Risk Factors for Type 2 Endoleak After Preemptive Side Branch Embolization During EVAR for Abdominal Aortic Aneurysm

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Background: Type 2 endoleak (T2EL) remains the most frequent complication after endovascular aneurysm repair (EVAR) for abdominal aortic aneurysm and is associated with sac enlargement and late adverse events. Preemptive embolization of aortic side branches has been introduced to reduce its incidence. This study aimed to evaluate the mid-term outcomes of EVAR with preemptive side branch embolization and to identify factors associated with persistent T2EL.
Methods: We retrospectively reviewed 217 patients who underwent EVAR with preemptive embolization of the inferior mesenteric artery and lumbar arteries (LAs) at our institution between April 2018 and March 2025. Patient characteristics, aneurysm morphology, and procedural details were analyzed. The primary endpoint was the occurrence of T2EL during follow-up. Risk factors were evaluated using univariable and multivariable logistic regression analyses.
Results: During a mean follow-up of 43.0 ± 22.6 months, T2EL occurred in 25 patients (11.5%). Sac enlargement $\geq$5 mm was significantly more frequent in patients with T2EL (36.0% vs. 4.7%, $P < 0.001$), while complete sac regression was observed only in the non-T2EL group (22.9% vs. 0%, $P = 0.007$). Multivariable analysis identified angulated neck (OR 2.90, 95% CI 1.10–7.66, $P = 0.031$) and the number of residual LAs (OR 1.74, 95% CI 1.12–2.70, $P = 0.013$) as independent predictors of T2EL.
Conclusion: Persistent T2EL after PBE was associated with unfavorable sac behavior and an increased need for reintervention. Residual LAs and angulated neck anatomy were independent predictors of persistent T2EL, suggesting the importance of complete embolization, particularly in patients with angulated neck anatomy.

INTRODUCTION

Endovascular aneurysm repair (EVAR) has become a widely accepted treatment for abdominal aortic aneurysm (AAA) due to its minimally invasive nature and favorable perioperative outcomes.[1] However, long-term durability remains a concern, particularly because of endoleak-related complications.[2]

Among these, type 2 endoleak (T2EL) is the most common, resulting from retrograde perfusion of the aneurysm sac via collateral branches such as the inferior mesenteric artery (IMA) and lumbar

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arteries (LAs). Although T2EL is often considered benign, several studies have demonstrated its association with aneurysm sac enlargement and an increased need for secondary interventions.[2,3] Furthermore, persistent sac pressurization may contribute to the development of more clinically significant endoleak, including type 1 endoleak.[4]

To prevent T2EL, various strategies have been proposed, including preemptive embolization of aortic side branches and aneurysm sac embolization. Previous studies have demonstrated a reduced incidence of T2EL after preemptive IMA embolization, with rates of 24.5% versus 49.1% in a randomized controlled trial for patients at high risk of T2EL by Samura et al. and 34.3% versus 49.4% in the study by Ward et al.[5,6] However, the 2024 ESVS guidelines do not recommend routine preemptive branch embolization because robust evidence demonstrating improved clinical outcomes remains limited.[7] In contrast, more recent studies have suggested that embolization of multiple side branches may further decrease T2EL occurrence, although the clinical benefit and optimal strategy remain controversial.[8–10]

At our institution, we initially performed selective IMA embolization targeting only large side branches considered to be high-risk.[11] However, the occurrence of T2EL-related sac enlargement in these cases prompted a shift toward a more aggressive strategy of attempting embolization of all detectable side branches, regardless of vessel size.

In this context, the present study aimed to evaluate the mid-term outcomes of EVAR with preemptive side branch embolization and to identify factors associated with the development of persistent T2EL.

MATERIAL AND METHODS

Study Design and Setting

This retrospective, single-center cohort study was conducted at Yamaguchi University Hospital in Japan. A total of 217 patients underwent elective EVAR for AAA at our hospital between April 2018 and March 2025. The patient's condition and other complications were considered in the indications for EVAR. Patients with isolated iliac artery aneurysms, saccular aneurysms, infected aneurysms, and ruptured aneurysms were excluded. Since 2018, our institution has adopted a policy of performing preemptive branch embolization (PBE) in all patients except for patients in poor general condition and who cannot undergo general anesthesia. The decision was at the discretion of the attending physician although a general institutional policy was applied. The strategy for PBE is to attempt embolization of all aortic side branches identified as patent on preoperative contrast-enhanced computed tomography (CT), regardless of vessel diameter. The percentage of intraluminal thrombus was defined as the ratio of mural thrombus thickness to the maximum aneurysm diameter on the axial slice with the largest aneurysm diameter. Mural thrombus thickness was measured as the maximum perpendicular distance between the contrast-enhanced lumen and the outer aneurysm wall. This retrospective study was approved by the Institutional Review Board (IRB) of Yamaguchi University (IRB No.H2019-062). We performed side branch embolization during EVAR under general anesthesia prior to device deployment. Target branches for embolization included the IMA, LAs, accessory renal arteries, and the median sacral artery. In this study, the median sacral artery was classified as an LA for analytical purposes. Because accessory renal arteries are rare, they were not analyzed. IMA was embolized proximal to the left colonic artery using coil embolization. For IMA embolization, a 0.035-inch Interlock detachable coil (Boston Scientific, Marlborough, MA) was primarily used. In cases where catheterization was challenging, a 0.018-inch EMBOLD fibered detachable coil (Boston Scientific, Marlborough, MA) was alternatively used. LAs were embolized at their origins using a packing technique with detachable coils, including Packing Coils (Penumbra, Alameda, CA) and other detachable microcoils. Operative time was defined as the total procedure time from skin incision to skin closure, including both the embolization procedure and EVAR. Postoperative acute kidney injury (AKI) was defined according to the kidney disease: Improving Global Outcomes criteria as an increase in serum creatinine of $\geq$0.3 mg/dL within 48 hours or $\geq$1.5 times the baseline value within 7 days after the procedure.

Postoperative Follow-Up and Reintervention

CT angiography was performed before EVAR, at discharge, at 3, 6, and 12 months, and every 6 or 12 months thereafter to evaluate aneurysm size and detect endoleak. T2EL was defined as the presence of contrast enhancement within the aneurysm sac on delayed-phase CT or as flow detected within the sac on duplex ultrasound. T2EL was assessed using contrast-enhanced CT with delayed-phase imaging or duplex ultrasound when contrast-enhanced CT was not feasible due to renal insufficiency. Duplex ultrasound was performed by a

Table I. Patient demographics and baseline characteristics

Variable	Type 2 EL (*N* = 25: 11.5%)	Non-type 2 EL (*N* = 192: 88.5%)	*P* value
Age (years)	78.4 ± 6.9	75.4 ± 8.0	0.106
Female sex	3 (12.0%)	34 (17.7%)	0.478
Comorbidities			
Hypertension	22 (88.0%)	151 (78.7%)	0.276
Dyslipidemia	17 (68.0%)	114 (59.4%)	0.409
Diabetes mellitus	5 (20.0%)	37 (19.3%)	0.931
Hemodialysis	0 (0%)	3 (1.6%)	0.530
Chronic obstructive pulmonary disease	1 (4.0%)	14 (7.3%)	0.544
Ischemic heart disease	7 (28.0%)	39 (20.3%)	0.379
Cerebral vascular disorder	5 (20.0%)	42 (21.9%)	0.831
Body mass index (kg/m2)	23.4 ± 2.7	23.6 ± 3.5	0.816
Smoking	18 (72.0%)	153 (79.7%)	0.379
Anti-coagulation use	6 (24.0%)	16 (8.3%)	0.015
Anti-platelet use	10 (40.0%)	96 (50.0%)	0.652
Statin use	16 (64.0%)	96 (50.0%)	0.189
Aneurysm diameter (mm)	56.1 ± 10.9	53.7 ± 10.6	0.013
Angulated neck (≥60°)	13 (52.0%)	39 (20.3%)	<0.001
Infrarenal neck length (mm)	31.0 ± 19.1	31.4 ± 17.6	0.974
Short neck (<10 mm)	5 (20.0%)	28 (14.6%)	0.480
IMA patency	21 (84.0%)	142 (74.0%)	0.277
IMA diameter (mm)	2.7 ± 1.1	2.8 ± 0.8	0.220
Maximal LA diameter (mm)	2.1 ± 0.6	2.4 ± 1.5	0.106
Patent number of LAs	3.9 ± 1.8	3.0 ± 1.7	0.022
Percentage of thrombus/aneurysm size (%)	19.1 ± 17.9	28.3 ± 16.7	0.019

single dedicated clinical laboratory technologist to ensure consistency. Sac enlargement was defined as an increase of ≥5 mm from the preoperative diameter, while changes <5 mm were considered stable. Complete sac regression was defined as complete disappearance of the aneurysm sac on follow-up imaging. Reintervention was considered in cases of sac enlargement due to T2EL, particularly when the sac diameter increased by ≥10 mm compared with the preoperative measurement.

Statistical Analysis

Continuous variables are expressed as the mean ± standard deviation, and categorical variables are presented as counts and percentages. The χ^2 test or Fisher's exact test was used for categorical variables, as appropriate. Continuous variables were additionally analyzed using the Mann—Whitney *U* test to account for non-normal distributions. Logistic regression analysis was performed to identify independent predictors of T2EL. Candidate variables for the multivariable model included all baseline demographic, clinical, anatomical, and embolization-related variables listed in Tables I and II, except for intraoperative procedural variables (operative time, blood loss, blood transfusion, fluoroscopy time, and contrast medium volume). Variables were selected based on univariable results, clinical relevance, and previous reports. Variables with potential collinearity were not included simultaneously in the model. Receiver operating characteristic (ROC) curve analysis was used to determine cutoff values for IMA and LA diameters. A *P* value <0.05 was considered statistically significant. All statistical analyses were performed using Stata Statistical Software: Release 15 (StataCorp LLC, College Station, TX).

RESULTS

Baseline Characteristics

The patient selection process is summarized in Figure 1. Between April 2018 and March 2025, 383 patients underwent elective EVAR. After excluding patients who met the predefined exclusion criteria and those with less than 6 months of follow-up, 217 patients were included in the final analysis. Patient characteristics and anatomical variables are summarized in Table I. During a mean follow-up of 43.0 ± 22.6 months, T2EL developed

Table II. Intraoperative and embolization-related variables

Variable	Type 2 EL (*N* = 25: 11.5%)	Non-type 2 EL (*N* = 192: 88.5%)	*P* value
Operative time (min)	239.0 ± 73.2	208.6 ± 80.6	0.031
Blood loss (g)	178.0 ± 155.9	146.4 ± 268.6	0.120
Blood transfusion	2 (8.0%)	8 (4.2%)	0.323
Fluoroscopic time (min)	103.3 ± 44.0	92.6 ± 41.3	0.151
Contrast medium usage (ml)	102.6 ± 36.6	90.5 ± 40.2	0.081
Main device			0.328
Endurant	19 (76.0%)	134 (70.0%)	
Excluder	1 (4.0%)	15 (7.8%)	
TREO	2 (8.0%)	19 (10.0%)	
Zenith	2 (8.0%)	15 (7.8%)	
Alto	1 (4.0%)	4 (2.1%)	
AFX	0 (0%)	5 (2.6%)	
IMA embolization success rate (21 cases vs 142 cases)	20 (95.2%)	137 (96.5%)	0.780
All LA embolization success rate (23 cases vs 168 cases)	7 (30.4%)	110 (66.1%)	<0.001
Embolized number of LAs	2.7 ± 1.5	3.0 ± 1.4	0.546
Residual number of LAs	1.1 ± 1.1	0.4 ± 0.8	<0.001
Maximal residual LA diameter (mm)	1.6 ± 0.4	1.5 ± 0.5	0.770

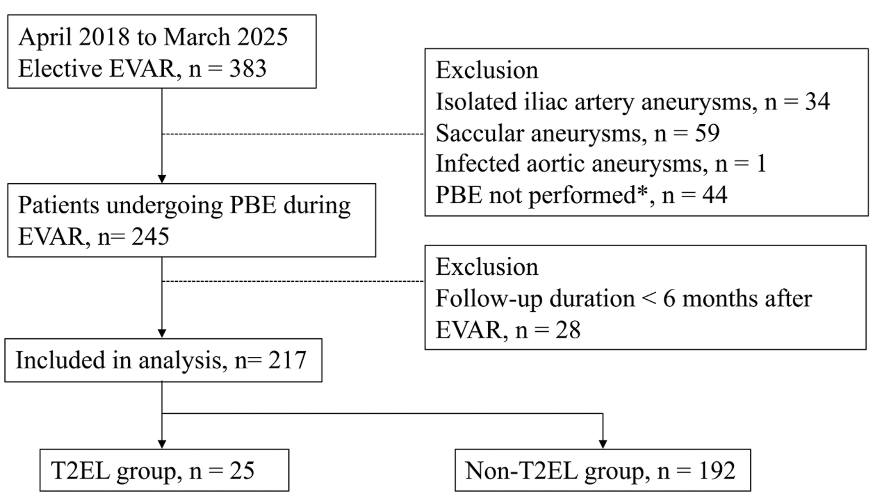

Fig. 1. Study flow diagram. Flowchart illustrating patient selection for the present study. Between April 2018 and March 2025, 383 patients underwent elective EVAR. After exclusion of patients with isolated iliac artery aneurysms, saccular aneurysms, infected aortic aneurysm, patients in whom preemptive branch embolization (PBE) was not performed, and those with less than 6 months of follow-up, 217 patients were included in the final analysis.*PBE was not performed in patients in poor general condition, unable to undergo general anesthesia, or when deemed inappropriate by the attending surgeon despite the institutional policy. EVAR, endovascular aneurysm repair; PBE, preemptive branch embolization; T2EL, type 2 endoleak.

in 25 patients (11.5%). Patients were stratified according to the presence or absence of T2EL. Most comorbidities were comparable between the groups; however, anticoagulation use was significantly more frequent in the T2EL group (24.0% vs. 8.3%, $P = 0.015$). Regarding aneurysm characteristics, the mean aneurysm diameter was significantly larger in patients with T2EL (56.1 ± 10.9 mm vs. 53.7 ± 10.6 mm, $P = 0.013$). Angulated proximal neck anatomy (≥60°) was also significantly more prevalent in the T2EL group (52.0% vs. 20.3%, $P < 0.001$), whereas infrarenal

TABLE III. Postoperative outcomes

Variable	Type 2 EL ($N = 25$: 11.5%)	Non-type 2 EL ($N = 192$: 88.5%)	P value
Follow-up period (month)	48.9 ± 20.0	42.2 ± 22.9	0.120
Endoleak			
Type 1a	0	2	
Type 1b	1	1	
Sac enlargement ($\geq$ 5 mm)	9 (36.0%)	9 (4.7%)	<0.001
Complete sac regression	0 (0%)	44 (22.9%)	0.007
Aneurysm-related death	0 (0%)	0 (0%)	1.000

neck length and the prevalence of short neck did not differ between groups. With respect to branch vessel anatomy, IMA patency and diameter were similar between the groups, as was maximal LA diameter. In contrast, the number of patent LAs was significantly higher in the T2EL group (3.9 ± 1.8 vs. 3.0 ± 1.7, $P = 0.022$). In addition, the percentage of mural thrombus relative to aneurysm diameter was significantly lower in patients with T2EL (19.1 ± 17.9% vs. 28.3 ± 16.7%, $P = 0.019$).

Intraoperative Data

Procedural and embolization-related variables are summarized in Table II. Operative time was longer in the T2EL group (239.0 ± 73.2 min vs. 208.6 ± 80.6 min, $P = 0.031$). No significant differences were observed in device type or other procedural variables. The success rate of IMA embolization was 95.2% in the T2EL group and 96.5% in the non-T2EL group ($P = 0.780$). Although the presence of patent LAs was similar between groups, complete embolization of all LAs was significantly less frequent in the T2EL group (30% vs. 66%, $P < 0.001$). Importantly, the number of residual LAs after embolization was significantly higher in patients with T2EL (1.1 ± 1.1 vs. 0.4 ± 0.8, $P < 0.001$), whereas LA diameter was not associated with T2EL development. The incidence of postoperative AKI did not differ between the groups, occurring in 9 patients in the non-T2EL group and in no patients in the T2EL group ($P = 0.603$).

Outcomes

The mid- to long-term outcomes are summarized in Table III. During a mean follow-up of 48.9 ± 20.0 months in the T2EL group and 42.2 ± 22.9 months in the non-T2EL group, there was no significant difference between the groups ($P = 0.120$). Type 1a and 1b endoleak occurred only in the non-T2EL group (type 1a: $n = 2$; type 1b: $n = 1$), and all required additional interventions. Sac enlargement $\geq$5 mm was significantly more frequent in the T2EL group than in the non-T2EL group (36.0% vs. 4.7%, $P < 0.001$). In contrast, complete sac regression was observed exclusively in the non-T2EL group (22.9% vs. 0%, $P = 0.007$). No aneurysm-related deaths occurred in either group. The sources of T2EL were residual LA (52.0%), LAs not detected preoperatively (32.0%), proximal branches from embolized LA (4.0%), combined IMA and residual LA (4.0%), internal iliac artery (4.0%), and vasa vasorum (4.0%). Kaplan—Meier analysis demonstrated no significant difference in overall survival between the groups (log-rank $P = 0.880$) (Fig. 2A). However, freedom from reintervention was significantly lower in the T2EL group (log-rank $P < 0.001$) (Fig. 2B). A total of 11 patients required reintervention during follow-up (4 in the persistent T2EL group and 7 in the non-T2EL group). Reinterventions in the T2EL group included sac plication with branch ligation in 2 patients and coil embolization in one patient for sac enlargement and one leg extension for a type 1b endoleak. In the non-T2EL group, reinterventions included 2 aortic extensions for type 1a endoleak, one leg extension for common iliac artery dilatation, one leg extension for a type 1b endoleak, 2 endovascular revascularizations for limb stenosis or occlusion, and one endovascular revascularization for renal artery occlusion.

Risk Factor Analysis

Univariable analysis identified anticoagulation use, aneurysm diameter, angulated neck, patent number of LAs, thrombus proportion, and residual number of LAs as significant factors associated with T2EL. On multivariable analysis, angulated neck (OR 2.90, 95% CI 1.10—7.66, $P = 0.031$) and residual number of LAs (OR 1.74, 95% CI 1.12—2.70, $P = 0.013$) remained independent predictors (Table IV).

ROC Curve Analysis

ROC curve analysis demonstrated that the residual number of LAs had moderate predictive ability for

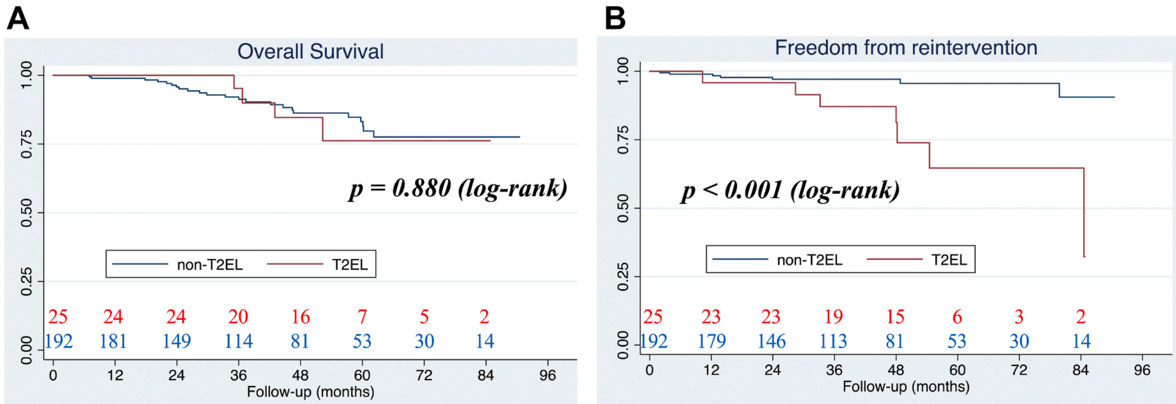

Fig. 2. Kaplan−Meier Analysis of Clinical Outcomes. **(A)** Overall survival after EVAR stratified by the presence or absence of type 2 endoleak (T2EL). **(B)** Freedom from reintervention after EVAR stratified by T2EL status.

Table IV. Logistic regression analysis for risk factors of T2EL

Variable	Univariable analysis OR (95% CI)	*P* value	Multivariable analysis OR (95% CI)	*P* value
Age	1.05 (0.99−1.11)	0.084		
Anti-coagulation	3.47 (1.21−9.94)	0.020	2.39 (0.73−7.90)	0.152
Aneurysm diameter	1.04 (1.01−1.07)	0.020	1.02 (0.99−1.06)	0.220
Angulated neck	4.25 (1.80−10.0)	0.001	2.90 (1.10−7.66)	0.031
Patent number of LAs	1.34 (1.03−1.75)	0.028		
Percentage of thrombus/aneurysm size	0.04 (0.003-0.50)	0.049		
Residual number of LAs	2.00 (1.34−2.97)	0.001	1.74 (1.12−2.70)	0.013

T2EL (AUC = 0.690) (Fig. 3). The optimal cutoff value was 1 residual LA, with a sensitivity of 64.0% and a specificity of 70.3%.

Risk Stratification

A risk score was constructed using the 2 independent predictors of residual LAs ≥1 and angulated neck. The incidence of T2EL increased according to the number of risk factors: 3.5% with no risk factors, 15.7% with residual LAs ≥1 alone, 16.7% with angulated neck alone, and 36.4% with both. Patients with both risk factors had a markedly increased risk (OR 5.98, 95% CI 2.20−16.3) (Table V), with high specificity (93%) but low sensitivity (32%).

Incidence of T2EL According to Conventional High-Risk Anatomy

To evaluate whether conventional anatomical high-risk features remained predictive in the present cohort, patients were stratified according to previously reported criteria (patent IMA ≥3 mm, LA diameter ≥2 mm, or aorto-iliac aneurysm type).[12] The incidence of T2EL was 10.6% (13/123) in the high-risk group and 12.8% (12/94) in the low-risk group, with no significant difference between the groups.

DISCUSSION

The present study evaluated factors associated with persistent T2EL after PBE during EVAR and demonstrated that patients without persistent T2EL showed more favorable sac behavior than those with persistent T2EL. In our cohort, T2EL occurred in 11.5% of the patients, with sac enlargement ≥5 mm observed in 36.0% of the T2EL cases compared with only 4.7% in those without T2EL ($P < 0.001$). Conversely, complete sac regression was observed exclusively in the non-T2EL group (22.9% vs. 0%, $P = 0.007$). In addition, patients without T2EL showed a significantly higher freedom from reintervention during follow-up (log-rank $P < 0.001$). These findings are consistent with previous reports indicating that T2EL is closely

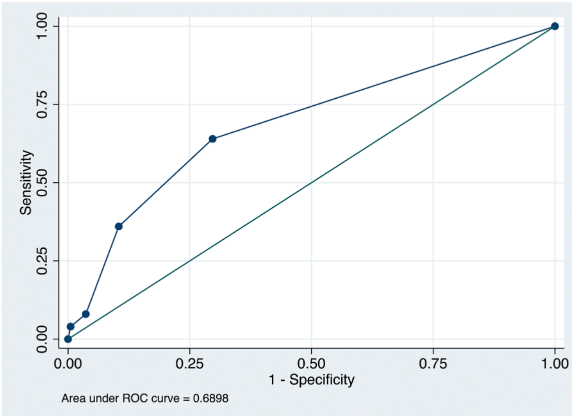

Fig. 3. Receiver Operating Characteristic (ROC) Curve for Residual Lumbar Arteries. ROC curve analysis demonstrating the predictive value of the residual number of lumbar arteries for the development of type 2 endoleak. The area under the curve (AUC) was 0.690. The optimal cutoff value was ≥1 residual lumbar artery.

Table V. Combined risk of T2EL in patients with both risk factors

Variable	Multivariable analysis OR (95% CI)	*P* value
Residual number of LA ≥ 1 and angulated neck	5.98 (2.20−16.3)	<0.001

associated with aneurysm sac enlargement and aneurysm-related adverse events, rather than being a benign condition.[13,14] In a large-scale Japanese national registry, T2EL has been reported to occur in a substantial proportion of patients (27.4%), underscoring its clinical relevance in real-world practice.[14] Notably, continued sac pressurization has been linked to the development of more serious endoleak, including type 1 and 3 endoleak, potentially compromising long-term durability of EVAR.[4,15] In this context, strategies to prevent T2EL are of critical importance. Additionally, we selected T2EL occurrence and sac enlargement as the primary endpoints rather than aneurysm rupture. Given the relatively low incidence of post-EVAR rupture, particularly in a cohort of this size, rupture would not be an appropriate endpoint to adequately assess clinical impact. Instead, sac behavior and T2EL were considered more sensitive and clinically relevant surrogate markers reflecting long-term outcomes after EVAR.

Our previous studies identified anatomical features associated with a high risk of T2EL and demonstrated that preemptive IMA embolization reduced T2EL and improved sac behavior in selected high-risk patients.[11,12] However, T2EL originating from LAs remained a major limitation, suggesting that IMA embolization alone may not be sufficient.[11] Furthermore, discrepancies between our randomized controlled trial and another randomized controlled trial, as well as prospective data from multicenter studies in Japan, suggest that IMA embolization alone may not be sufficient in all cases.[16] While some patients may achieve adequate outcomes with IMA-only embolization, our findings support the concept that a more comprehensive strategy targeting all potential inflow vessels may be necessary to effectively prevent T2EL-related sac enlargement and associated adverse events. These findings highlight the limitation of IMA-only embolization and suggest that additional sources, particularly LAs, play a critical role in the persistence of T2EL. More comprehensive embolization strategies targeting multiple side branches have shown favorable outcomes.[9,10,17–30] A recent meta-analysis also demonstrated reductions in T2EL, sac enlargement, and reintervention with preemptive embolization.[31] Our findings are consistent with these observations.

As previously reported, high-risk anatomical features such as a patent IMA with a diameter ≥3 mm, LA diameter ≥2 mm, or an aorto-iliac aneurysm type are associated with an increased risk of T2EL.[12] However, in the present cohort, as shown in the results, the difference in T2EL incidence between conventionally defined high- and low-risk anatomies was markedly attenuated (10.6% vs. 12.8%). This finding may reflect the effectiveness of preemptive embolization in mitigating the excess risk associated with high-risk anatomy.

Regarding predictive factors, previous studies have highlighted the importance of preoperative branch anatomy. For example, Ide et al. reported that, in patients with a patent IMA, those with ≥4 patent LAs had a higher incidence of T2EL (59.7% vs. 36.5%) and a lower freedom from sac enlargement at 5 years (69.0% vs. 81.7%) compared with those with ≤3 LAs.[32] In the present study, the number of patent LAs was associated with T2EL on univariable analysis, consistent with previous reports emphasizing the importance of preoperative branch anatomy. However, given the close relationship between preoperative patent branches and residual LAs after embolization, including both variables in the same multivariable model may introduce collinearity bias. Therefore, only the number of residual LAs was included in the multivariable analysis. As a result, the number of residual LAs emerged as an independent predictor of T2EL (OR 1.74, $P = 0.013$), and ROC analysis identified $\geq$1 residual LA as the optimal cutoff (AUC = 0.690). These findings are consistent with previous reports highlighting the importance of residual branches. For example, Shirasu et al. demonstrated that T2EL occurred in 7.5% of the patients with 0–2 residual LAs, compared with 35.6% in those with $\geq$3 branches at 3 years, emphasizing the importance of minimizing residual branches.[21]

Furthermore, patients with both angulated neck and residual LAs had a markedly increased risk (OR 5.98), highlighting the importance of both anatomical and technical factors. In cases with marked neck angulation, incomplete coverage of LA orifices at the aneurysm transition zone may contribute to persistent retrograde flow. Although this mechanism was not directly evaluated, complete embolization of LAs, including those near the aneurysm transition zone, may help reduce persistent T2EL and facilitate recognition of occult proximal endoleak during follow-up.

Regarding the source of T2EL, residual LAs accounted for the majority (52.0%), followed by LAs not detected preoperatively (32.0%). These findings emphasize the importance of meticulous preoperative imaging assessment. However, the relatively high proportion of previously undetected LAs also suggests that collateral network remodeling may occur after EVAR, as described in the experimental studies of spinal collateral circulation.[33] Therefore, even small or occult branches may become clinically relevant over time.

Finally, when compared with a historical nonembolization cohort of 183 patients who underwent EVAR at our institution between April 2007 and September 2014, PBE demonstrated a favorable clinical impact (Supplemental Table 1). Although no significant difference in overall survival was observed, reintervention-free survival was significantly improved in the PBE group (log-rank $P < 0.001$) (Supplemental Fig. 1A, B). These findings might suggest that PBE contributes to improved clinical stability by suppressing sac enlargement and reducing the need for secondary procedures, thereby supporting its role as a strategy to enhance the long-term durability of EVAR despite differences in treatment eras.

From a clinical perspective, management of T2EL-related sac enlargement remains challenging. Current ESVS guidelines recommend reintervention for sac enlargement $\geq$10 mm.[7] However, endovascular treatment is often unsuccessful, and some patients ultimately require open surgical conversion.[34] Therefore, prevention of persistent T2EL remains clinically important. PBE was associated with longer operative time, fluoroscopy time, and contrast volume, highlighting the need to balance procedural invasiveness against clinical benefit. These findings suggest that selective application of PBE to patients most likely to benefit may be a reasonable strategy.

LIMITATIONS

This study has several limitations. First, this was a retrospective, single-center study, and the indication for preemptive branch embolization was not strictly standardized, potentially introducing selection bias. Although our institution adopted a policy of attempting embolization in most patients, the final decision was left to the discretion of the operating surgeon, and patient factors such as age, functional status, and comorbidities may have influenced treatment selection.

Second, a potential learning curve effect cannot be excluded, as procedural techniques and operator experience in achieving complete embolization may have evolved over the study period, which may have influenced the number of residual LAs and the incidence of T2EL.

Third, the follow-up duration varied among patients, which may have affected the assessment of long-term outcomes, particularly the incidence of late T2EL and sac behavior.

Fourth, the sample size was relatively limited, which may have reduced the statistical power to detect additional risk factors.

Finally, residual LAs were assessed based on postoperative imaging, and the possibility of undetected small branches or dynamic changes in collateral circulation cannot be excluded.

Further prospective studies with standardized protocols and longer follow-up are warranted to validate these findings and to establish optimal indications for selective embolization strategies.

CONCLUSION

Persistent T2EL after PBE was associated with unfavorable sac behavior and an increased need for reintervention. Residual LAs and angulated neck anatomy were independent predictors of persistent T2EL. These findings may help identify patients at increased risk for persistent T2EL after PBE and may contribute to procedural planning and postoperative surveillance. Further comparative studies are warranted to clarify the clinical benefit and optimal indications for PBE. In particular, when PBE is performed in patients with angulated neck anatomy, achieving complete embolization may be critical to minimize the risk of persistent T2EL.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Takahiro Mizoguchi: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Noriyasu Morikage:** Writing – review & editing, Resources, Investigation, Data curation, Conceptualization. **Yuriko Takeuchi:** Software, Methodology, Conceptualization. **Makoto Samura:** Investigation, Data curation, Conceptualization. **Takasuke Harada:** Conceptualization. **Hiroshi Kurazumi:** Visualization, Conceptualization. **Kotaro Suehiro:** Data curation, Conceptualization.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.avsg.2026.07.006.

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