation ≥50%[e]	9 (13.2)	23 (6.6)	.063	2.14 (0.94-4.86)
Distal landing zone in the EIA	26 (38.2)	92 (26.6)	.052	1.71 (0.99-2.95)

AAA, Abdominal aortic aneurysm; *ASA,* American Society of Anesthesiologists; *AUI,* aortouni-iliac; *CI,* confidence interval; *EIA,* external iliac artery; *EVAR,* endovascular aneurysm repair; *OR,* odds ratio.
Continuous data are presented as mean ± standard deviation or median (interquartile range) and categorical data as count (percentage).
[a]Unavailable data for 31 patients (7.5%).
[b]According to the Society for Vascular Surgery/American Association for Vascular Surgery medical comorbidity grading system.
[c]Unavailable data for 59 patients (14.9%).
[d]Unavailable data for 21 patients (5.1%).
[e]Measured between cross-sectional area at the start of the first covered stent and maximum cross-sectional area of the endograft main body.

and significance with the independent samples test for variables with normal distributions. Survival curves for freedom from thromboembolic events were estimated by Kaplan-Meier methods, and equality was tested with the Mantel-Cox log-rank test. Multivariate logistic regression was performed to assess independent association between endograft mural thrombus accumulation and significant variables determined by univariate analysis. Confidence intervals (CIs) of 95% were used, and statistical significance was considered if $P < .05$. All statistical analysis was performed with Statistical Package for Social Sciences (SPSS) 21.0 (IBM Inc, Chicago, Ill).

RESULTS

Among the 473 AAA patients submitted to EVAR at our institution from 2000 to 2012, 414 fulfilled the inclusion criteria. Mean age was 71.8 (±9.0) years; 371 (89.6%) were men. Sixty-eight patients presenting with intraprosthetic mural thrombus were included in the study group, and the remaining 346 were considered controls. Baseline characteristics are depicted in Table I.

Median follow-up was 3.54 years (1.99-5.47) and did not differ between groups (thrombus group, 3.99 years

[2.26-3.41]; no-thrombus group, 3.44 years [1.80-5.37]; $P = .107$).

Median time at diagnosis of mural thrombotic deposition was 12.0 months (1.2-23.0 months) in the thrombus group (N = 68). Substantial mural thrombus was identified on 30-day CTA in 22 patients (32.4%), 6-month CTA in 8 patients (11.8%), 1-year CTA in 17 patients (25%), 2-year CTA in 9 patients (13.2%), and 3-year CTA or after in 12 patients (17.6%).

Thromboembolic events. Seventeen patients (4.1%) presented with thromboembolic events after a median time of 15.0 months (6.0-23.8). Main body occlusions were reported in two patients in the control group (0.5% overall), both aortouni-iliac (AUI) devices. None of these patients showed thrombotic deposits in the main body, nor were any runoff abnormalities noted on the immediately preceding CTA, performed 2 months earlier in both cases. In one patient, the endograft occlusion had been preceded 1 year before by a stent graft migration that had been treated with an AUI conversion. This patient ultimately underwent an axillary-bifemoral bypass. The second patient was treated primarily for a ruptured AAA with an AUI stent graft, which
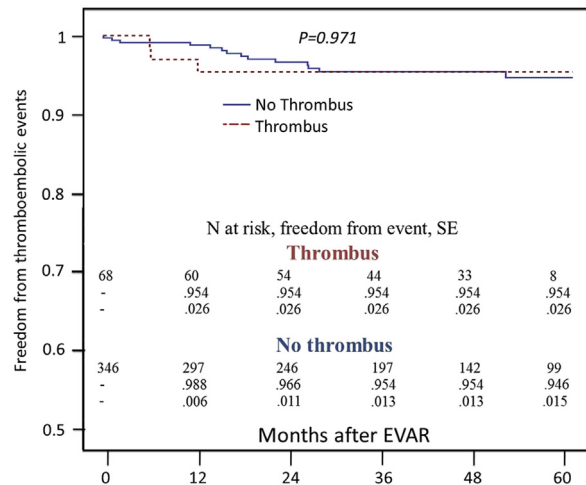
Fig 2. Kaplan-Meier survival estimates for freedom from composite end point of endograft or limb occlusion and acute limb ischemia. *EVAR,* Endovascular aneurysm repair; *SE,* standard error.

occluded after 12 months of follow-up and was treated with thrombolysis followed by surgical thrombectomy.

Thromboembolic events including device occlusion, iliac limb occlusions, acute limb ischemia, and blue toe syndrome occurred in 3 patients (4.4%) with significant mural thrombus and in 12 patients (3.5%) of the no-thrombus group ($P = .70$). Thirteen patients were treated with catheter-directed thrombolysis, followed by iliac percutaneous transluminal angioplasty in six patients, limb extensions in three patients, surgical thrombectomy in two patients, and a femoral-femoral crossover in one patient. The remaining two patients had no significant symptoms and remained untreated. None of the reported patients underwent major amputations. The estimated freedom from thromboembolic events at 2 and 5 years was 95% in the thrombus group; in the no-thrombus group, it was 96% and 95% ($P = .97$) (Fig 2).

Clinical variables. Overall, 62 patients (91.2%) in the study group and 295 patients (85.3%) in the control group were receiving antiplatelet therapy at the time of implantation ($P = .215$; Table I). Regarding oral anticoagulation therapy, there were 7 patients (10.3%) in the study group and 50 (15.4%) in the control group receiving this therapy at the time of implantation ($P = .24$). Oral anticoagulation at the time of implantation was found not to be a significant protection factor against in-graft thrombus accumulation on univariate regression analysis (hazard ratio, 0.63; 95% CI, 0.27-1.46).

In regard to previous or concurrent tobacco abuse at the time of implantation, the study group did not differ significantly from the controls ($P = .166$; Table I).

Morphologic characteristics. Median AAA diameter at baseline was 60.0 mm (55.0-72.0 mm) and did not differ significantly between groups ($P = .5$; Table I). Aneurysm growth ≥5 mm was identified in 10 patients in the study group (14.7%) and in 50 in the control group (14.6%) ($P = .978$).

Patients with shorter proximal aortic necks (≤15 mm) at baseline presented higher odds of thrombus formation (odds ratio [OR], 2.4; 95% CI, 1.3-4.2; Table II). Overall median native aortic neck diameter at baseline was significantly larger in the study group ($P = .03$). Patients with preoperative neck diameters ≥30 mm presented higher odds of endograft mural thrombus buildup (OR, 2.4; 95% CI, 1.3-4.6).

Proximal native neck thrombus coverage at baseline of >25% occurred in 26 patients (38.2%) in the study group and in 94 patients (27.2%) in the control group ($P = .016$). On multivariate analysis, baseline proximal aneurysm neck thrombus was an independent predictor of in-graft thrombus development (OR, 1.9; 95% CI, 1.1-3.3).

In the study group, thrombus extended into the iliac limbs in 15 patients (22.1%); in the control group, focal thrombus deposits were identified in 24 cases (6.9%) within the iliac limbs ($P < .001$). In regard to the iliac arteries, iliac stenosis was identified in 1 patient (1.5%) in the thrombus group and in 10 patients (2.9%; $P = .51$) in the control group (patent lumen, >7 mm; extension, <3 cm). The external iliac artery was one of the distal landing zones in 26 patients (22%) in the study group and in 42 patients (14.2%) in the control group ($P = .052$) but was not found to be an independent predictor of main body thrombus formation in multivariate analysis (Table II). Bilateral external iliac landing in bifurcated devices or external iliac landing of AUI devices was separately assessed for association with in-graft thrombus accumulation but was also statistically not significant in univariable analysis ($P = .816$).

Thrombus dynamics. First thrombotic deposits were identified among the study group on 30-day CTA in 22 patients (32.4%), 6-month CTA in 8 patients (11.8%), 1-year CTA in 17 patients (25%), 2-year CTA in 9 patients (13.2%), and 3-year CTA or after in 12 patients (17.6%).

Forty-four of these patients (64.7%) had undergone more than one CTA evaluation during follow-up. Mean variation of the maximum thickness was 3.3 mm (±5.01) and ranged from −3.20 to +29.5 mm. Partial thrombus regression was identified in four patients (9.1%), ranging from −0.40 to −3.20 mm in maximum thickness. Complete resolution was not identified, and of these four patients, only two were taking anticoagulants. The remaining 40 patients from this subgroup (58.8% of the study group) all demonstrated progressive thrombus accumulation from the first positive postoperative CTA scan for mural thrombus until the last CTA scan available (Fig 3). At the last CTA scan available, median lumen reduction by mural thrombosis in the study group was 33.2% and ranged from 12.7% to 78.5%.

Device-related features. Deployed devices differed significantly among groups ($P = .007$). Overall, Endurant (Medtronic, Santa Rosa, Calif) stent grafts were implanted in 190 patients (45.9%); Excluder Low-Permeability devices (W. L. Gore & Associates, Flagstaff, Ariz), in 124 (30.0%); Excluder stent grafts (original device), in 55 (13.3%); Zenith endografts (Cook, Bloomington, Ind), in 25 (6%); Talent devices (Medtronic), in 16 (3.0%); and LifePath System (McKinney, Tex) balloon-expandable endografts, in 4 (1.0%).

Table II. Multivariate analysis for in-graft thrombus accumulation

	Multivariate analysis		
	OR	95% CI	P *value*
Clinical variables			
Age ≥70 years	0.81	0.49-1.37	.429
Morphologic variables			
Neck thrombus ≥25%	1.90	1.10-3.31	.020
Neck calcification ≥25%	1.66	0.90-3.07	.105
Neck length ≤15 mm	2.35	1.31-4.23	.004
Neck diameter ≥30 mm	2.39	1.25-4.58	.008
Device-related variables			
AUI graft configuration	2.20	1.88-5.49	.050
Polyester fabric	3.98	2.17-7-29	<.001
Ratio between cross-sectional areas of main body and limbs ≥2.3	1.17	0.68-2.02	.576
Variation of main body cross-sectional area ≥50%	6.92	1.69-28.31	.007
Distal landing zone EIA	1.24	0.67-2.30	.495

AUI, Aortouni-iliac; *CI,* confidence interval; *EIA,* external iliac artery; *OR,* odds ratio.

AUI endografts were implanted in 10 patients in the study group (14.7%) and in 21 controls (6.1%). AUI configuration was found to account for a 2.2-fold odds increase of in-graft thrombotic deposition (95% CI, 1.9-5.5; Table II). As referred to previously, both device occlusions occurred in AUI devices, but none had been preceded by intraprosthetic thrombotic deposits.

In our population, polyester-coated devices (Endurant, Zenith, Talent, and LifePath devices) were more prone to building up significant thrombus (OR, 4.0; 95% CI, 2.2-7.3). Six-month estimates for freedom from in-graft thrombus were 77% for polyester-based AUI endografts, 92% for polyester-covered aortobi-iliac endografts, and 96% for expanded polytetrafluoroethylene-covered aortobi-iliac endografts. At 18 months, the estimated freedom from thrombus formation was 67%, 81%, and 92%, respectively ($P < .001$) (Fig 4). Increased endograft thrombus accumulation was found in cases of "barrel-like" configuration of the main component (Fig 5) with a cross-sectional area increase ≥50% throughout the main body (OR, 6.9; 95% CI, 1.7-28.3; Table II).

Thrombus formation within the iliac limbs was identified in 10 (19.6%) of the patients with bell-bottom (≥24 mm) iliac extensions and in 29 (8%) of those without ($P = .008$). Deposition of thrombus within the main body was not significantly different among patients with large (≥20 mm) ($P = .35$) or bell-bottom (≥24 mm) iliac limbs ($P = .34$).

DISCUSSION

Development of significant mural thrombus has cast uncertainty on long-term outcomes after EVAR, and several mechanisms have been proposed to explain its formation. We provide the largest study assessing the clinical impact of mural thrombus formation within the main body of abdominal aortic endografts and identify clinical, morphologic, and device-related risk factors for its development. This information was obtained in a large population of EVAR patients with long-term follow-up and adds new insights into the mechanisms of mural thrombus accumulation within the main component of abdominal aortic endografts. Although a frequent event, in our population, endograft mural thrombus formation was not associated with thromboembolic events during follow-up. Endograft characteristics such as configuration, fabric, and main body geometry were found to be distinctly associated with the appearance of in-graft thrombus.

Endograft mural thrombosis is a common event in abdominal aortic endografts, with reported rates ranging from 19% to 33%,[6,11,12] but it has also been reported in thoracic aortic stent grafts.[13,14] Whether in-graft mural thrombus predicts future limb or endoprosthesis occlusion in the long term has remained unresolved.[4] Moreover, different strategies have been suggested after diagnosis, including intensification of surveillance and even oral anticoagulation.[7] Mestres et al[5] reported an association between endograft mural thrombotic deposits and device occlusion during a follow-up period of 24 months ($P = .003$). In contrast, in our population, an increased propensity of graft or limb occlusions among the study group was not identified. In addition, limb occlusions did not occur preferentially among patients with thrombus accumulation within the endograft's main body, nor were those events preceded by thrombus deposition on the immediately preceding CTA scan. Indeed, limb occlusion may be related to kinking or the presence of iliac lesions with hemodynamic impact, as pointed out by van Zeggeren et al.[15] Therefore, our results suggest that neither an interventional attitude nor an intensification of postoperative imaging is warranted in patients presenting with in-graft mural thrombus.

Thrombus accumulation within the endograft seems to be a dynamic phenomenon. Cases of partial regression were identified among our study group, but we did not identify complete resolution as reported elsewhere.[4] This discrepancy may be explained by our inclusion criteria, which selected patients with significant thrombus load within the endograft, and the follow-up time. Although only a small proportion of our population was receiving oral anticoagulation, it was not found to be protective against endograft thrombus accumulation, as reported also by Wu et al,[16] or to induce thrombus regression among the study group.

In-graft thrombus accumulation is a multifactorial process, resulting from the complex interaction of systemic and local hemodynamic factors, hemorheologic properties, and endograft characteristics. Smoking is associated with a sustained low-grade systemic inflammatory response and produces an imbalance of rheologic, coagulation, and endothelial functions.[17] The consequent increase in blood viscosity[18] has been demonstrated to modify wall shear stress.[19] However, in our sample, we could not relate thrombus accumulation to smoking habits.

Mestres et al[5] proposed that mural thrombus of the aneurysmatic native aorta might lead to incomplete
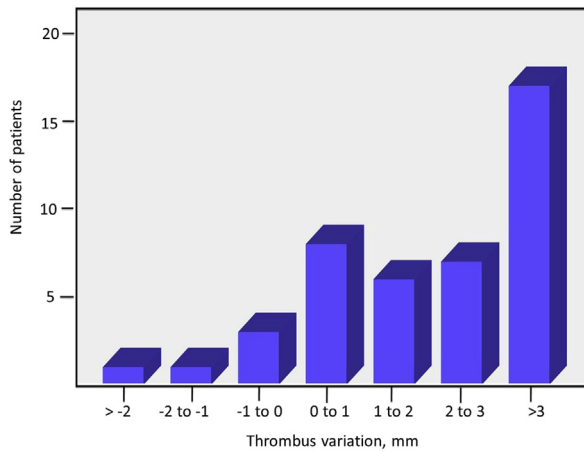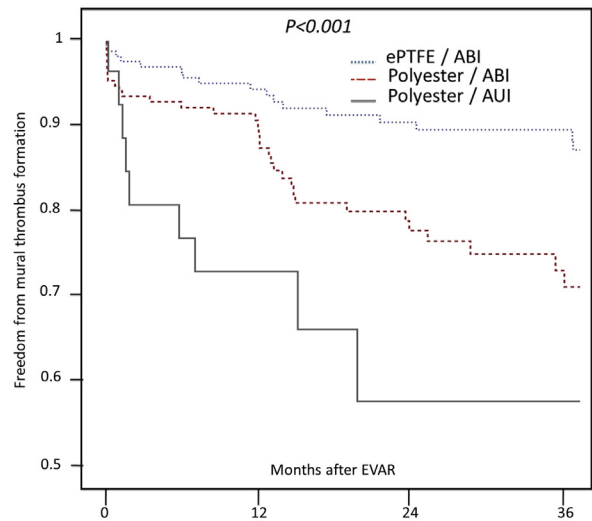
Fig 3. Thrombus thickness variation. Subgroup analysis of patients in the study group with more than one postoperative computed tomography angiography (CTA) scan (n = 44) during a median follow-up of 3.54 years (1.99-5.47). Measurements were performed using the last available and first postoperative CTA scans.

N at risk, freedom from event, SE			
ePTFE / ABI			
179	135	107	80
-	.945	.907	.898
-	.018	.024	.025
Polyester / ABI			
204	110	69	37
-	.893	.781	.716
-	.024	.037	.047
Polyester / AUI			
30	16	5	3
-	.734	.584	.584
-	.086	.118	.118

Fig 4. Kaplan-Meier survival estimates for freedom from mural thrombus comparing different combinations of endograft configuration and fabric. *ABI,* Aortobi-iliac; *AUI,* aortouni-iliac; *ePTFE,* expanded polytetrafluoroethylene; *EVAR,* endovascular aneurysm repair; *SE,* standard error.

expansion of the endograft's main body and subsequent generation of turbulent flow, which might predict endograft thrombus formation. However, as demonstrated by Bastos Gonçalves et al,[20] after stent graft implantation, aneurysm neck thrombus progressively reduces over time and ultimately disappears. Moreover, in a significant proportion of our study group, thrombus reappeared intraluminally within the device during follow-up, similar to Houdini's famous "walking through a brick wall" illusion. We hypothesize that in addition to device-related factors, hemorheologic and hemodynamic factors may also play a role in this "Houdini effect."

Abdominal aortic blood flow patterns are complex, differing significantly according to the physiologic state.[21-23] Local morphologic features such as angulation[24] and aortic arch-generated vortical flow patterns may also influence wall shear stress and blood stasis.[25,26] Endograft implantation may further modify these flow patterns,[27,28] which may in part contribute to the consistently reported reduced time elapsed until detection of the first in-graft thrombotic deposits.[4,5,11,16] Our study group also demonstrated such findings. Chong et al[29] demonstrated in vitro that proximal aneurysm neck angulation may produce complex turbulent flow and recirculation patterns within abdominal aortic endografts. However, in our population, we were not able to demonstrate this association.

Endograft features seem to play a role in the development of in-graft thrombus. Wu et al[16] correlated intraprosthetic thrombus development with a specific device (the Zenith endograft). However, more important, stent graft configuration[30] and main body geometric configuration may be the factors responsible for in-graft thrombus formation, leading to modified flow conditions within the device and to thrombus accumulation.[6,31] Wu et al also correlated

thrombus development to flow deceleration ("plug flow") within the device. Accordingly, this hemodynamic condition seems to be produced by sharp cross-sectional area decreases, such as in AUI devices or in stent graft extension to the external iliac arteries. In our population, both AUI configuration and an increased ratio between main body and cumulative limb cross-sectional areas were associated with an increased risk of endograft mural thrombosis in univariable analysis, which is in accordance with other reports.[5] However, we hypothesized that the higher prevalence of AUI stent grafts among the study group might contribute greatly to this finding, and in correcting for this factor, unlike in the study of Wu et al,[16] a higher ratio between the cross-sectional areas of main body and limbs and distal landing in the external iliac artery were not found to be independent predictors of thrombus accumulation.

Our results suggest that along with device configuration, a geometric barrel-like configuration of the main component after endograft deployment may also play a role. This event may be more pronounced in devices with larger diameters and in patients with shorter neck lengths, thus restraining less the endograft's full expansion to its diameter. Consequently, decreased flow
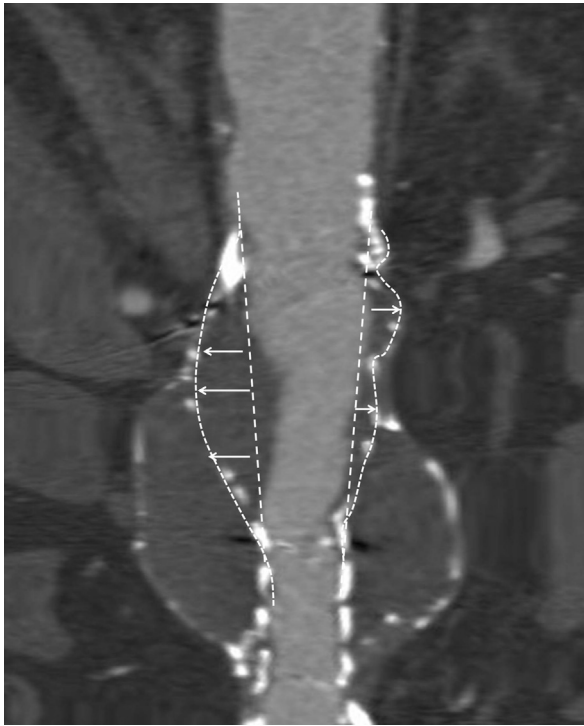
Fig 5. Midsection dilation of the main body component with thrombus formation. The *dashed lines* and *arrows* demonstrate the barrel-like configuration of the main component within the aneurysm sac.

velocities and recirculating fluxes in the peripheral endograft lumen can lead to subsequent thrombus accumulation.[16] In our study, patients receiving larger devices and with shorter proximal necks presented more frequently with endograft thrombus. In addition, midsection dilation of the main component (barrel-like configuration) was also found to be an independent predictor of significant endograft thrombus lining. The same mechanism can also explain the similar phenomenon among patients with bell-bottom iliac extensions in our study, which was statistically significant.

Device fabric may also play a role in mural thrombus accumulation. Polyester has been reported to be more thrombogenic than others fabrics.[32,33] In line with the findings of other authors,[5,6] we also identified an increased risk of intraprosthetic thrombus accumulation in patients receiving polyester-covered devices.

The method of thrombus assessment chosen may be pointed out as a drawback in our study. Thrombus-covered circumference has been preferentially used in studies reporting on mural thrombus within the native aorta.[10,34-37] However, this method does not inform on the thickness or the degree of lumen reduction caused by the thrombotic accumulation. Quantitative methods as reported by Wyss et al,[38] although providing overall quantification, fail to inform also on circumferential involvement or degree of lumen restriction, as the latter also depends on

the distribution of thrombus within the endoprosthesis and its dimensions. Our selection criteria included both the circumferential coverage of the endograft's main body surface by thrombus and its maximum thickness in part to overcome these limitations. Furthermore, unlike other reports that resorted to nondedicated imaging software[5] or did not also provide circumferential or quantitative assessments,[4,6,16] we provide maximum lumen reduction by thrombus formation calculated from reproducible measurements performed on dedicated imaging software. Other limitations that can be noted are the retrospective design of our study, thus making data about the compliance of patients with antiplatelet therapy after EVAR and the duration of oral anticoagulation irretrievable. Also, histopathologic confirmation of the thrombus was not performed. However, we chose significant thrombus thickness and circumferential coverage thresholds for the selection of the thrombus group to exclude patients with focal thrombus or fibrin accumulation. Importantly, our results must be interpreted with caution in light of the limited follow-up period of our studied population, and therefore subsequent investigation is warranted to further assess the clinical significance of intraprosthetic thrombus after EVAR. Finally, our conclusions may not apply to endografts deployed in other anatomic locations, but further investigation is warranted.

CONCLUSIONS

This study suggests that development of thrombotic deposits within the main body of an abdominal aortic endoprosthesis is not associated with endograft or limb thrombosis. Consequently, a conservative approach may be followed in patients with asymptomatic intraprosthetic thrombus accumulation during the midterm. Long-term results are still necessary to determine the safety of watchful waiting in these cases. In regard to surveillance, our findings do not support an intensification of the imaging protocol in patients with uneventful mural thrombus formation within abdominal stent grafts. In addition, oral anticoagulation did not decrease the odds for development of significant thrombus within abdominal aortic endografts. In our study, significant endograft thrombus deposition was independently associated with baseline thrombus load in the proximal aneurysm neck, proximal neck diameter, AUI endograft configuration, and polyester fabric.

AUTHOR CONTRIBUTIONS

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