Post-EVAR Endoleaks: A Morphovolumetric Approach to Prediction, Surveillance, and Management

Külahcıoğlu Emre * , Özçelik Sinan , Koçak Nuh Can , Çiçekyurt Emre , Akkaya Bekir Boğaçhan , Aytekin Bahadır , İşcan Hakkı Zafer

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Article

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Abstract

Objective: To evaluate the association of preoperative morphometric and morphovolumetric parameters with post-endovascular aneurysm repair (EVAR) sac remodeling, endoleak development, and secondary interventions, and to assess the role of volumetric analysis in post-EVAR surveillance. **Methods**: This retrospective single-center study included 383 patients who underwent elective EVAR for infrarenal abdominal aortic aneurysm between 2016 and 2024, with available pre- and postoperative computed tomography angiography and at least 1 year of follow-up. Diameter- and volume-based sac dynamics were analyzed using standardized morphometric and 3-dimensional morphovolumetric measurements. Endoleak subtype distribution, risk factors, secondary interventions, and survival were assessed using regression and survival analyses. **Results**: Endoleaks were detected in 26.1% of patients (n = 100), with type II endoleak being the most frequent subtype (12.3%, n = 47), followed by type Ib (6.8%, n = 26), type III (5.5%, n = 21), type Ia (4.2%, n = 16), and 1 patient with type V endoleak in the revised manuscript framework. Secondary interventions were required in 14.1% of patients (n = 54), mainly for type I and III endoleaks, with a mean time to reintervention of 21.7 ± 10 months. Diameter and volume changes were strongly correlated; a 10% increase in aneurysm volume corresponded to an average 4 mm increase in diameter (R^2 = 0.72, $p < 0.001$). Volumetric analysis detected sac change earlier than diameter measurements, particularly in stable sacs and type II endoleaks. Significant predictors of overall endoleak included dual antiplatelet therapy, aneurysm length >133 mm, elevated pre- and postoperative D-dimer levels, aneurysm diameter >59 mm, aneurysm volume >164 cm^3, and thrombus volume >89 cm^3. Subtype-specific analyses identified distinct risk profiles for type Ia, Ib, II, and III endoleaks. Overall survival did not differ significantly between patients with and without endoleaks (p = 0.227), although worse survival was observed in type Ia and III endoleaks than in type II and Ib endoleaks. **Conclusion**: Preoperative morphovolumetric parameters are significant predictors of post-EVAR endoleaks and secondary interventions. Volumetric analysis appears more sensitive than diameter-based assessment for early detection of sac remodeling, especially in type II endoleaks. Post-EVAR management should integrate endoleak subtype, sac behavior, and patient-specific morphovolumetric risk factors to improve surveillance and treatment selection.

Keywords: endoleak; EVAR; aortic aneurysm; endovascular; volumetric

1. Introduction

Endovascular aneurysm repair (EVAR) has revolutionized the management of infrarenal abdominal aortic aneurysms (AAA), providing a less invasive alternative to open surgical repair

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(OSR), with reduced perioperative morbidity and mortality. Randomized controlled trials (RCTs), including EVAR-1, DREAM, OVER, and ACE, have demonstrated favorable early outcomes with EVAR, such as lower 30-day mortality and faster recovery, leading to its widespread adoption for anatomically suitable patients. [1-3] Advances in graft technology, including new-generation materials and active fixation systems, have expanded anatomical applicability, improved sealing, and reduced complications.[1-5]

EVAR offers several advantages over OSR, including shorter hospital stays, decreased blood loss, faster recovery, and lower early mortality [3] however long-term survival rates tend to converge.[2, 6] EVAR is particularly advantageous in elderly or comorbid patients at high risk for open surgery.[7, 8] Its minimally invasive nature allows treatment of a broader patient population, including those with significant comorbidities.[9, 10]

New generation stent-grafts improved conformability, sealing and fixation therefore reduced complications such as endoleaks and graft migration. These facts allowed tailored approaches to complex anatomies.[4, 5] Active fixation systems, including EndoAnchors and EndoStaples, mechanically attach the graft to the aortic wall, enhancing the proximal seal and minimizing the risk of migration, especially in hostile neck anatomy (short, angulated, conical necks).[2, 4, 11] These devices demonstrate high technical success and durable outcomes in preventing type I endoleaks. Low-profile delivery systems and improved materials have expanded the applicability of EVAR to patients with challenging iliac anatomy and smaller access vessels.[4, 5]

Endoleaks are persistent blood flow outside the endograft but within the aneurysm sac, the most common complication after EVAR, with incidence rates reported between 15% and 30%.[4, 5, 7, 12, 13] They are classified into five types based on origin and pathophysiology:

- **Type I**: Inadequate seal at proximal (Ia) or distal (Ib) attachment sites, resulting in direct sac pressurization with high rupture risk requiring prompt intervention
- **Type II**: Retrograde flow from collateral vessels (inferior mesenteric artery [IMA], lumbar arteries, accessory renal artery), most common and often benign but may cause sac enlargement necessitating treatment
- **Type III**: Structural failure of the graft, including modular component disconnection (IIIa) or fabric disruption (IIIb), leading to high-flow leaks with significant rupture risk
- **Type IV**: Relatively uncommon today because of new generation endografts and is usually transient**.** It results from graft fabric porosity, allowing blood to seep through the graft material into the aneurysm sac.
- **Type V (Endotension)**: Sac enlargement without identifiable leak, possibly due to transmitted pressure or occult leaks

Management strategies vary by endoleak type:

- **Type I and III** require urgent repair. Endovascular options include balloon angioplasty, extension cuffs, embolization, and active fixation devices like EndoAnchors.[5-8, 11, 12, 14] Surgical conversion remains the definitive option when endovascular treatment fails.[5]
- **Type II** From a clinical perspective, the decision to treat type II endoleaks (T2EL) should not be based solely on their presence but rather on their hemodynamic significance. Current evidence supports intervention primarily in cases demonstrating aneurysm sac expansion greater than 5 mm, persistence beyond 6 months, or the presence of multiple large feeding vessels. In contrast, stable aneurysm sacs without evidence of growth may be safely managed with surveillance alone. Preemptive selective vessel or sac embolization are also potential alternative techniques for T2EL management.
- **Type IV** endoleaks mostly resolve spontaneously, therefore observation and correction of coagulopathy is the standard, persistent cases should trigger reassessment of diagnosis and intervention is rarely required
- **Type V** endoleaks require close monitoring; relining or open repair is considered if sac enlargement continues.[7]

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Despite significant advances in endovascular technology and imaging modalities, the optimal management of endoleaks remains a subject of ongoing debate. In particular, the management of T2EL varies widely across institutions, reflecting uncertainty regarding treatment thresholds and optimal intervention strategies.

The primary tool for EVAR surveillance was CTA. CDUS was also a surveillance tool for our patient cohort however, for this study, morphovolumetric analysis was performed, and volumetric or conventional diameter measurements were utilized for sac Dynamics.[15, 16] Consequently, the 2-phase of (venous and arterial phase) CTA was considered the preferred approach to identify endoleaks for post-EVAR follow-up.

Currently, there is no universally accepted, clinically applicable framework that integrates anatomical features, hemodynamic behavior, and aneurysm sac dynamics into a structured decision-making process. Therefore, this study aims to provide a comprehensive overview of endoleak management and propose a practical algorithm to guide treatment selection in clinical practice, however our study does not go in depth to describe each treatment.

2. Materials and Methods

Patients who underwent elective endovascular aneurysm repair (EVAR) for infrarenal abdominal aortic aneurysms (AAA) between 2016 and 2024 at our single tertiary medical center were retrospectively evaluated. Inclusion criteria comprised availability of both preoperative and postoperative contrast-enhanced computed tomography angiography (CTA) and a minimum follow-up duration of one year. A total of 383 patients met these criteria. Ethical approval was obtained from the Health Sciences University Ankara Bilkent City Hospital Medical Research Scientific and Ethical Review Board (decision no: TABED 1-25-1189, dated 09.04.2025).

Exclusion criteria included patients with ruptured AAAs requiring emergency intervention, those with concomitant descending thoracic aortic aneurysms treated with TEVAR, juxtarenal AAAs, complex endovascular procedures, incomplete preoperative or postoperative CTA data, and follow-up shorter than one year. All procedures were performed by the same surgical team.

The primary endpoints of the study were to assess the impact of morphological and morphovolumetric parameters on aneurysm sac diameter and volume changes following EVAR, as well as their association with endoleak development. Secondary endpoints included rates and causes of secondary interventions, mortality, and morbidity post-EVAR.

Data collection was categorized into preoperative, intraoperative, postoperative, and follow-up phases. Preoperative data encompassed patient demographics, ejection fraction, history of prior abdominal surgeries, CTA-based measurements including aneurysm sac diameter, presence and localization of thrombus within the sac and neck, neck calcification, iliac tortuosity, and presence of iliac aneurysms. Three-dimensional (3D) total aneurysm sac volume, thrombus volume, and thrombus density were quantified. Intraoperative data included fluoroscopy times, contrast volumes used, and the occurrence of Type 1 endoleaks during or immediately after the procedure. Postoperative data comprised intensive care and ward stay durations, complications, length of hospitalization, and early mortality. Follow-up data included serial CTA measurements of aneurysm diameter, 3D total volume, thrombus volume and density, presence of endoleaks, secondary interventions, and late mortality. All patients were enrolled in a standardized postoperative surveillance protocol following EVAR. Follow-up evaluations were systematically conducted at 1 month, 6 months, and 12 months after the index procedure. At each time point, patients underwent clinical assessment and contrast-enhanced computed tomography angiography (CTA) using the same acquisition protocol as the preoperative imaging. Follow-up imaging focused on aneurysm sac diameter and volumetric changes, thrombus characteristics, graft integrity, and detection and classification of endoleaks. In addition, secondary interventions and late complications were recorded. In patients with contraindications to contrast agents, duplex ultrasonography was used as an alternative modality. This structured follow-up allowed consistent longitudinal evaluation of aneurysm sac remodeling and post-EVAR complications.

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Postoperatively, all patients received β-blockers and Acetyl Salicilic asit (ASA). In cases with external iliac artery extension, severe iliac tortuosity or significant atherosclerotic changes, dual antiplatelet therapy (ASA and clopidogrel) was initiated.

2.1. CTA Measurements

Preoperative and postoperative CTA-based diameter and angle measurements were performed using 3MENSIO Vascular software and the Sarus Workstation connected to the Ankara City Hospital database. Coronal, sagittal, axial, and 3D reconstructions were analyzed, and data were exported to Excel. Morphometric parameters commonly used in infrarenal aortic aneurysm preoperative planning included maximum aneurysm diameter, neck length, neck diameter, aneurysm length, and aortic angulation (Figure 1).

3D morphovolumetric measurements were conducted by a cardiovascular surgeon and a radiologist with 10 years of experience using the Sarus Workstation. Volumes were measured in cubic centimeters (cm^3), and densities in Hounsfield units (HU), from the proximal, mid, and distal aneurysm segments; the average of these three measurements was recorded. CTA scans were acquired with 128- and 512-detector CT scanners (GE Healthcare) following intravenous administration of 120 ml contrast at 4 ml/s during the arterial phase (20 seconds). Images were reviewed in axial, coronal, and sagittal planes, and semi-automated volumetric software (Advantage Workstation 4.2, GE Healthcare Technologies) was used to delineate the aneurysm sac outer wall circularly at the widest diameter to calculate diameter and volume. Thrombus volume was derived by subtracting patent lumen volume from total aneurysm volume.

Preoperative and postoperative CTA measurements were performed with identical protocols.

Aneurysm sac dynamics post-EVAR were primarily monitored via changes in diameter and volume, which are the most widely accepted parameters. The Society for Vascular Surgery (SVS) defines significant sac growth as an increase in diameter of ≥5 mm or volume increase of ≥5%. Literature frequently uses a 5 mm threshold for diameter change and volume thresholds ranging from 5% to 10%. In this study, linear regression analysis demonstrated that a 10% increase in aneurysm volume corresponded to a 4 mm increase in diameter; thus, a 10% volume increase was adopted as the cutoff for positive remodeling.

Sac size changes were classified as follows: an increase in maximum diameter ≥5 mm was defined as "expanding sac," a decrease ≥5 mm as "shrinking sac," and changes within these limits as "stable sac." Similarly, volumetric analysis categorized >10% decrease as "shrinking sac," >10% increase as "expanding sac," and changes between these values as "stable sac."

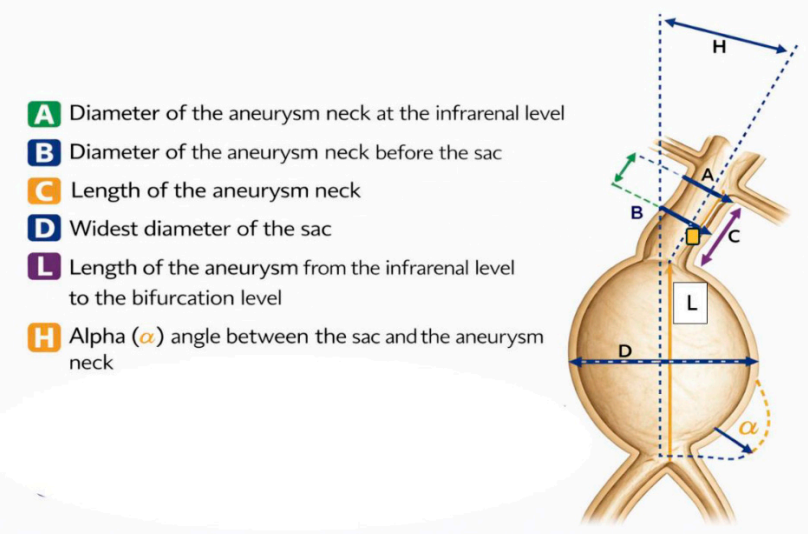

Figure 1. Morphometric parameters of Infrarenal Aortic Aneurysm.

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2.2. Statistics

Data analysis was performed using IBM SPSS 27.0 and MedCalc 15.8. Descriptive statistics included frequency, percentage, mean, standard deviation, median, and range. Categorical variables were compared with the Chi-square test. Normality was assessed via Kolmogorov-Smirnov test, skewness-kurtosis, and graphical methods (histogram, Q-Q plot, stem-and-leaf, boxplot). For normally distributed continuous variables, Independent Samples t-test was used; for non-normal data, Mann-Whitney U test was applied. ROC curve analysis evaluated variable discriminative ability, binary logistic regression assessed risk factors, and Kaplan-Meier with Log-Rank tests analyzed survival. Pearson correlation tested relationships between variables, and linear regression assessed effects. Statistical significance was set at $p < 0.05$.

3. Results

A total of 383 patients undergoing elective EVAR for iAAA were retrospectively analyzed. The cohort was predominantly male (93%) with a mean age of 71.8 ± 7.8 years. Comorbidities were common, with hypertension (82%), smoking history (70%), and coronary artery disease (53%) being most prevalent.

Endoleaks were detected in 26.1% (n=100) of the patients during follow-up. The distribution of endoleak subtypes was as follows (Table 1)

Table 1. Clinical outcomes, endoleak distribution, complications, risk factors and mortality after EVAR (n = 383).

Variable	Threshold / Definition	Type Ia (p / OR)	Type Ib (p)	Type II (p / OR)	Type III (p)	Overall Endoleak (p)
Age	—	**0.021 / —**	—	—	—	—
Neck length	**Short**	**0.001 / —**	—	—	—	—
Conical neck morphology	—	**<0.001 / 16.9**	—	—	—	—
Alpha angle	**>55°**	**<0.001 / 5.7**	—	—	—	—
Neck calcification	**Present**	**<0.001 / 21.3**	—	—	—	—
Neck thrombus	**Present**	**0.010 / 4.2**	—	—	—	—
Peripheral arterial disease	—	—	**0.004**	—	—	—
Iliac artery aneurysm	—	—	**0.001**	—	**<0.001**	—
Aneurysm length	**>133 mm**	—	**0.001**	—	—	**<0.001**
Aneurysm length	**>139 mm**	—	—	—	**<0.001**	—

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Aneurysm diameter	**>59 mm**	**—**	**—**	**—**	**—**	**<0.001**
Aneurysm diameter	**>62 mm**	**—**	**—**	**—**	**0.001**	**—**
Aneurysm volume	**>164 cm³**	**—**	**—**	**—**	**—**	**<0.001**
Aneurysm volume	**>208 cm³**	**—**	**—**	**—**	**0.004**	**—**
Thrombus volume	**>89 cm³**	**—**	**—**	**—**	**—**	**0.006**
Thrombus volume	**>118 cm³**	**—**	**—**	**—**	**0.002**	**—**
TR/AO ratio	**—**	**—**	**—**	**0.010 / 0.96**	**—**	**—**
TR/AO ratio	**>52%**	**—**	**—**	**—**	**<0.001**	**—**
IMA diameter	**>3 mm**	**—**	**—**	**<0.001 / 17.5**	**—**	**—**
Lumbar arteries	**≥4**	**—**	**—**	**0.001**	**—**	**—**
Posterior thrombus	**—**	**—**	**—**	**<0.001 / 2.9**	**—**	**—**
Iliac tortuosity	**—**	**—**	**—**	**—**	**<0.001**	**—**
Dual antiplatelet therapy (ASA + clopidogrel)	**—**	**—**	**—**	**<0.001 / 9.2**	**—**	**<0.001**
D-dimer (preoperative)	**Elevated**	**—**	**—**	**—**	**—**	**0.006**
D-dimer (postoperative)	**Elevated**	**—**	**—**	**—**	**—**	**0.010**

- Type II: 12.3% (n=47) – most frequent subtype, primarily arising from lumbar arteries and inferior mesenteric artery (IMA).
- Type Ib: 6.8% (n=26)
- Type III: 5.5% (n=21)
- Type Ia: 4.2% (n=16)
- Type V: 0.3% (n=1)

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Multiple endoleak types were observed concurrently in a subset of patients during follow-up. In some cases, more than one endoleak subtype required simultaneous treatment within the same intervention session. Due to overlapping classifications and retrospective data structure, a precise numerical breakdown of combined endoleak patterns (e.g., dual or triple combinations) could not be consistently determined.

3.1. Mean Time to Endoleak Diagnosis and Intervention by Endoleak Type

Secondary interventions were necessary in 14.1% (n=54) of patients, mainly for Type I and III endoleaks, reflecting their higher rupture risk and clinical significance. The mean time to secondary intervention was 21.7 ± 10 months. Among these:

- Type Ia endoleaks (n=16): Type Ia endoleaks (n=16) were predominantly managed with endovascular techniques, in accordance with current EVAR guidelines recommending prompt treatment due to their direct systemic pressurization of the aneurysm sac. [5,6]
- Type Ib endoleaks (n=26): All treated with iliac extensions.
- Type III endoleaks (n=21): 16 treated endovascularly, 1 with open surgery, 3 untreated due to refusal or clinical status.

Volumetric and diameter analyses demonstrated a strong correlation (R^2=0.72, p<0.001) where a 10% change in aneurysm volume corresponded to an average 4 mm change in diameter. Volumetric measurements detected sac changes earlier than diameter alone, particularly in stable sacs and type II endoleaks, underscoring the sensitivity of volumetric assessment in endoleak monitoring. (Figure 2,3)

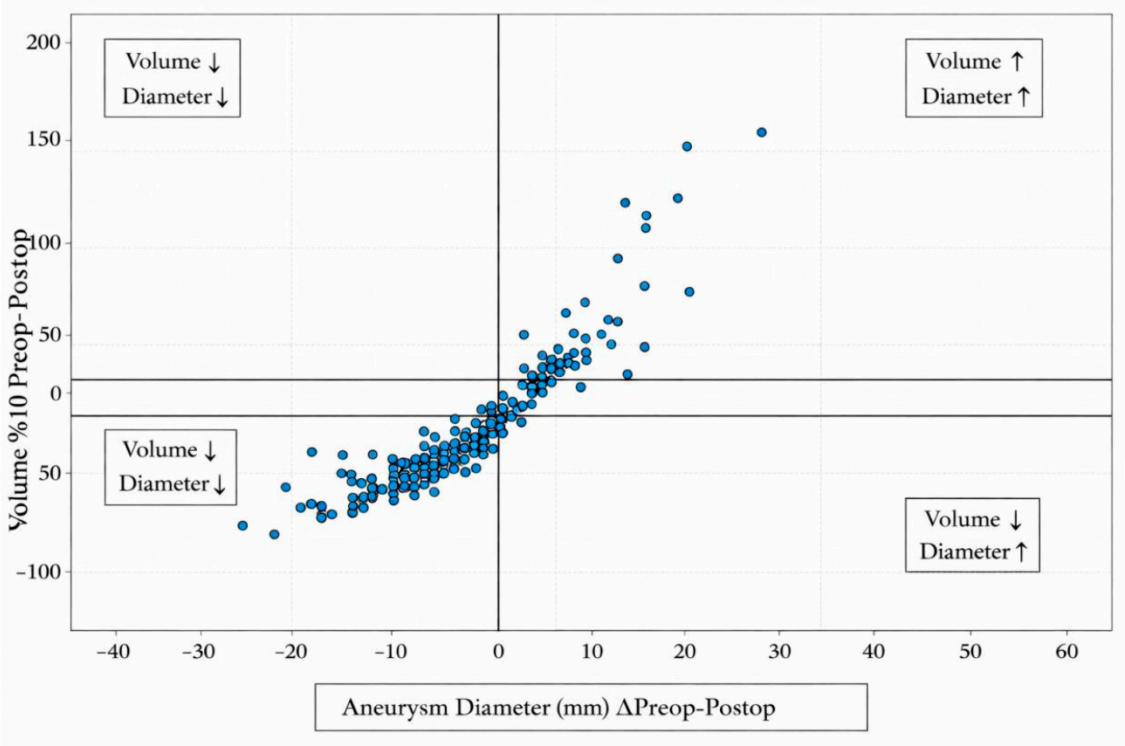

Figure 2. Scatter plot showing the relationship between aneurysm diameter and volume changes.

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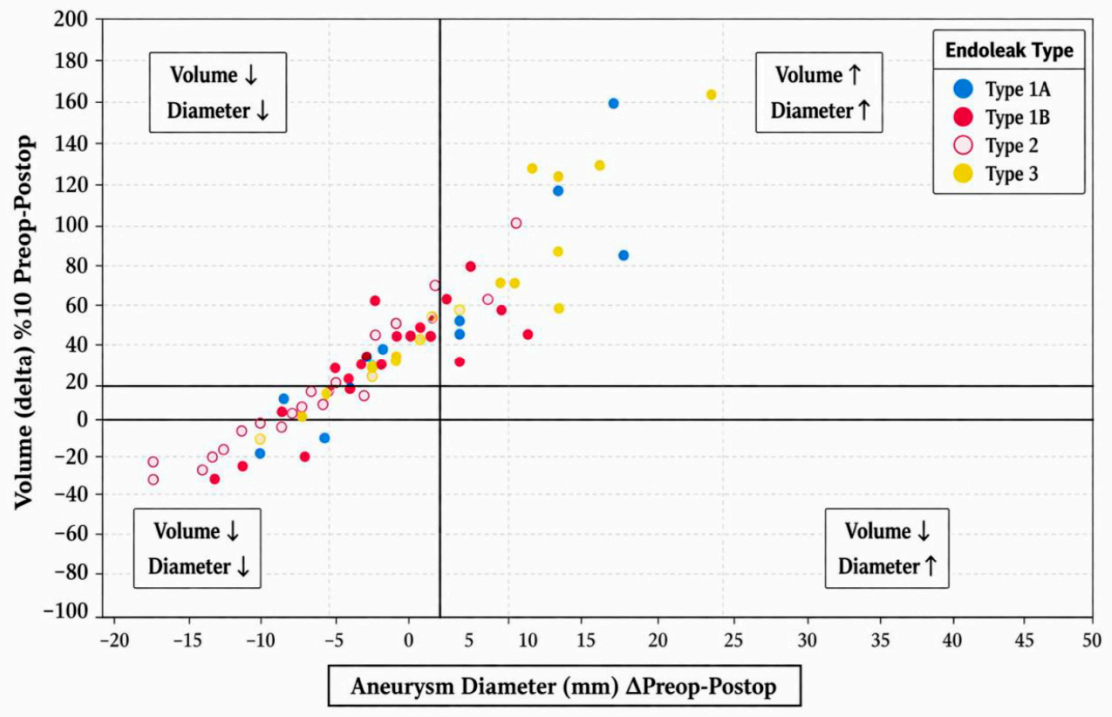

Figure 3. Distribution of sac diameter and volume changes by endoleak type.

Multifactorial analysis identified several significant risk factors associated with overall endoleak development

- Dual antiplatelet therapy (ASA + clopidogrel) ($p<0.001$)
- Preoperative aneurysm length >133 mm ($p<0.001$)
- Elevated preoperative ($p=0.006$) and postoperative ($p=0.010$) D-dimer levels
- Preoperative aneurysm diameter >59 mm ($p<0.001$)
- Aneurysm volume >164 cm^3 ($p<0.001$)
- Thrombus volume >89 cm^3 ($p=0.006$)

3.2. Endoleak Subtype-Specific Risk Profiles

- **Type Ia Endoleak:** Associated with advanced age, short neck length, conical neck morphology, alpha angle >55°, neck calcification, and neck thrombus presence (Table 1).
- **Type Ib Endoleak:** Correlated with peripheral arterial disease, aneurysm length >133 mm, and presence of iliac artery aneurysms
- **Type II Endoleak:** Risk factors included dual antiplatelet therapy, IMA diameter >3 mm, presence of ≥4 patent lumbar arteries, thrombus ratio to aortic lumen (TR/AO), and posterior thrombus localization. These parameters reflect the importance of collateral vessel anatomy and thrombus characteristics in type II endoleak pathophysiology (Table 1)
- **Type III Endoleak:** Linked to larger aneurysm dimensions, thrombus volume, iliac tortuosity, and iliac aneurysm presence. These findings highlight mechanical stresses and graft component integrity as key factors in type III endoleak development

At follow-up, 74.7% of patients exhibited aneurysm sac diameter reduction, 18.5% had stable sac size, and 6.8% experienced sac enlargement. Volumetric analysis revealed more sensitive detection of sac expansion, particularly in type II endoleaks (Table 1).

Kaplan–Meier survival analyses showed no statistically significant difference in overall survival between patients with and without endoleaks ($p=0.227$), suggesting that vigilant follow-up and timely secondary interventions may mitigate adverse outcomes (figure 4)

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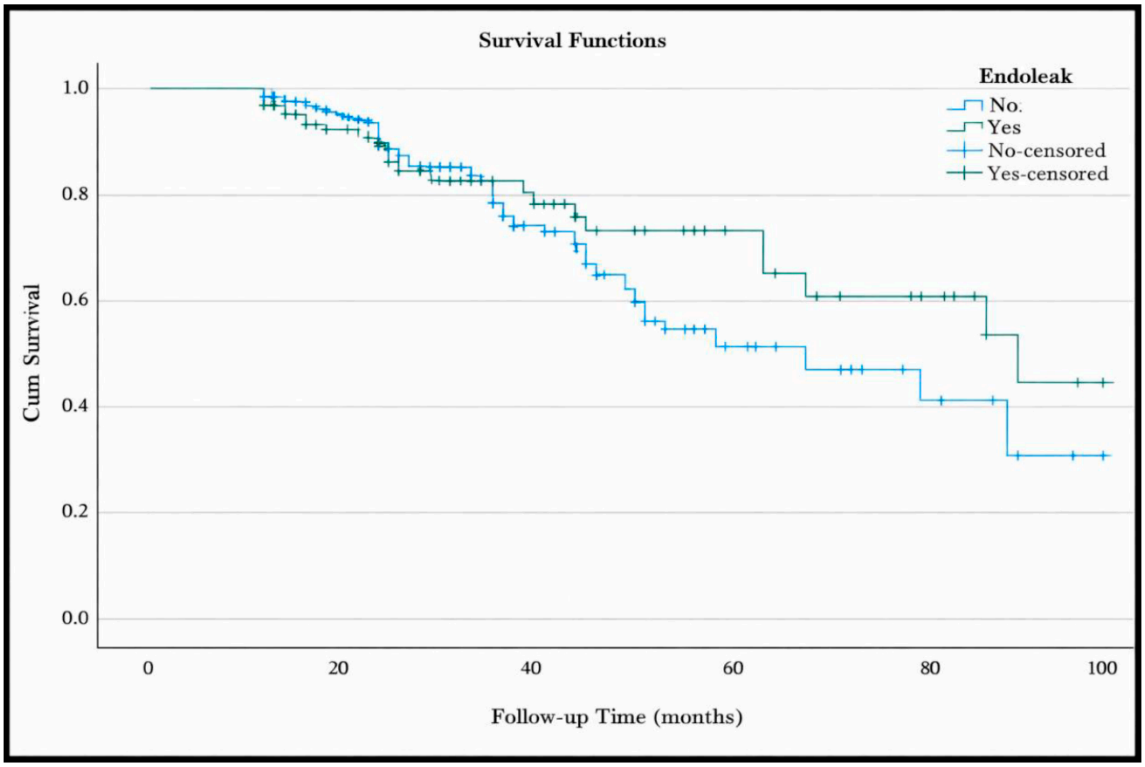

Figure 4. Kaplan–Meier survival curves by endoleak presence.

However, subtype analysis demonstrated worse survival associated with type Ia and III endoleaks compared to type II and Ib, consistent with their higher rupture risk profiles.

Based on current evidence and clinical practice, we propose a structured decision-making framework for the management of endoleaks following EVAR. (figure 5)

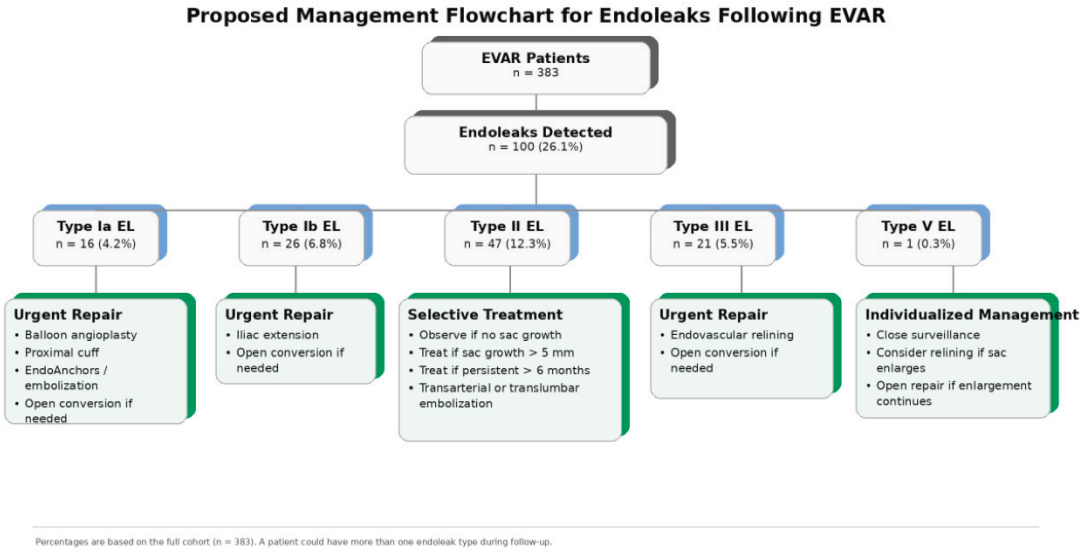

Figure 5. Proposed Management Flowchart for Endoleaks Following EVAR.

Type I and Type III endoleaks require urgent intervention due to direct pressurization of the aneurysm sac. Initial management includes balloon angioplasty and extension cuff placement, with consideration of endoanchors or embolization in refractory cases.

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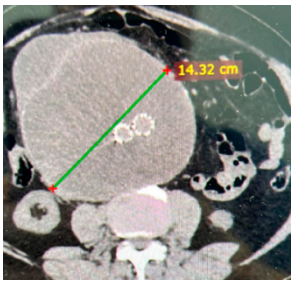
T2ELs should be managed selectively. In cases without aneurysm sac expansion, conservative surveillance is appropriate. Intervention is recommended in patients with sac enlargement greater than 5 mm, persistent endoleaks beyond 6 months, or complex inflow-outflow vessel anatomy.

For treatment, transarterial embolization is preferred in patients with accessible feeding vessels, whereas translumbar embolization should be considered in cases of unfavorable vascular anatomy or prior failed interventions.

Endotension (Type V) remains a diagnostic and therapeutic challenge, with management strategies ranging from observation to endograft relining or open surgical conversion depending on clinical progression. There was only one patient in our cohort with a documented type V endoleak who declined surgical intervention, likely due to frailty and advanced age. This patient presented with aneurysm rupture and died 11 months later. (Image 1).



4. Discussion

The management of endoleaks continues to represent one of the most complex and debated aspects of EVAR follow-up. While the need for immediate intervention in Type I and III endoleaks is well established due to direct aneurysm sac pressurization, significant controversy persists regarding the optimal management of T2ELs, particularly in asymptomatic patients without sac expansion. In our cohort, T2ELS were the predominant subtype encountered (12.3%), yet only a limited number of patients (n=2) required secondary intervention, while a substantial proportion (53.2%) resolved spontaneously during follow-up. These findings suggest that most Type II endoleaks have a relatively benign natural course and may not necessitate immediate intervention. In contrast, Type I and Type III endoleaks were managed with early intervention due to their direct hemodynamic impact and associated risk of persistent aneurysm sac pressurization and rupture. Therefore, our results support a management strategy in which treatment decisions are guided primarily by aneurysm sac behavior and endoleak type, rather than the mere presence of an endoleak.

EVAR has become the preferred treatment modality for iAAAs owing to its less invasive nature and favorable early outcomes.[1-3, 6, 9, 11, 14, 17-21] However, concerns regarding long-term durability persist, as complications such as endoleaks and secondary interventions have been reported in up to 30% of patients within a decade.[3] In our previously published study on late EVAR conversion, patients requiring conversion to open repair demonstrated significantly increased perioperative morbidity and mortality, highlighting the substantial clinical burden associated with late EVAR failure.[22] These findings emphasize the importance of meticulous preoperative planning and detailed anatomical assessment. Although adherence to device-specific instructions for use (IFU) has been associated with improved outcomes in previous studies, [23, 24] our dataset did not include a formal analysis of IFU compliance; therefore, this aspect should be interpreted in the context of existing literature rather than as a direct finding of the present study. In our cohort, preoperative parameters such as aneurysm length, maximum diameter, total sac volume, and thrombus burden were significantly associated with the development of endoleaks and the need for secondary interventions. These results highlight the value of morphovolumetric assessment in predicting post-EVAR outcomes and support a more individualized risk stratification strategy rather than a uniform surveillance approach.

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Volumetric sac analysis appears to provide greater sensitivity than conventional diameter-based measurements (Dmax) in detecting early aneurysm sac changes, particularly in patients with T2ELs, where subtle volumetric expansion may precede measurable diameter increase. Despite this advantage, maximum sac diameter remains the most widely used parameter in routine clinical practice due to its simplicity, rapid assessment, and reproducibility across centers. However, reliance solely on diameter measurements may underestimate clinically relevant sac progression, especially in cases with asymmetric or localized expansion. In contrast, volumetric analysis offers a more comprehensive evaluation of sac dynamics and may improve early risk stratification. With the development of automated and semi-automated imaging software, volumetric assessment is becoming increasingly feasible and time-efficient, suggesting that it may play a more prominent role in post-EVAR surveillance in the future, particularly for patients at higher risk of persistent endoleaks.

Endoleak subtype-specific analyses revealed distinct and clinically relevant risk profiles. Type Ia endoleak was significantly associated with advanced age, short proximal neck length, conical neck morphology, α-angle >55°, presence of neck calcification, and neck thrombus (all $p<0.05$). Also supported by previous studies that presence of more than one risk factor of those significantly effects development of Type Ia endoleak.[25] Type Ib endoleak was significantly correlated with peripheral arterial disease, aneurysm length >133 mm, and the presence of iliac artery aneurysms ($p<0.05$). Ongoing aneurysmal disease and the radial force of the endograft may also be factors influencing this type of endoleak. Type II endoleak demonstrated strong associations with dual antiplatelet therapy ($p<0.001$), inferior mesenteric artery diameter >3 mm ($p<0.05$), the presence of ≥4 patent lumbar arteries ($p<0.05$), increased thrombus-to-lumen ratio (TR/AO) ($p<0.05$), and posterior thrombus localization ($p<0.05$). Type III endoleak was significantly associated with larger aneurysm diameter, increased thrombus volume, iliac tortuosity, and iliac artery aneurysm presence ($p<0.05$).

Our study also identified dual antiplatelet therapy as a significant factor associated with increased endoleak risk. This finding can be explained by impaired thrombus formation within the aneurysm sac, facilitating persistent retrograde perfusion, particularly T2ELs. This observation highlights the potential impact of systemic pharmacotherapy on endoleak persistence and suggests that antiplatelet regimens may need to be considered when evaluating post-EVAR sac behavior.

The management of T2EL remains particularly challenging. Consistent with prior studies, our findings support a selective treatment approach based on aneurysm sac dynamics rather than endoleak presence alone. Persistent endoleaks associated with sac expansion, especially greater than 5 mm, should prompt intervention, whereas stable sacs may be safely observed. Endovascular treatment strategies for T2EL primarily include transarterial and translumbar embolization techniques, each with distinct advantages and limitations. Transarterial approaches are less invasive and suitable for anatomically favorable cases but may be limited by vessel tortuosity and incomplete nidus occlusion. In contrast, translumbar embolization allows direct access to the aneurysm sac and has demonstrated higher technical success and durability, particularly in cases with complex collateral anatomy or failed prior interventions. In our opinion, translumbar embolization should be considered the preferred approach in such complex cases, while transarterial embolization remains a valid first-line option in selected patients. In our cohort, no preemptive intervention was performed for T2ELs, and only two patients required post-EVAR intervention during follow-up. Despite advances in embolization techniques, recurrence remains a significant issue, often related to incomplete treatment of the endoleak nidus and collateral vessels. Therefore, effective management requires embolization of both inflow and outflow vessels in addition to the nidus itself, frequently utilizing combined embolic materials such as coils and liquid agents to improve long-term occlusion rates.[24]

Technological advancements in endograft design have contributed to improved procedural outcomes. Devices incorporating active fixation mechanisms, such as EndoAnchors, have been shown to enhance proximal sealing and reduce the incidence of type I endoleaks, particularly in patients with hostile neck anatomy.[2, 7, 26] However, in our practice, EndoAnchor use has been

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limited, primarily due to additional procedural cost and resource considerations. Therefore, our approach continues to rely on careful preoperative planning and strict adherence to anatomical suitability criteria to achieve adequate proximal sealing. Nevertheless, type III endoleaks, often related to modular disconnection or graft material fatigue, remain a concern, particularly in large aneurysms and those with significant iliac tortuosity.[11,18-20, 27]

Imaging surveillance remains a cornerstone of post-EVAR management. Current guidelines from the Society for Vascular Surgery (SVS) and European Society for Vascular Surgery (ESVS) recommend structured follow-up protocols, typically incorporating computed tomography angiography (CTA) at 1, 6, and 12 months, followed by annual imaging.[7, 12] Alternative modalities such as duplex ultrasound (CDUS), contrast-enhanced ultrasound (CEUS), and magnetic resonance angiography (MRA) may be utilized selectively, particularly in patients requiring reduced radiation or contrast exposure. It has been reported that approximately 0.5% of patients undergoing EVAR may develop radiation-induced malignancy over their lifetime, largely attributable to serial postoperative CT imaging.[28] This underscores the importance of tailoring follow-up protocols based on individual patient risk, aneurysm sac behavior and the presence or absence of endoleaks. In selected low-risk patients, alternative imaging modalities such as DUS or CEUS may reduce radiation exposure while maintaining adequate surveillance.

In our cohort, comparison of patients who underwent secondary intervention versus those who did not revealed a median survival of 86 months and 66 months, respectively. However, this difference was not statistically significant according to Kaplan–Meier analysis (log-rank $p = 0.556$). These findings suggest appropriate secondary interventions on time may mitigate the potential adverse impact of post-EVAR complications on long-term survival. The integration of volumetric analysis into follow-up protocols may further improve sensitivity for detecting clinically relevant changes.

This study has several limitations. As a non-randomized observational analysis, the findings are subject to potential selection bias and institutional variability in imaging and treatment strategies. Additionally, although volumetric analysis provides valuable insights, its routine clinical implementation may be limited by availability and standardization across centers. Also Covid-19 pandemia was an important obstacle for proper surveillance.

Advances in imaging technologies and computational modeling may further enhance individualized patient management. The endoleak management following EVAR requires a nuanced, patient-specific approach integrating anatomical characteristics, aneurysm sac dynamics, and procedural considerations. Rather than relying solely on endoleak classification, a comprehensive strategy incorporating morphovolumetric assessment and tailored intervention thresholds may improve long-term outcomes.

5. Conclusion

Endovascular aneurysm repair (EVAR) remains the preferred treatment for infrarenal abdominal aortic aneurysms, although long-term outcomes are influenced by complications such as endoleaks and the need for secondary interventions.

In this study, preoperative morphovolumetric parameters—including aneurysm sac volume, diameter, and thrombus burden—were identified as significant predictors of post-EVAR outcomes. These findings highlight the value of detailed anatomical assessment in risk stratification and individualized patient management. Volumetric analysis demonstrated superior sensitivity compared to diameter-based measurements in detecting early sac changes, particularly in patients with type II endoleaks, suggesting its potential role in improving surveillance accuracy and clinical decision-making. Endoleak management should be guided by both endoleak type and aneurysm sac behavior. While Type I and III endoleaks require urgent intervention, T2ELs should be managed selectively, with treatment reserved for cases demonstrating sac expansion or persistence. Overall, a tailored approach integrating morphovolumetric assessment, patient-specific risk factors, and

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structured imaging follow-up may improve long-term outcomes and optimize post-EVAR management.

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