Eur J Vasc Endovasc Surg (2025) 69, 38—45

EJVES Open Access

Branch Thrombus after Endovascular Treatment with Arch Branched Devices for Aortic Arch Pathologies

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WHAT THIS PAPER ADDS

Endovascular treatment of aortic arch pathology with arch branched devices is relatively new, and little is known about the performance of branches in the medium to long term. One complication is thrombus formation within the branches, which may lead to a potential risk of thromboembolic complications, including stroke. This study assessed patient related and branch related factors associated with thrombus formation after endovascular intervention with an arch branched device.

Objective: The aim of this study was to describe the occurrence of branch thrombosis following endovascular treatment of aortic arch pathology using an arch branched device (ABD) and to determine whether this is influenced by clinical and geometric parameters.

Methods: In this retrospective observational study of patients treated with an ABD in three centres, the primary endpoint was thrombus formation within a branch during follow up. Secondary endpoints were technical success, serious adverse events (SAEs), early and late death, stroke, and re-interventions. Geometric measurements (tortuosity index and curvature) were determined on pre- and post-operative computed tomography angiograms.

Results: Thirty nine patients were treated and 68 antegrade branches were analysed (innominate artery, $n = 27$; common carotid artery [CCA], $n = 40$; left subclavian artery [LSA], $n = 1$). Thrombus was identified within seven branches (10%) on surveillance imaging (innominate artery, $n = 6$; CCA, $n = 1$; LSA, $n = 0$; $p = .021$) and was associated with a wider distal bridging stent diameter (median 14.0 mm [13.3, 15.3] *vs*. 8.7 mm [IQR 5.9]; $p = .026$), a higher degree of reversed tapering (4.3 mm [3.8, 5.2] *vs*. 1.2 mm [0.3, 3.1]; $p = .023$), use of polyethylene terephthalate (Dacron) covered (*vs*. expanded polytetrafluoroethylene) bridging stents (23% *vs*. 2%; $p = .011$), and higher body mass index (BMI) (32.1 kg/m^2 [28.7, 36.2] *vs*. 25.7 kg/m^2 [23.8, 29.2]; $p = .029$), but not with pre-operative or post-operative tortuosity index or curvature or alterations. Regarding secondary outcomes, the technical success rate was 97%, SAEs occurred in 15 patients (38%), early and late death rates were 8% and 23%, respectively, and early and late stroke rates were 5% and 23%, respectively.

Conclusion: The risk of developing branch thrombosis after endovascular intervention with an ABD is considerable, especially of innominate artery branches, characterised by Dacron covered large diameter bridging stents, and in patients with a high BMI. Large prospective studies are required to analyse factors associated with branch thrombosis.

Keywords: Aortic arch syndrome, Endovascular procedure, Thrombosis
Article history: Received 2 January 2024, Accepted 18 July 2024, Available online 23 July 2024

INTRODUCTION

Endovascular treatment of aortic arch pathology with an arch branched device (ABD) is an alternative approach in patients who do not qualify for open or hybrid repair. Despite the technical and clinical challenges of the treatment, favourable results have been reported.[1–5] Early complications include systemic and access related complications, with cerebrovascular complications constituting one of the major risks.

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https://doi.org/10.1016/j.ejvs.2024.07.023

Late re-intervention has a varying incidence of up to 28.6%, mainly for treating endoleaks.[1−3,5] Issues with branch patency have been reported less frequently: three cases of branch thrombus or occlusion have been reported, all of which involved the branch to the left common carotid artery (LCCA).[1,6,7] Thrombus in the aortic arch and supra-aortic vessels can embolise, causing potentially life threatening stroke, and should be prevented and treated adequately. High variation in the rate of peri-operative stroke has been reported (up to 42.9%), as well as stroke during follow up.[8]

For other endovascular procedures, multiple risk factors for decreased patency have been identified. Iliac limb occlusion after endovascular aneurysm repair (EVAR) has been associated with smaller limb diameters, high iliac tortuosity, and a high body mass index (BMI).[9,10] High branch tortuosity is also a predictor for branch instability after branched EVAR in thoraco-abdominal aortic aneurysms.[11,12] Moreover, a study by Oliveira *et al.*[13] reported an increased risk of developing endograft thrombus after EVAR with polyethylene terephthalate (PET) endografts, also known as Dacron, compared with expanded polytetrafluoroethylene (ePTFE) endografts. Naturally, different anticoagulation protocols could lead to in stent thrombus formation.

The effect of such factors on the patency of ABD branches is not well reported. On the basis of the results of other endovascular interventions, it is hypothesised that the development of branch thrombus after an ABD is affected by branch characteristics such as tortuosity, the type of bridging stent, and patient characteristics. The objective of the present study was to describe the occurrence of branch thrombus after treatment with an ABD and to assess potential associated clinical and geometric factors.

MATERIALS AND METHODS

Study design and population

This observational cohort study was a retrospective analysis of patients who underwent endovascular repair with an ABD at three centres (Maastricht University Medical Centre, the Netherlands; Uppsala University Hospital, Sweden; and Waikato Hospital, New Zealand). Only patients treated with a Zenith ABD (Cook Medical, Bloomington, IN, USA) were included. All patients were treated between February 2015 and November 2022. The study was approved by the respective local ethical committees.

Procedure planning and technique

A pre-operative computed tomography angiogram (CTA) was carried out and reconstructed on a 3D workstation (Aquarius iNtuition Viewer 4.7.0; TeraRecon Inc., Durham, NC, USA) to assess suitability for treatment with an ABD and to design the endovascular devices. Devices contained up to three inner branches for the supra-aortic target vessels. If indicated, implantation of the ABD was preceded by a supra-aortic revascularisation procedure, such as a LCCA to left subclavian artery (LSA) bypass. The endovascular technique of the ABD has been described by Spanos *et al.*[14] All procedures were carried out under general anaesthesia with cerebral monitoring. After systemic heparinisation (activated clotting time $>$ 250 seconds), the main device was introduced from a femoral access, leading the nose cone into the left ventricle over a double curved Lunderquist wire. The main device was deployed under decreased ventricular output achieved by rapid ventricular pacing or caval balloon occlusion. In some cases, the stent graft was then extended distally with a thoracic endograft. The target vessels and inner branches were cannulated from either the brachial arteries, common carotid arteries (CCAs), or femoral artery. The innominate artery was bridged with a custom made stent graft (Cook Medical), whereas the LCCA, right common carotid artery (RCCA), and LSA were bridged with an off the shelf covered stent. An additional bare stent was placed in some target vessels. All patients were admitted to the intensive care unit after surgery, and all were prescribed single antiplatelet therapy (SAPT) or dual antiplatelet therapy (DAPT), or anticoagulation therapy with exception for cases with a concomitant indication (Supplementary Table S1).

Computed tomography angiography geometry analysis

Standard surveillance consisted of CTA evaluation before discharge, after six months, after one year, and annually thereafter. To evaluate the geometric characteristics for the present study, semi-automated centrelines were generated on the pre-operative and first post-operative CTAs using an Aquarius iNtuition Viewer in all antegrade branches in patients undergoing follow up beyond 30 days. Geometric measurements were taken on centreline segments defined by five pre-defined landmarks, ranging from P1 to P5 as follows (Fig. 1): P1 = proximal end of internal branch; P2 = origin of target vessel; P3 = distal end of covered bridging stent; P4 = distal end of bare metal stent; and P5 = innominate artery bifurcation.

All reconstructed centrelines and landmarks were verified by the senior author. Between the abovementioned landmarks, the tortuosity index (TI) and the curvature were measured. The TI is defined as the ratio between the distance over the centreline (L1) and the straight line distance (L2), resulting in a value $>$ 1.0. The curvature is defined as the inverse of the average radius (cm^{-1}) of the target vessel along the centreline, resulting in a value $<$ 1.0. (Fig. 2). For both metrics, a higher value indicates increased tortuosity. The post-operative TI and curvature were measured between P1 and P3 for the innominate artery and LCCA branches. In an innominate artery branch subanalysis, the pre- and post-operative TI and curvature were measured between P2 and P5, after which the alterations of TI and curvature (ΔTI and Δcurvature, respectively) were calculated. This was not carried out for the LCCA and LSA branches because no distal fixed landmark (such as P5) could be defined. Furthermore, the proximal and distal diameters (P1 and P3, respectively) were measured in a perpendicular plane over all post-operative antegrade branch centrelines, and the change of diameter between P1

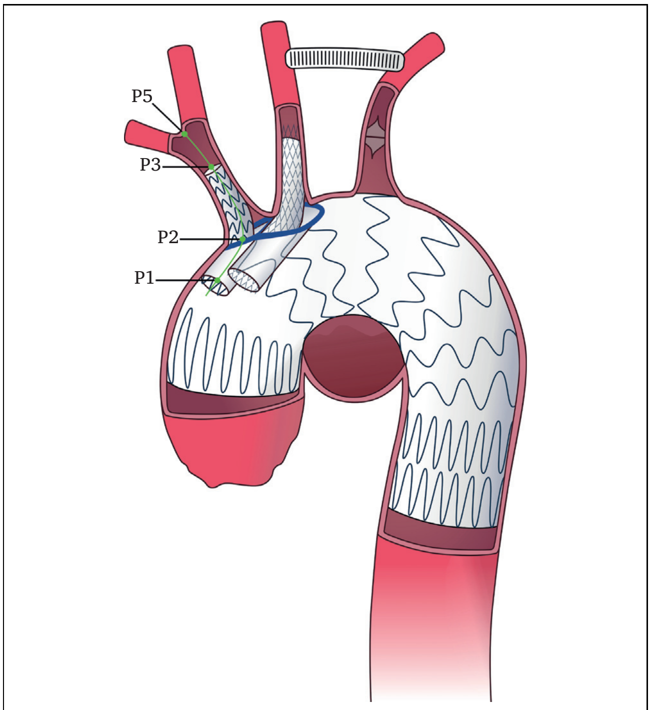

Figure 1. An arch branched device for a saccular aneurysm of the aortic arch with a centreline through the branch to the innominate artery with pre-defined landmarks P1 to P5. P1 = proximal end of the internal branch; P2 = origin of the target vessel; P3 = distal end of covered bridging stent; P5 = innominate artery bifurcation.

and P3 was calculated. The percentage of stent shortening, i.e., the difference between the original stent length and the actual length over a post-operative centreline, was also calculated.

Study outcomes and definitions

The primary outcome was the occurrence of thrombus in the branches and target vessels during the surveillance following ABD implantation. Patients who were not followed up because of death or loss to follow up were excluded from the branch analysis. Moreover, retrograde branches were excluded for reasons of heterogeneity owing to an expected atypical flow pattern. Along with the described geometry measurements, patient characteristics and stent graft information were analysed for association with thrombus formation. Secondary outcomes were technical success, early serious adverse events (SAEs), clinical stroke, death, and re-interventions within and after 30 days. Technical success was defined as successful exclusion of the aortic pathology by the endovascular procedure with full intra-operative patency of all graft components and intended target vessels, without conversion to open repair and intra-operative death and without type I or III endoleak on completion angiography.

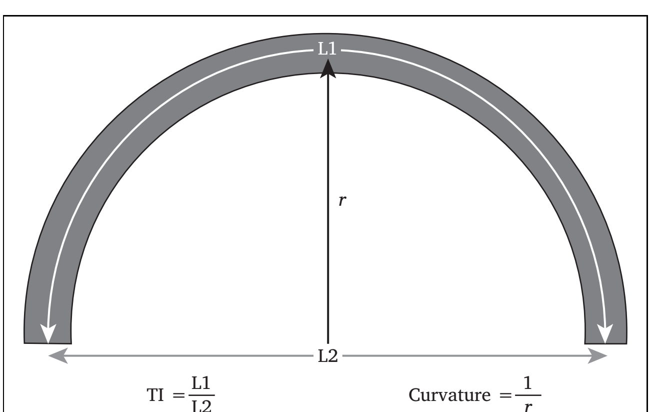

Figure 2. Curve demonstrating measurement of the tortuosity index (TI), defined as the centreline length (L1)/straight line distance (L2), and the curvature, defined as 1/radius (*r*).

Statistical analysis

IBM SPSS Statistics Version 25.0 (IBM Corp, Armonk, NY, USA) was used for statistical analysis. Categorical variables are presented as numbers with percentages and were analysed using the Pearson's χ^2 test and Fisher's exact test. Continuous variables are expressed as the median and interquartile range (IQR) and were tested using Mann—Whitney *U* test. A *p* value of $\leq$.050 was considered as statistically significant.

RESULTS

Thirty nine patients (Maastricht UMC+, $n = 13$; Uppsala University Hospital, $n = 20$; Waikato Hospital, $n = 6$) (male 72%, median age 70 years [64, 73]) were treated with an ABD. The median aneurysm diameter was 60.5 mm [55.0, 67.0]. The main device landed in surgical graft material proximally in 22 patients (56%) and distally in seven patients (18%). Ten patients (26%) had a prior cerebrovascular event (Table 1). In most patients, a double branched main device (82%) was implanted. Other patients received a single or triple branched device (3% and 15%, respectively) (Supplementary Table S1).

Patient results

Technical success was achieved in 38 procedures (97%): one left ventricular perforation required a surgical repair through a left thoracotomy. Early death occurred in three patients (8%) (multi-organ failure, $n = 1$; heart failure, $n = 1$; iliac aneurysm rupture after thrombolysis for major stroke, $n = 1$). In total, two early strokes with hemiparesis were observed (5%), and 15 patients (38%) were diagnosed with 17 SAEs. On routine CTA before discharge, one of these patients was diagnosed with a type A dissection, which was successfully managed conservatively. Three early re-interventions (8%) were carried out: one false lumen embolisation, one femoral pseudoaneurysm repair and one relining of an innominate artery branch for branch compression. No branch thrombus was established in the early period.

There were 35 patients with surveillance beyond 30 days (median follow up 20.0 months [IQR 41]), during which eight patients (23%) died. Twelve patients (34%) underwent

Table 1. Baseline patient characteristics ($n = 39$).

Characteristic	Patients ($n = 39$)
Male sex	28 (72)
Age – y	70.0 (64, 73)
ASA classification	
2	7 (18)
3	28 (72)
4	4 (10)
BMI – kg/m^2	25.8 (23.6, 29.5)
Smoker*	8 (22)
Chronic kidney disease†	15 (38)
COPD	10 (26)
Coronary arterial disease	4 (10)
Peripheral arterial disease	3 (8)
Prior stroke or transient ischaemic attack	10 (26)
Hypertension	33 (85)
Dyslipidaemia	23 (59)
Diabetes mellitus	3 (8)
Prior aortic repair	
Ascending	22 (56)
Thoracic	7 (18)
Aetiology	
Degenerative aneurysm	14 (36)
Fusiform	6 (15)
Saccular	8 (21)
Post-dissection aneurysm	19 (49)
Type Ia endoleak after prior TEVAR	4 (10)
Penetrating atherosclerotic ulcer	1 (3)
Para-anastomotic aneurysm	1 (3)
Maximum aortic arch diameter – mm	60.5 (55.0, 67.0)

Data are presented as n (%) or median (Q1, Q3). ASA = American Society of Anesthesiologists; BMI = body mass index; COPD = chronic obstructive pulmonary disease; TEVAR = thoracic endovascular aneurysm repair.
* The percentage was calculated out of $n = 36$ because of missing data.
† Estimated glomerular filtration rate < 60 mL/min/1.73m^2.

a re-intervention (distal extension, $n = 2$; plug embolisation for endoleak or false lumen perfusion, $n = 4$; re-intervention for branch thromboembolism, $n = 5$; and ascending repair, $n = 1$). Eight patients (23%) developed a stroke on surveillance (left, $n = 1$; right, $n = 3$; bilateral, $n = 3$; unknown, $n = 1$). One patient with a right sided stroke had thrombus in the PET based innominate artery branch, and in seven stroke patients branch thrombus was absent. Of the three patients who had a bilateral stroke, one had a PET based innominate artery branch, whereas the other branches had ePTFE covered stents. The patient with a left sided stroke was diagnosed with cardiac dysrhythmia with a concomitant left carotid stenosis, necessitating a carotid endarterectomy. All right sided strokes occurred in patients with a PET based innominate artery branch, of which in one innominate artery branch thrombus was observed.

Branch analysis

Of the 83 target vessels, eight branches in four patients who were not followed up beyond 30 days, and an additional seven retrograde LSA branches were excluded from the branch analysis. No branch thrombus was observed during follow up in any of the antegrade or retrograde LSA branches. Of the remaining 68 branches, 27 targeted the innominate artery, 40 the CCA, and one the LSA. Most innominate artery branches (96%) were bridged with a PET covered stent graft, whereas the CCAs and LSAs were all bridged with ePTFE covered stents ($p < .001$) (Table 2). During surveillance, branch thrombus was identified in seven branches (10%) (innominate artery, $n = 6$ [22%]; CCA, $n = 1$ [3%]; LSA, $n = 0$ [0%]; $p = .021$) in seven patients (20%) (Fig. 3).

Five of the seven patients with branch thrombus were symptomatic. Three patients with innominate artery thrombus presented with right arm ischaemia after 9, 17, and 19 months: all three required embolectomy of the right brachial artery, and two of them underwent innominate artery branch relining with a GORE EXCLUDER Internal Iliac Component (W.L. Gore & Associates Inc., Newark, DE, USA). One patient presented with a right hemispheric stroke after four months and innominate artery thrombus was identified on CTA, which was managed medically. One patient with a

Table 2. Post-operative branch characteristics ($n = 68$) of antegrade branches in patients with a follow up of more than 30 days.

Variable	Innominate artery ($n = 27$)	Common carotid artery ($n = 40$)	Left subclavian artery ($n = 1$)	p value
Graft fabric				<.001
PET	26 (96)	0 (0)	0 (0)	
ePTFE	1 (4)	40 (100)	1 (100)	
Bare stent	0 (0)	14 (35)	0 (0)	<.001
Diameter – mm				
P1	10.1 (1.1)	7.0 (0.6)		<.001*
P3	14.0 (2.5)	7.5 (1.8)		<.001*
Diameter change (P1–P3)	4.0 (2.7)	0.5 (1.7)		<.001*
Tortuosity (P1–P3)				
Tortuosity index	1.04 (1.02, 1.08)	1.03 (1.02, 1.05)		.47*
Curvature – cm^{-1}	0.244 (0.212, 0.280)	0.263 (0.216, 0.314)		.35*

Data are presented as n (%) or median (interquartile range). PET = polyethylene terephthalate, i.e., Dacron; ePTFE = expanded polytetrafluoroethylene; P1 = proximal edge of internal branch; P3 = distal edge of covered bridging stent.
* Statistical analysis conducted for innominate artery and common carotid artery groups, as left subclavian artery group only included one patient.

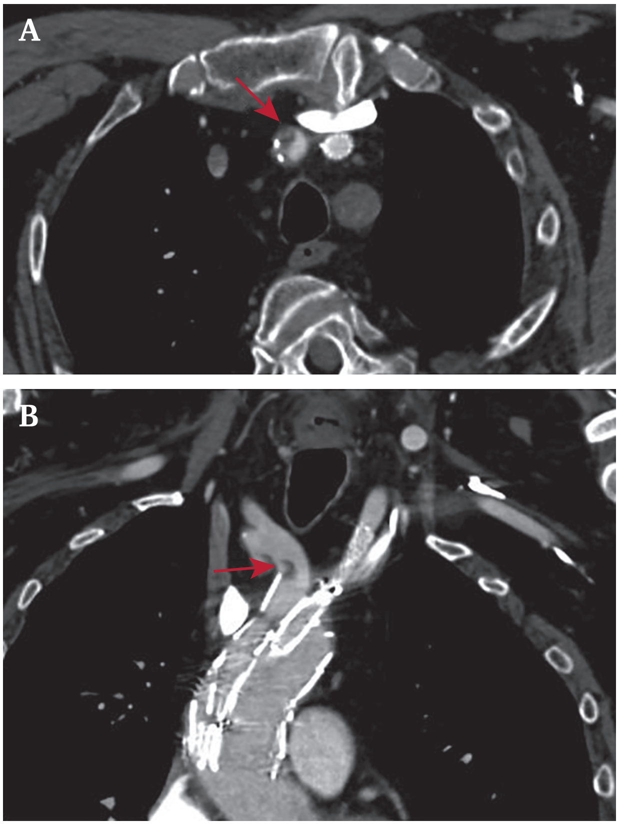

Figure 3. (A) Transverse and (B) coronal computed tomography angiography views of an arch branched device with branches to the innominate and left common carotid artery, showing thrombus in the innominate artery branch (red arrows).

Table 3. Pooled analysis of antegrade branches ($n = 68$) in patients followed up beyond 30 days, comparing branches with and without thrombus.

Variable	Branch thrombus ($n = 7$)	No branch thrombus ($n = 61$)	p value
Target vessel			.021
Innominate artery	6 (86)	21 (34)	
Common carotid artery	1 (14)	39 (64)	
Left subclavian artery	0	1 (2)	
Bridging stent type			.011
PET covered	6 (86)	20 (33)	
ePTFE covered	1 (14)	41 (67)	
Bare metal stent	0 (0)	14 (23)	.33
Post-operative tortuosity (P1–P3)			
Tortuosity index	1.03 (1.01, 1.07)	1.04 (1.02, 1.06)	.40
Curvature – cm^{-1}	0.221 (0.212, 0.229)	0.262 (0.217, 0.312)	.063
Diameter – mm			
P1	9.8 (9.0, 10.1)	7.4 (6.8, 9.9)	.059
P3	14.0 (13.3, 15.3)	8.7 (7.1, 13.0)	.026
Diameter change (P1–P3)	4.3 (3.8, 5.2)	1.2 (0.3, 3.1)	.023
Bridging stent shortening – %	91.0 (87.7, 95.0)	98.3 (91.3, 102.5)	.37

Data are presented as n (%) or median (interquartile range). PET = polyethylene terephthalate, i.e., Dacron; ePTFE = expanded polytetrafluoroethylene; P1 = proximal edge of internal branch; P3 = distal edge of covered bridging stent.

LCCA branch occlusion presented with nausea, dizziness, and visual disturbance after 10 months, which was ascribed to a global hypoperfusion phenomenon. The LCCA branch was recanalised and relined with an Advanta V12 (Atrium Medical Corporation, Merrimack, USA) and a VBX stent (W.L. Gore & Associates Inc., Newark, USA) after which the symptoms resolved. Thrombus within the innominate artery branch was identified on surveillance imaging in two asymptomatic patients at 11 months and 15 months, of which one was managed medically with DAPT and one underwent relining with a covered stent graft (Cook Medical). None of the patients with branch thrombus had a recurrence.

Regarding patient characteristics, patients with branch thrombus were not statistically significantly different regarding sex ($p = 1.0$), age ($p = .18$), or history of smoking ($p = 1.0$). Neither was there a statistically significant association with aortic pathology in terms of aneurysm or dissection ($p = .69$) or the use of SAPT, DAPT, or anticoagulation therapy ($p = .64$). Patients with branch thrombus had a higher pre-operative BMI (32.1 kg/m^2 [28.7, 36.2] *vs*. 25.7 kg/m^2 [23.8, 29.2], $p = .029$).

Regarding branch characteristics, thrombus formation occurred in 23% of branches with a PET covered stent compared with 2% of branches with an ePTFE covered stent ($p = .011$). No statistically significant difference was found in proximal diameter ($p = .059$), but branches with thrombus had a wider distal diameter (14.0 mm [13.3, 15.3] *vs*. 8.7 mm [7.1, 13.0]; $p = .026$) and a larger degree of reversed tapering (4.3 mm [3.8, 5.2] *vs*. 1.2 mm [0.3, 3.1]; $p = .023$). Neither the TI nor the curvature of the branches were associated with thrombus formation (TI 1.03 [1.01, 1.07] *vs*. 1.04 [1.02, 1.06], $p = .40$; curvature 0.221 cm^{-1} [0.212, 0.229] *vs*. 0.262 cm^{-1} [0.217, 0.312] $p = .063$) (Table 3).

In the analysis of 27 innominate artery branches, thrombus was not associated with the pre- and post-operative assessments for TI ($p = .31$ and $p = .090$, respectively) and curvature ($p = .73$ and $p = .24$, respectively) (Table 4). Moreover, no significant differences were found in alterations of geometry between innominate artery branches with and without thrombus (ΔTI, $p = .10$; Δcurvature, $p = .33$).

DISCUSSION

The present study reports the outcomes of patients with aortic arch pathology treated with an ABD, with an emphasis on branch thrombus during follow up, which was found in 20% of patients. This corresponds to 10% of the antegrade branches, most of which involved the innominate artery branch, whereas only one LCCA occlusion was found

Table 4. Subanalysis of innominate artery branches ($n = 27$) comparing innominate branches with and without branch thrombus.

Variable	Innominate artery branch with thrombus ($n = 6$)	Innominate artery without branch thrombus ($n = 21$)	p value
Diameter − mm			
P1	9.9 (9.5, 10.2)	10.1 (9.5, 10.7)	.35
P3	14.5 (13.5, 15.5)	14.0 (13.0, 15.7)	.47
Diameter change (P1−P3)	4.3 (4.0, 5.5)	3.9 (2.7, 5.6)	.29
Pre-operative tortuosity (P2−P5)			
Tortuosity index	1.11 (1.09, 1.17)	1.09 (1.04, 1.13)	.31
Curvature − cm^{-1}	0.378 (0.344, 0.476)	0.379 (0.288, 0.477)	.73
Post-operative tortuosity (P2−P5)			
Tortuosity index	1.17 (1.08)	1.06 (1.02, 1.16)	.090
Curvature − cm^{-1}	0.450 (0.322, 0.597)	0.345 (0.242, 0.472)	.24
Alterations in tortuosity (P2−P5)			
Tortuosity index	0.07 (−0.03, 0.245)	−0.01 (−0.06, 1.02)	.10
Curvature − cm^{-1}	0.001 (−0.036, 0.145)	−0.028 (−0.149, 0.081)	.33
Uncovered innominate artery (P3−P5)			
Post-operative curvature − cm^{-1}	0.523 (0.323, 0.735)	0.387 (0.238, 0.493)	.15
Percentage uncovered innominate artery*	69.7 (42.6, 74.1)	52.1 (43.9, 65.5)	.38

Data are presented as median (interquartile range). P1 = proximal edge of internal branch; P2 = ostium of innominate artery; P3 = distal edge of covered bridging stent; P5 = bifurcation of innominate artery.
* Uncovered innominate artery/total innominate artery (%).

and no thrombus was observed in the RCCA or LSA branches. In contrast, three studies have described compromised branch patency after an ABD, all of which only involved the LCCA branch. Van der Weijde *et al.*[6] and Hauck *et al.*[7] reported an asymptomatic LCCA occlusion after treatment with the double branched RELAY device (Terumo Aortic, Somerset, NJ, USA), which was treated conservatively. One re-intervention for a partially obstructed LCCA branch after an ABD was carried out by Haulon *et al.*[1] Moreover, they described one innominate artery branch thrombosis within 30 days, but no further information on this event was provided. As the treatment of aortic arch pathology with a branched endograft is a relatively new technique, available data are limited. Most studies describe the early results of an ABD and do not focus on patency rates in follow up. Hence, the reported actual rate of branch thrombosis during follow up of an ABD may be underestimated.

The present study evaluated branches with CTA confirmed branch thrombus. Of the eight patients with a late stroke (23%), seven patients had no branch thrombus. However, it cannot be ruled out that these strokes were caused by thromboembolism originating in the branches, possibly underestimating the overall branch thrombus rate. The two right sided strokes occurred distal to a PET covered innominate artery branch, whereas two patients who developed a bilateral stroke had ePTFE branches to the LCCA and only one had a PET covered innominate artery branch. Despite limited documentation on late strokes after an ABD, the incidence of late stroke ranges up to 7%, but only Verscheure *et al.*[2] have specifically ruled out branch thrombosis as a possible cause of late strokes.[1,15] Early strokes are less likely caused by branch thrombosis, but it is thought that cerebral embolisation caused by manipulation of the aortic arch, air embolisation during device employment, or coverage of supra-aortic vessels mainly cause early strokes.[3,16]

In the present study, factors that were possibly associated with the occurrence of branch thrombus after an ABD were investigated. The only patient factor that was associated with branch thrombus was a high BMI. This may be explained by the increased thrombotic tendency due to enhanced platelet activity and coagulation, resulting in obesity being a risk factor for venous and arterial thrombosis.[9,17]

Regarding branch specific features, branch thrombus was not only associated with the innominate artery branch, but also with the use of PET covered stent grafts. Similarly, various studies have reported an increased rate of in stent thrombosis with PET covered endografts owing to higher thrombogenicity of the material.[13,18,19] For EVARs, PET covered endografts are more than twice as likely to develop mural thrombus than ePTFE covered endografts, according to a meta-analysis by Perini *et al.*[18] As in the present study PET covered stents were placed in most innominate artery branches, it would still be uncertain whether the stent material or the vessel geometry contributes to the thrombus formation. However, in the geometric analysis, the pre-operative or post-operative tortuosity or the alterations thereof were not associated with branch thrombus. Yet branch thrombus occurred more frequently in bridging stents with a wider distal diameter and increased degree of reversed tapering. On the basis of the present data, it is not possible to determine whether the bridging stent material or its diameter, or a combination of both, is the determining factor. In contrast to the current findings, a high TI has been identified as an independent predictor for branch instability after treatment of thoraco-abdominal aortic aneurysms with branched EVARs, which has been explained by haemodynamic disturbances,[11,12,20,21] whereas Sylvan *et al.*[22]

reported an increased branch occlusion and re-intervention rate in vessels with a low curvature.

Despite the separate analysis of several clinical and geometric characteristics, thrombus formation inside branches is thought to be a multifactorial process. In all probability, also haematological parameters, e.g., haemoglobin levels, and haemodynamic conditions, e.g., blood pressure, are responsible for this issue. Also, patient compliance, the use of antiplatelet or anticoagulation therapy, and the efficacy of antiplatelet therapy due to genetic variability, may affect the branch thrombus formation.[23] Moreover, similar to iliac limbs, it is thought that some infolding of the fabric could result in altered flow patterns and consequently in thrombus formation.[24]

Based on the results of this study, it is not possible to determine whether the bridging stent material or its diameter, or a combination of both, is the determining factor. Because the innominate artery diameter cannot be changed, most investigators propose a preference for ePTFE covered bridging stents instead of PET covered stents for the target vessels after an ABD, both for the innominate artery and carotid branches. Nevertheless, in cases in which ePTFE stents are not suitable for the innominate artery, an ePTFE stent into the RCCA along with a bypass or transposition could be considered, or, extending the aorto-iliac European Society for Vascular Surgery guideline,[25] a PET covered stent could be placed with DAPT.

This study is limited by the small sample size, restricting the statistical analysis. Because of its retrospective character, no standardised antiplatelet protocol was followed, and the analysis was confined to the available CTA data, which did not consistently depict the entire course of the supra-aortic vessels. Furthermore, larger prospective studies and analyses of computational fluid dynamics would be valuable for a better understanding of thrombus formation after implantation of an ABD.

Conclusion

In the authors' experience, after endovascular intervention with an ABD there is a considerable risk of developing branch thrombosis, especially in patients with a higher BMI and in innominate artery branches, which are characterised by PET covered large diameter bridging stents. Ultimately, it is proposed to avoid the use of PET covered branches after an ABD. More studies are required to further explore possible geometric and haemodynamic risk factors of branch thrombosis.

CONFLICTS OF INTEREST

None.

FUNDING

None.

APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejvs.2024.07.023.

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COUP D'OEIL

Inferior Mesenteric Artery Aneurysm: A Rare Entity

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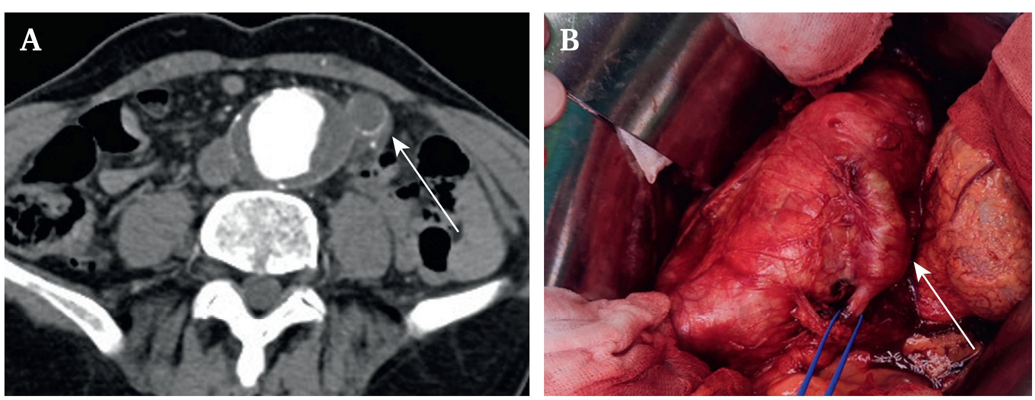

A 63 year old man with a history of hypertension and coronary artery stenting presented with a tender, pulsatile, painful abdominal mass. Computed tomography angiography revealed a non-ruptured 58 mm infrarenal abdominal aortic aneurysm (AAA) and a thrombosed 21 mm inferior mesenteric artery aneurysm (IMAA) (A, arrow). The superior mesenteric artery and coeliac trunk were both patent. The symptomatic AAA was treated urgently and replaced with a knitted polyester 18 $\times$ 9 mm bifurcated graft. The chronically thrombosed IMAA (B, arrow) was resected and the inferior mesenteric artery ligated. The patient's symptoms resolved and the post-operative course was uneventful.

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https://doi.org/10.1016/j.ejvs.2024.10.003