

Review

Contrast-Enhanced Ultrasound and CT Fusion Imaging in EVAR Follow-Up: Diagnostic Workflow, Endoleak Detection, and Imaging Pitfalls

Manuela Montatore ¹, Gianmichele Muscatella ¹, Ruggiero Tupputi ², Eluisa Muscogiuri ³
and Giuseppe Guglielmi ^{1,2,*}

- ¹ Department of Clinical and Experimental Medicine, Foggia University School of Medicine, Via Antonio Gramsci, 89, 71122 Foggia, Italy; manuela.montatore@unifg.it (M.M.); gianmichele_muscatella.552759@unifg.it (G.M.)
² Radiology Unit, “M. Dimiccoli” Hospital, 76121 Barletta, Italy; ruggiero.tupputi@aslbat.it
³ Radiology Unit, “A. Perrino” Hospital, SS 7, 72100 Brindisi, Italy; eluisa.muscogiuri@asl.brindisi.it
* Correspondence: giuseppe.guglielmi@unifg.it

Simple Summary

Endovascular aneurysm repair is widely used to treat abdominal aortic aneurysms, but long-term imaging surveillance remains necessary because complications may occur even years after treatment. Among these, endoleaks are the most frequent and clinically relevant findings. Computed tomography angiography provides detailed anatomical information, whereas contrast-enhanced ultrasound allows real-time assessment of blood flow inside the aneurysm sac. However, these techniques may provide complementary but sometimes difficult-to-integrate information. CT–ultrasound fusion imaging combines pre-acquired CT data with real-time ultrasound, enabling simultaneous evaluation of vascular anatomy and flow. This review critically appraises the current evidence on CT–ultrasound fusion imaging, discussing its potential role in improving diagnostic workflow, endoleak characterization, anatomical localization, and diagnostic confidence in complex post-EVAR surveillance.

Abstract

Endovascular aneurysm repair (EVAR) has become a widely adopted treatment for abdominal aortic aneurysms, offering lower perioperative morbidity and mortality than open surgical repair. Nevertheless, long-term imaging surveillance remains essential because procedure-related complications may occur years after treatment. Among these, endoleaks represent the most frequent and clinically relevant finding, particularly Type II endoleaks, which are sustained by retrograde collateral perfusion and may be associated with persistent aneurysm sac filling and sac enlargement. Computed tomography angiography (CTA) remains the reference standard for anatomical assessment after EVAR, providing detailed evaluation of endograft integrity, aneurysm sac morphology, and vascular anatomy. However, repeated CTA examinations involve cumulative radiation exposure and iodinated contrast administration and may be limited in the detection of low-flow or intermittent endoleaks. Contrast-enhanced ultrasound (CEUS) provides real-time hemodynamic assessment, improves detection of slow-flow endoleaks, and avoids both ionizing radiation and nephrotoxic contrast agents. Nevertheless, CEUS may be affected by operator dependency and limited anatomical overview. CT–ultrasound fusion imaging combines pre-acquired CTA datasets with real-time ultrasound through spatial co-registration and probe tracking, enabling simultaneous evaluation of vascular anatomy and flow dynamics. This narrative review critically synthesizes current evidence regarding CTA, CEUS, and CT–ultrasound



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fusion imaging in post-EVAR surveillance, with particular emphasis on the incremental clinical value of fusion imaging beyond standalone CTA and CEUS. Particular attention is devoted to diagnostic performance, technical implementation, clinical applicability, current limitations, and future perspectives of CT–CEUS fusion imaging.

Keywords: abdominal aortic aneurysm; EVAR; endoleak; contrast-enhanced ultrasound; CEUS; computed tomography angiography; CTA; fusion imaging; image registration; vascular imaging; surveillance

1. Introduction

This narrative review was designed to provide a comprehensive, imaging-oriented, and critically appraised synthesis of the current evidence regarding computed tomography angiography (CTA), contrast-enhanced ultrasound (CEUS), and CT–ultrasound fusion imaging in post-endovascular aneurysm repair (EVAR) surveillance. Particular emphasis was placed on the incremental clinical value of fusion imaging in relation to standalone CTA and CEUS, with the aim of highlighting not only its technical principles but also the level of supporting evidence, current clinical applications, and existing limitations.

Relevant literature was identified through targeted searches of PubMed/MEDLINE, Embase, Scopus, and Web of Science, complemented by consultation of contemporary international guidelines and key reference lists. Search terms included combinations of “EVAR”, “abdominal aortic aneurysm”, “endoleak”, “type II endoleak”, “computed tomography angiography”, “CTA”, “contrast-enhanced ultrasound”, “CEUS”, “fusion imaging”, and “post-EVAR surveillance”. Priority was given to recent international guidelines, systematic reviews, meta-analyses, comparative imaging studies, prospective investigations, and clinically relevant technical reports published between January 2015 and June 2026, while seminal earlier publications were included whenever necessary to provide historical or technical context.

As a narrative review, this work does not follow a formal systematic review methodology and therefore no PRISMA flow diagram or formal risk-of-bias assessment was performed. Rather than providing pooled quantitative estimates, the objective was to critically synthesize the available literature, emphasizing study design, diagnostic performance, clinical applicability, technical implementation, strengths, limitations, and current knowledge gaps relevant to multimodality imaging after EVAR.

Endovascular aneurysm repair (EVAR) has become the preferred treatment for many patients with abdominal aortic aneurysms (AAA), offering lower perioperative morbidity and mortality than conventional open surgical repair in anatomically suitable candidates [1]. Nevertheless, EVAR excludes rather than removes the aneurysm sac, making long-term imaging surveillance mandatory to detect complications that may compromise procedural durability and increase the risk of aneurysm rupture [2,3].

Among post-EVAR complications, endoleaks remain the most frequent and clinically significant finding during follow-up. Their clinical impact depends on the underlying mechanism, persistence over time, hemodynamic characteristics, and, most importantly, their relationship with aneurysm sac behavior. While some endoleaks resolve spontaneously without clinical consequences, others may lead to persistent sac pressurization, progressive aneurysm enlargement, secondary interventions, or, in selected cases, late rupture [4–6]. Consequently, modern surveillance strategies extend beyond simple endoleak detection and increasingly focus on comprehensive risk stratification by integrating anatomical, functional, and temporal imaging findings.

CTA remains the reference standard for anatomical assessment after EVAR because of its excellent spatial resolution and comprehensive evaluation of endograft integrity, aneurysm sac morphology, branch vessel anatomy, and sealing zones. However, repeated CTA examinations expose patients to cumulative ionizing radiation and iodinated contrast media and may fail to detect low-flow or intermittent endoleaks because of their static acquisition protocol.

Conversely, CEUS provides real-time evaluation of intraluminal blood flow and has demonstrated excellent diagnostic performance for detecting low-flow endoleaks, particularly Type II endoleaks, while avoiding ionizing radiation and nephrotoxic contrast agents [7–9]. Nevertheless, CEUS remains operator-dependent, offers a more limited anatomical overview, and may be technically challenging in patients with obesity, bowel gas, or complex collateral anatomy.

Rather than representing competing modalities, CTA and CEUS provide complementary anatomical and hemodynamic information. Their integration becomes particularly valuable when imaging findings are discordant or when precise anatomical localization of endoleak inflow is required. In this context, CT–ultrasound fusion imaging combines pre-acquired CTA datasets with real-time CEUS through spatial co-registration and electromagnetic tracking, potentially improving anatomical orientation, lesion localization, diagnostic confidence, and procedural planning in selected complex cases [10–12].

The present review therefore follows the complete diagnostic pathway from EVAR and endoleak classification to contemporary multimodality surveillance, critically examining the available evidence supporting CTA, CEUS, and CT–ultrasound fusion imaging, with particular attention to their complementary roles, current limitations, and future perspectives.

2. EVAR and the Need for Imaging Follow-Up

2.1. EVAR: Concept and Post-Procedural Surveillance

EVAR is based on the endovascular placement of a stent-graft within the abdominal aorta and iliac arteries to exclude the aneurysm sac from systemic arterial pressure. In standard infrarenal AAA, the endograft is typically deployed below the renal arteries and extended into the iliac arteries [13,14]. A bifurcated aorto-bi-iliac endograft is commonly used to reconstruct the aortoiliac axis while excluding the aneurysmal segment (Figure 1).

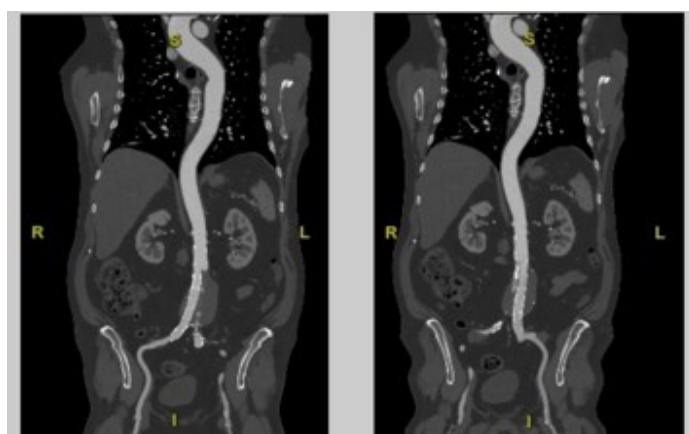


Figure 1. Representative post-EVAR anatomy. Contrast-enhanced CT image showing a bifurcated aorto-bi-iliac endograft after EVAR for fusiform infrarenal abdominal aortic aneurysm. The aneurysm sac remains in situ and requires long-term imaging surveillance. Figure derived from anonymized institutional imaging material.

Although EVAR reduces early invasiveness compared with open surgical repair, the aneurysm sac remains in situ. This explains why imaging surveillance is mandatory. Follow-

up imaging evaluates endograft position, patency, integrity, sealing zones, aneurysm sac diameter, sac morphology, and the presence or absence of endoleaks. The clinical significance of post-EVAR imaging lies in identifying those patients who remain stable and those who require closer surveillance or secondary treatment.

2.2. Post-EVAR Complications

Post-EVAR complications include endograft migration or malposition, limb occlusion or thrombosis, aneurysm sac expansion, vascular complications, infection, structural graft failure, and late rupture [15,16]. Some complications are primarily anatomical and are well assessed with CTA. Others, such as endoleaks, require both anatomical and hemodynamic interpretation.

Among all post-EVAR complications, endoleaks occupy a central role because they indicate persistent perfusion of the aneurysm sac. Persistent sac perfusion may prevent sac shrinkage, promote sac expansion, and compromise the protective effect of EVAR. The identification and characterization of endoleaks therefore directly influence clinical decision-making [17–19].

3. Endoleaks: Definition, Classification, and Clinical Relevance

3.1. Definition of Endoleak

Endoleak is defined as persistent blood flow within the aneurysm sac outside the endograft lumen after EVAR. It may be detected during early postoperative assessment or appear later during long-term surveillance. Because endoleaks can develop even years after the initial procedure, their detection requires structured imaging follow-up.

The presence of an endoleak should always be interpreted together with aneurysm sac behavior. A stable or shrinking sac may support conservative follow-up in selected cases, whereas sac enlargement raises concern for persistent pressurization and potential treatment failure [20,21].

3.2. Classification of Endoleaks

Endoleak classification is fundamental because it directly guides risk stratification, surveillance intensity, and treatment strategy [22]. **Type I** endoleaks are caused by an inadequate seal between the endograft and the native arterial wall. They are divided into Type Ia, involving the proximal attachment site, and Type Ib, involving the distal iliac sealing zone. Because Type I endoleaks are associated with direct systemic pressurization of the aneurysm sac, they are considered high-risk complications and usually require prompt correction.

Type II endoleaks are caused by retrograde perfusion of the aneurysm sac through collateral vessels, most commonly lumbar arteries and the inferior mesenteric artery. They represent the most frequent endoleak subtype after EVAR and generally have a more heterogeneous clinical course. Management is usually selective and depends on persistence, aneurysm sac behavior, and clinical context.

Type III endoleaks are caused by structural failure of the endograft and are traditionally divided into Type IIIa and Type IIIb. Type IIIa endoleaks result from modular disconnection or component separation, whereas Type IIIb endoleaks are caused by defects or tears in the graft fabric. Combined Type IIIa and Type IIIb endoleaks may also occur when component separation and fabric disruption coexist. Similar to Type I endoleaks, Type III endoleaks are considered high risk because they allow direct transmission of systemic pressure into the aneurysm sac and generally require urgent treatment.

Type IV endoleaks are related to graft fabric porosity and are now uncommon with contemporary endograft materials. **Type V** endoleak, or endotension, refers to aneurysm sac enlargement or pressurization without a clearly demonstrable source of endoleak.

This entity remains diagnostically challenging and requires careful imaging follow-up (Figure 2).

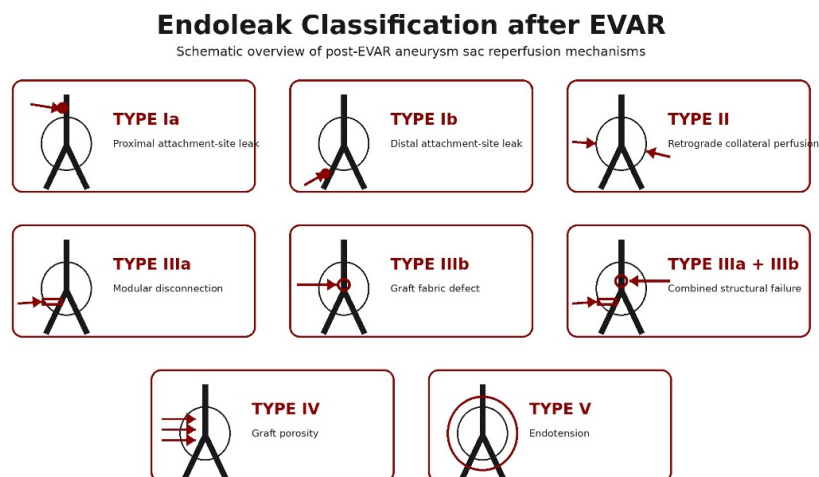


Figure 2. Classification of endoleaks after EVAR. Schematic representation of the principal mechanisms of aneurysm sac reperfusion after EVAR, including Type Ia and Ib attachment-site leaks, Type II retrograde collateral perfusion, Type IIIa modular disconnection, Type IIIb graft fabric defect, Type IV graft porosity, and Type V endotension. Type I and Type III endoleaks are generally considered high-risk lesions, whereas Type II endoleak management is usually guided by persistence and aneurysm sac behavior. Created by the authors.

3.3. Type II Endoleak: The Main Diagnostic Challenge

Type II endoleaks represent the most frequent complication following EVAR, with reported incidences generally ranging from 10% to 30%, although considerable heterogeneity exists among published series [23–25]. This variability reflects differences in patient populations, endograft design, surveillance protocols, imaging modalities, timing of follow-up examinations, and diagnostic criteria adopted across studies. Early postoperative imaging often detects transient collateral perfusion that subsequently resolves spontaneously, whereas longer follow-up preferentially identifies persistent Type II endoleaks with greater clinical significance.

Type II endoleaks result from retrograde perfusion of the excluded aneurysm sac through collateral arteries, most commonly the lumbar arteries and the inferior mesenteric artery, although accessory renal, median sacral, or internal iliac branches may occasionally contribute. Unlike Type I and Type III endoleaks, they do not usually reflect endograft sealing failure or structural device malfunction. Consequently, their natural history is considerably more heterogeneous and depends primarily on the balance between collateral inflow and outflow, the resulting sac pressurization, and aneurysm sac behavior over time. Most Type II endoleaks remain clinically benign and either resolve spontaneously or remain stable during follow-up without requiring intervention. However, a subset persists over time and becomes associated with progressive aneurysm sac enlargement, continued sac pressurization, or recurrent endoleak after embolization. Current evidence therefore suggests that the clinical significance of a Type II endoleak should not be determined solely by its presence but rather by integrating multiple imaging findings, including persistence over serial examinations, aneurysm sac dynamics, identification of feeding vessels, and associated hemodynamic characteristics.

Although Type II endoleaks are often considered benign, persistent Type II endoleaks may be associated with sac enlargement and reintervention. Management has therefore evolved from simple observation toward selective treatment based on imaging findings, including aneurysm sac growth, persistence of the endoleak, and hemodynamic features. Sac expansion greater than 5 mm is commonly used in literature as an important threshold for closer evaluation or treatment consideration, although specific management varies across centers and guidelines.

For radiologists, Type II endoleaks represent one of the most challenging scenarios in post-EVAR surveillance because blood flow is frequently slow, delayed, intermittent, or confined to the posterior aspect of the aneurysm sac. Consequently, the diagnostic objective extends well beyond simply detecting intraluminal contrast enhancement. Comprehensive characterization requires identification of the precise site of sac reperfusion, the feeding collateral vessels, temporal enhancement patterns, hemodynamic behavior, and their relationship with aneurysm sac evolution. This multidimensional assessment forms the basis for selecting the most appropriate surveillance strategy and identifying patients who may benefit from further intervention (Figures 3–9).

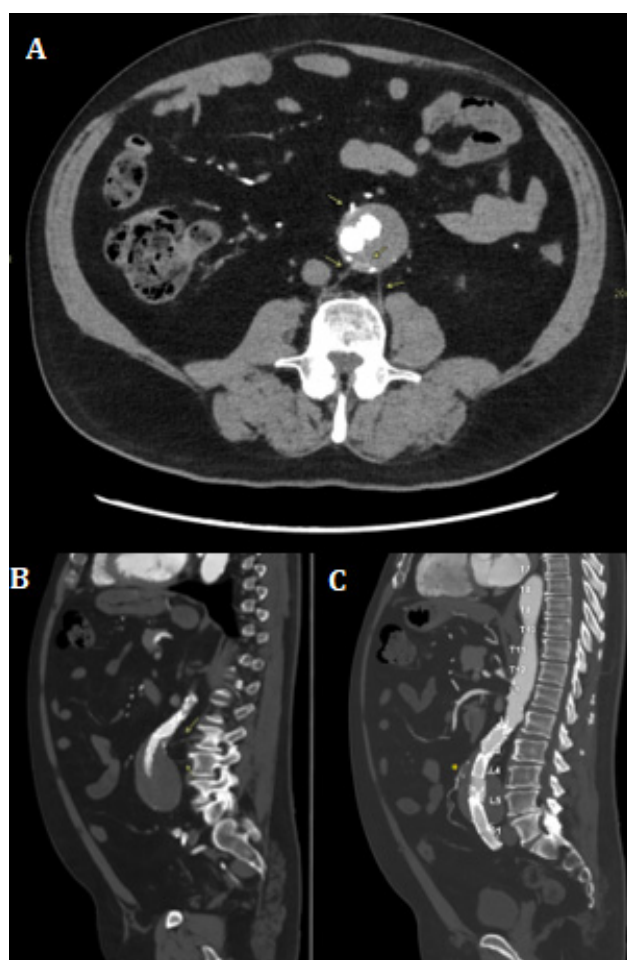


Figure 3. Representative Type II endoleak. Contrast-enhanced CT images showing Type II endoleak after EVAR ((A): axial; (B,C): sagittal). At the L3–L4 level, contrast enhancement is visible along the posterior-left aspect of the aneurysm sac, with additional retrograde flow arising from the inferior mesenteric artery. Figure derived from anonymized institutional imaging material. (A) The arrows identify the feeding vessels arising from the lumbar arteries and the inferior mesenteric artery, which supply the aneurysm sac and account for the type II endoleak. (B) The yellow arrow highlights the lumbar artery inflow. (C) The asterisk denotes the inferior mesenteric artery.



Figure 4. Representative Type III endoleak. Contrast-enhanced CTA demonstrates direct reperfusion of a large infrarenal aneurysm sac (maximum diameter 7 cm) following aorto-bi-iliac EVAR. The endoleak is caused by structural graft failure, resulting in direct systemic pressurization of the aneurysm sac. Type III endoleaks are considered high-risk lesions and generally require urgent endovascular correction. Images derived from anonymized institutional imaging material.

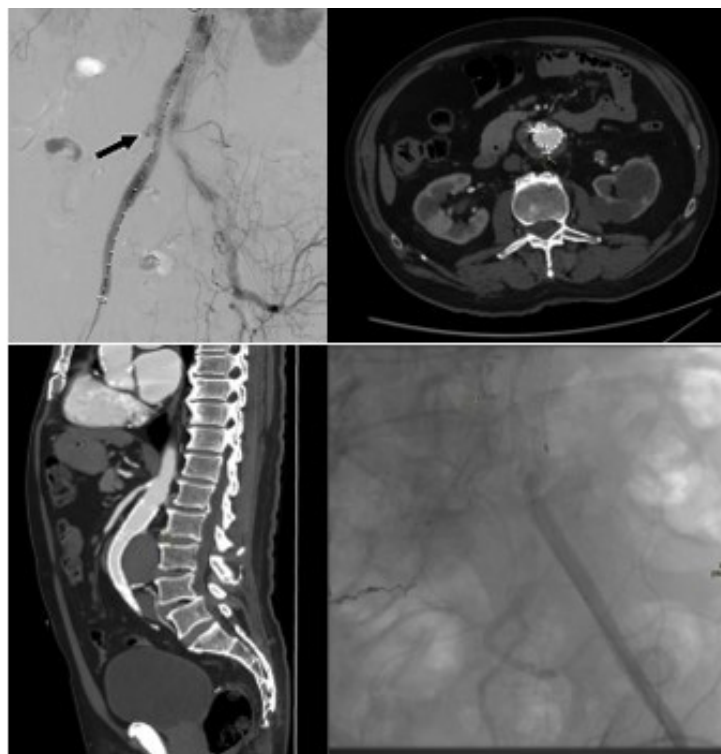


Figure 5. Residual low-flow Type II endoleak after successful treatment of a Type III endoleak. Follow-up CTA and angiographic imaging performed after secondary intervention demonstrate exclusion of the previously identified high-risk Type III endoleak, with persistence of a small residual focus of delayed sac enhancement compatible with a low-flow Type II endoleak. A stable aneurysm sac diameter supported conservative surveillance. Images derived from anonymized institutional imaging material. The black arrow indicates the angiographic point of origin of the endoleak.

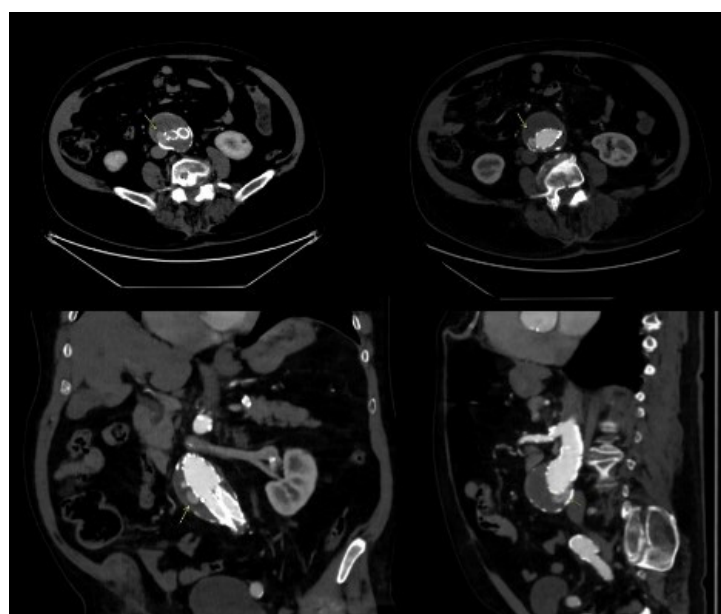


Figure 6. Representative Type Ib endoleak. CTA demonstrates persistent distal sealing failure at the origin of the right common iliac artery, resulting in focal perigraft contrast opacification along the posterolateral aspect of the aneurysm sac. This finding is consistent with a Type Ib endoleak and reflects incomplete distal exclusion of the aneurysmal sac. Images derived from anonymized institutional imaging material. The yellow arrows identify the sites of contrast extravasation corresponding to the endoleak.



Figure 7. Representative Type IIIb endoleak. CTA demonstrates direct aneurysm sac opacification caused by focal disruption of the superior mesenteric artery stent-graft fabric. Type IIIb endoleaks are associated with structural graft failure and direct systemic pressurization of the aneurysm sac, generally requiring prompt correction. Images derived from anonymized institutional imaging material. The yellow arrows identify the sites of contrast extravasation corresponding to the endoleak.

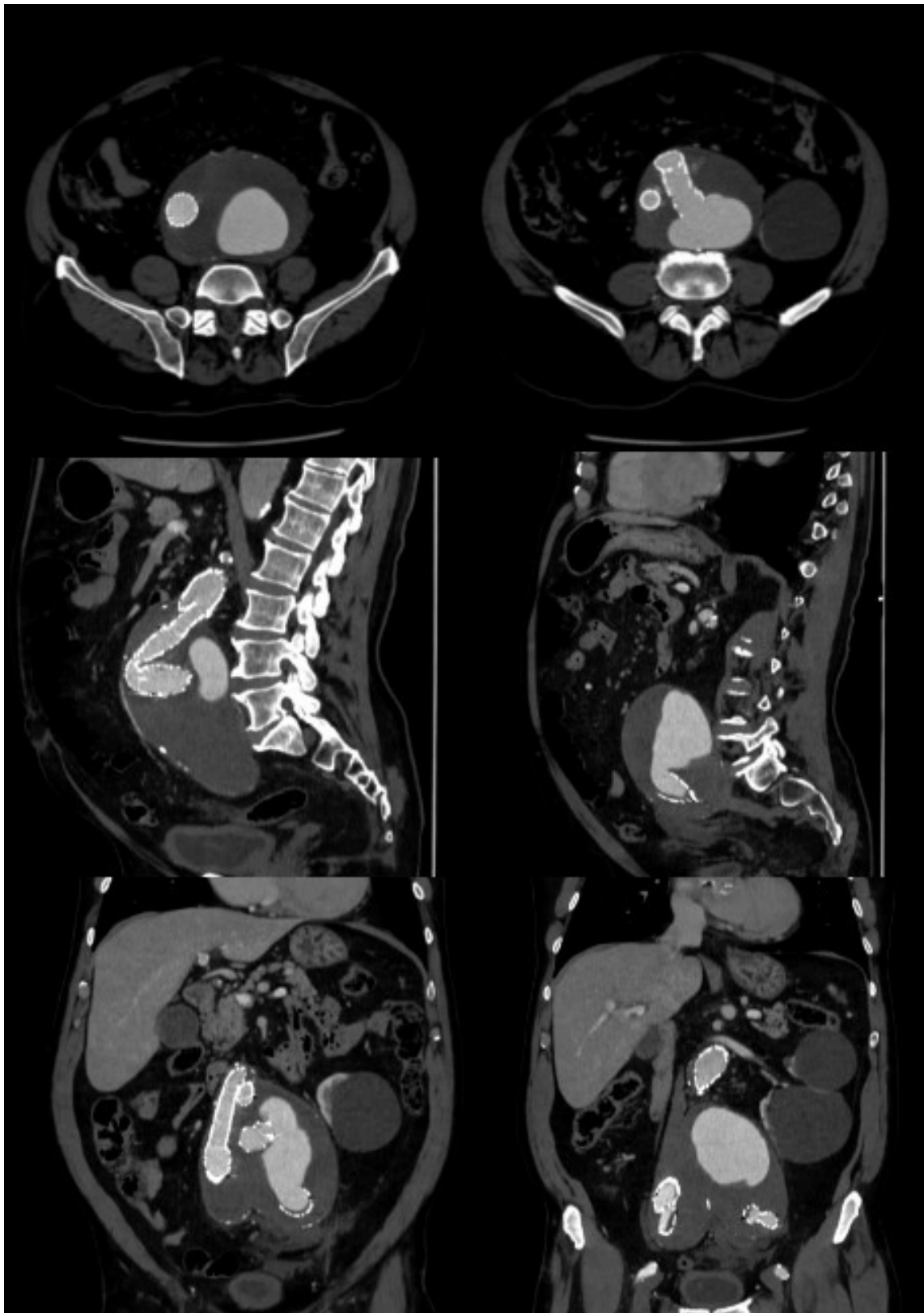


Figure 8. Combined Type IIIa and Type IIIb endoleak. CTA demonstrates separation of the left iliac limb from the main endograft body, consistent with a Type IIIa endoleak, associated with additional perigraft contrast opacification suggestive of concomitant graft fabric disruption (Type IIIb component). Extensive reperfusion of the aneurysm sac is observed. Images derived from anonymized institutional imaging material.

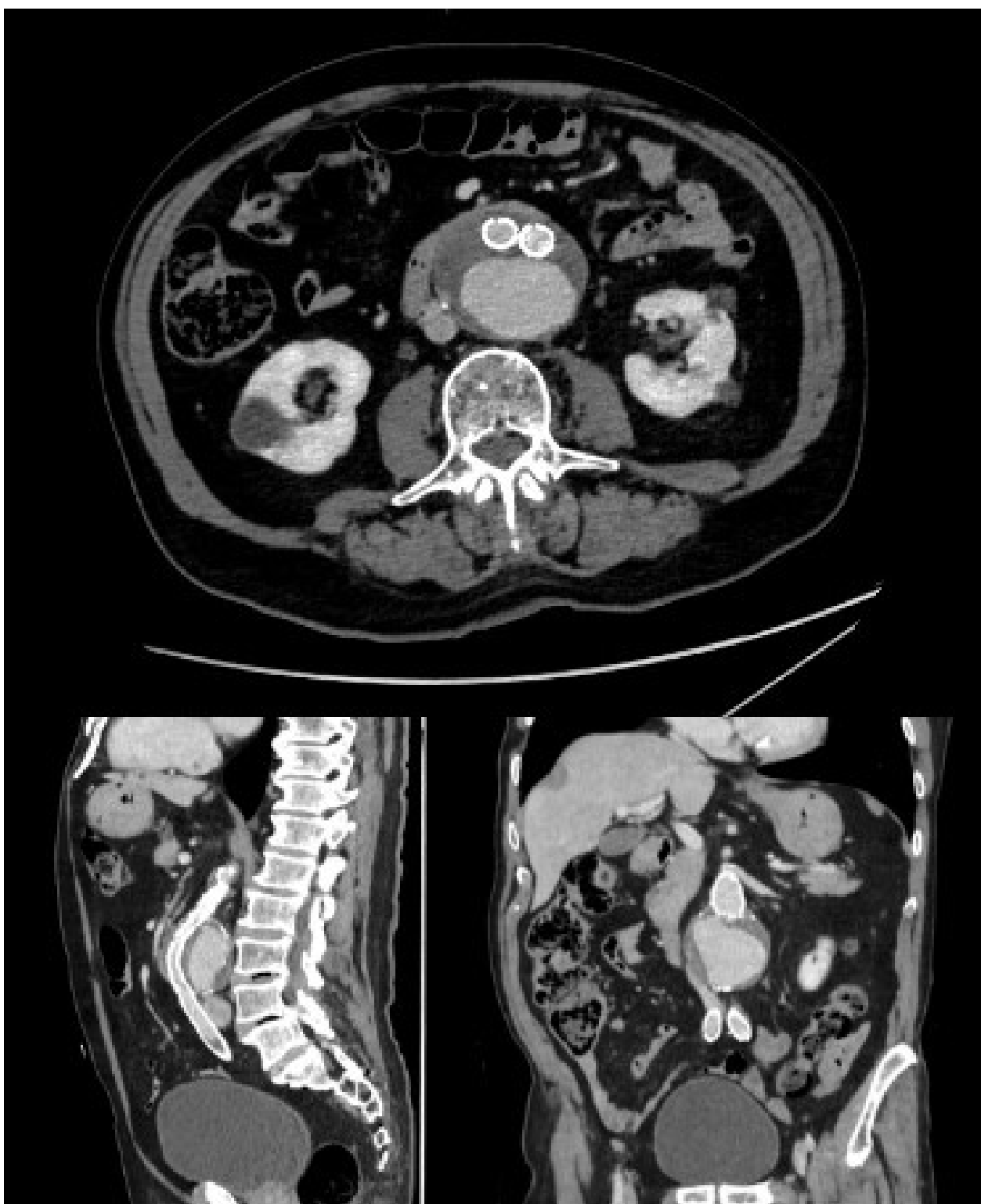


Figure 9. Progressive Type III endoleak with aneurysm sac enlargement. CTA demonstrates progressive reperfusion of the aneurysm sac associated with structural endograft failure in a previously implanted aorto-bi-iliac endograft. Progressive sac enlargement highlights the clinical significance of Type III endoleaks and the need for timely reintervention. Images derived from anonymized institutional imaging material.

4. Imaging Modalities in Post-EVAR Surveillance

4.1. Computed Tomography Angiography

CTA is widely regarded as the reference standard for post-EVAR anatomical assessment. It provides high spatial resolution and allows comprehensive evaluation of endograft morphology, proximal and distal sealing zones, branch patency, sac diameter, calcifications, thrombus, and periaortic structures [26–28]. CTA is particularly useful when endograft migration, limb occlusion, structural graft abnormality, sac enlargement, or high-risk endoleak is suspected.

Despite these advantages, CTA has limitations. First, repeated CTA examinations contribute to cumulative radiation exposure. Second, iodinated contrast administration may be contraindicated or undesirable in patients with chronic kidney disease or contrast allergy. Third, CTA provides static imaging information. Endoleak detection depends on acquisition phase and timing, and low-flow or intermittent Type II endoleaks may not be visible if sac filling occurs outside the acquisition window. For this reason, the absence of aneurysm sac opacification on CTA does not necessarily exclude a low-flow endoleak, particularly when sac enlargement is present.

4.2. Conventional Ultrasound and Color Doppler

Conventional abdominal ultrasound, including B-mode and color Doppler imaging, is widely available, inexpensive, repeatable, and free of ionizing radiation. It can be used to monitor aneurysm sac diameter and may identify flow within the aneurysm sac in selected cases. These characteristics make ultrasound attractive for routine surveillance.

However, B-mode and color Doppler ultrasound may underestimate small or low-flow endoleaks. Color Doppler is limited by flow velocity, depth, angle dependency, and patient-related factors. In Type II endoleaks, where flow may be slow or delayed, color Doppler sensitivity may be insufficient. Therefore, conventional ultrasound is useful as a first-line tool but is often inadequate for complete endoleak characterization [29,30].

4.3. Contrast-Enhanced Ultrasound

Contrast-enhanced ultrasound (CEUS) has become an established complementary imaging modality for post-EVAR surveillance because it provides dynamic, real-time visualization of blood flow within the aneurysm sac without exposing patients to ionizing radiation or iodinated contrast agents. Unlike CTA, which acquires static volumetric datasets at predefined time points, CEUS enables continuous assessment of contrast dynamics, allowing visualization of delayed, low-flow, or intermittent endoleaks that may otherwise remain occult on conventional CTA acquisitions. Consequently, CEUS has emerged as a valuable second-line examination when CTA findings are equivocal, when repeated radiation exposure is undesirable, or when renal impairment limits iodinated contrast administration.

Studies comparing CEUS with CTA have reported high diagnostic accuracy of CEUS for endoleak detection, with particular value in Type II endoleaks [31,32].

Over the past decade, numerous prospective studies and several meta-analyses have demonstrated excellent diagnostic performance of CEUS for endoleak detection. Reported pooled sensitivities generally range between 91% and 98%, while pooled specificities range from approximately 85% to 95%, depending on the reference standard, imaging protocol, and patient selection. Diagnostic performance is particularly high for Type II endoleaks because continuous real-time acquisition facilitates visualization of delayed collateral filling that may not coincide with the acquisition timing of CTA. Nevertheless, published estimates remain heterogeneous owing to differences in study design, operator experience, ultrasound equipment, contrast administration protocols, and follow-up schedules.

Beyond simple endoleak detection, CEUS provides valuable hemodynamic information that cannot be directly obtained from CTA. The temporal pattern of contrast enhancement, direction of flow, filling sequence, wash-in and wash-out characteristics, and visualization of feeding and draining vessels contribute to more accurate endoleak characterization and may facilitate therapeutic planning, particularly before endovascular embolization procedures. These functional capabilities explain why CEUS frequently identifies persistent low-flow Type II endoleaks despite apparently negative or indeterminate CTA findings.

CEUS has several advantages: it provides dynamic real-time information, detects slow or intermittent flow, avoids ionizing radiation, and does not require iodinated contrast. These properties make CEUS especially useful in patients requiring repeated follow-up or in those with renal impairment [33].

Despite its excellent diagnostic performance, CEUS presents several well-recognized limitations. Image quality may be degraded by obesity, excessive bowel gas, deep aneurysm location, extensive mural calcifications, or limited acoustic windows. In addition, the examination remains operator-dependent and requires adequate expertise in both contrast-enhanced ultrasound and vascular imaging. Furthermore, CEUS provides a more restricted anatomical field of view than CTA and may be less suitable for comprehensive evaluation of endograft integrity, migration, component separation, or extra-aneurysmal vascular complications. Accordingly, CEUS should be considered complementary rather than interchangeable with CTA within contemporary multimodality surveillance strategies (Table 1).

Table 1. Imaging modalities in post-EVAR surveillance: advantages, limitations and clinical role.

Imaging Modality	Main Advantages	Main Limitations	Principal Clinical Role	Preferred Clinical Scenario
CTA	High spatial resolution; comprehensive anatomical evaluation; assessment of endograft integrity and aneurysm sac size	Ionizing radiation; iodinated contrast media; static acquisition; limited sensitivity for some low-flow or intermittent endoleaks	Reference standard for anatomical surveillance	Baseline post-EVAR assessment; suspected graft-related complication; sac enlargement; suspected Type I or Type III endoleak
B-mode US	Widely available; inexpensive; repeatable; no radiation exposure	Limited sensitivity for endoleak detection; operator and acoustic-window dependence	Routine surveillance and aneurysm sac diameter measurement	Stable aneurysm sac without suspected endoleak
Color Doppler US	Real-time flow evaluation; widely accessible; no contrast agent required	Operator dependence; angle dependence; limited performance for slow-flow or deep endoleaks	Initial assessment of sac perfusion	First-line screening during routine ultrasound follow-up
CEUS	High sensitivity for low-flow endoleaks; real-time hemodynamic assessment; no ionizing radiation; no iodinated contrast	Acoustic-window limitations; operator dependence; limited anatomical overview	Dynamic characterization of endoleak flow, especially Type II endoleaks	Suspected low-flow Type II endoleak; renal impairment; CTA-negative/uncertain but clinically suspicious cases

Table 1. Cont.

Imaging Modality	Main Advantages	Main Limitations	Principal Clinical Role	Preferred Clinical Scenario
CTA–CEUS Fusion Imaging	Simultaneous anatomical and hemodynamic information; improved localization of endoleaks; increased diagnostic confidence	Registration errors, learning curve, dependence on CTA, and ultrasound image quality	Problem-solving tool in complex or equivocal cases	Discordant CTA/CEUS findings; unclear source of sac perfusion; post-embolization follow-up; complex Type II endoleak characterization

Current international guidelines increasingly recognize CEUS as an important adjunctive imaging technique within individualized EVAR surveillance algorithms rather than a universal replacement for CTA. In contemporary clinical practice, CTA remains indispensable for comprehensive anatomical assessment, whereas CEUS contributes complementary functional information regarding endoleak hemodynamics. The integration of these two modalities therefore represents a multimodality imaging strategy that maximizes diagnostic confidence while potentially reducing cumulative radiation exposure and unnecessary iodinated contrast administration during long-term follow-up.

4.4. Current Surveillance Algorithms After EVAR

Long-term imaging surveillance remains mandatory after EVAR because late complications may occur even in patients with initially successful aneurysm exclusion. Current surveillance protocols aim to detect endoleaks, monitor aneurysm sac behavior, assess endograft integrity, and identify complications requiring secondary intervention. Although surveillance strategies vary among institutions, most contemporary recommendations are based on risk stratification and aneurysm sac evolution over time [34–36].

The 2024 European Society for Vascular Surgery (ESVS) guidelines support individualized surveillance strategies rather than uniform lifelong CTA examinations for all patients. CTA remains the reference modality for baseline post-procedural assessment because it provides a comprehensive evaluation of endograft position, sealing zones, branch vessel patency, and aneurysm sac morphology. In many centers, CTA is performed within the first month after EVAR and subsequently integrated with ultrasound-based follow-up according to patient risk profile and imaging findings [37].

In patients demonstrating stable aneurysm sac size, absence of endoleak, and no evidence of graft-related complications, ultrasound surveillance may reduce the frequency of repeated CTA examinations. CEUS has emerged as a particularly valuable tool in this setting because of its high sensitivity for low-flow endoleaks and its ability to provide dynamic hemodynamic information without exposure to ionizing radiation or nephrotoxic iodinated contrast agents [38–40].

Conversely, CTA remains necessary when aneurysm sac enlargement is detected, when graft migration or structural failure is suspected, when high-risk Type I or Type III endoleaks are considered, or when pre-interventional planning is required. In these situations, detailed anatomical information remains essential for clinical decision-making.

A practical challenge arises when CTA and CEUS findings are discordant. Examples include aneurysm sac enlargement despite apparently negative CTA findings, equivocal sac enhancement on CTA, or CEUS evidence of delayed sac perfusion without clear anatomical correlation. In such circumstances, CT–ultrasound fusion imaging may serve as a problem-solving technique by combining the anatomical information provided by CTA with the real-time hemodynamic assessment of CEUS. Rather than replacing established surveillance

modalities, fusion imaging may help clarify equivocal findings and improve diagnostic confidence in selected complex cases [41] (Table 2).

Table 2. Suggested role of imaging modalities within post-EVAR surveillance.

Clinical Scenario	Preferred Imaging Modality	Potential Role of Fusion Imaging
Routine surveillance with a stable sac	US $\pm$ CEUS	Usually not required
Suspected low-flow Type II endoleak	CEUS	Improved anatomical localization
CTA-negative but CEUS-positive findings	CTA + CEUS	Problem-solving tool
Sac enlargement of unclear origin	CTA + CEUS	Clarification of flow–anatomy relationship
Suspected Type I or Type III endoleak	CTA	Limited complementary role
Post-embolization follow-up	CEUS + CTA	Assessment of residual perfusion and treatment response

5. CTA–CEUS Discordance: Anatomy and Flow Do Not Always Overlap

In clinical practice, discrepancies between CTA and CEUS are not uncommon. A typical scenario is an equivocal or apparently negative CTA with CEUS evidence of retrograde flow. This is particularly relevant in Type II endoleaks, where blood flow may be delayed, low in velocity, intermittent, or dependent on collateral pathways.

CTA and CEUS answer different diagnostic questions. CTA defines anatomy: endograft position, sac morphology, vessel anatomy, and visible contrast opacification. CEUS defines hemodynamics as the presence of flow, timing of sac filling, flow direction, persistence, and delayed enhancement. Both types of information are important, but they are not always easily integrated when the examinations are performed and interpreted separately.

The key challenge in suspected Type II endoleak is not only identifying whether an endoleak is present. The radiologist must also define where it is located, where it originates, how it fills, and whether it is associated with sac enlargement. The diagnostic gap between CTA and CEUS therefore creates the need for an integrated imaging approach.

6. Principles of CT–Ultrasound Fusion Imaging

6.1. Concept of Fusion Imaging

Fusion imaging has been increasingly explored in complex endovascular aortic procedures as a strategy to integrate pre-acquired cross-sectional imaging with real-time procedural or ultrasound guidance, thereby improving anatomical orientation and image interpretation. The technical workflow relies on dataset importation, spatial registration, and real-time probe or instrument tracking, with automated registration approaches aiming to improve feasibility and accuracy. However, current evidence remains heterogeneous, and available meta-analytic data support its role mainly as an adjunctive tool rather than as a universal replacement for conventional imaging pathways. Fusion imaging is a multi-modality technique that integrates real-time ultrasound with a pre-acquired cross-sectional imaging dataset, most commonly CTA or MRI. In post-EVAR surveillance, CT–ultrasound fusion imaging allows the operator to use CTA as an anatomical roadmap during real-time ultrasound and CEUS assessment [42,43].

The principle is to transform a static anatomical dataset into a navigable reference for dynamic ultrasound examination. In this setting, the radiologist no longer evaluates ultrasound images in isolation but navigates within the patient’s vascular anatomy. This may improve orientation, anatomical localization, and interpretation of CEUS findings.

6.2. Incremental Clinical Value of CT–Ultrasound Fusion Imaging Beyond Standalone CTA and CEUS

Although CTA and CEUS each provide excellent diagnostic performance for post-EVAR surveillance, CT–ultrasound fusion imaging should not be regarded as a simple combination of two imaging modalities. Rather, its principal value lies in the integration of complementary anatomical and hemodynamic information into a single real-time examination, thereby facilitating image interpretation and clinical decision-making in selected complex cases.

Current evidence suggests that fusion imaging does not necessarily increase the overall sensitivity for endoleak detection compared with high-quality standalone CEUS. Instead, its incremental value derives from improved spatial orientation, more accurate anatomical localization of endoleak inflow, enhanced identification of feeding collateral vessels, and greater confidence in correlating real-time vascular enhancement with the corresponding CTA anatomy. These advantages become particularly relevant in patients with complex vascular anatomy, multiple collateral pathways, large aneurysm sacs, equivocal CTA findings, or recurrent endoleaks following embolization.

Fusion imaging also facilitates communication between diagnostic and interventional teams by providing an intuitive anatomical correlation between cross-sectional imaging and ultrasound findings. Accurate localization of inflow vessels may simplify procedural planning, potentially reducing procedure duration, repeated angiographic acquisitions, unnecessary catheter manipulation, and contrast administration during subsequent endovascular treatment.

Importantly, currently available evidence supporting CT–ultrasound fusion imaging remains relatively limited. Most published studies consist of single-center experiences with relatively small patient cohorts and heterogeneous imaging protocols, preventing robust quantitative comparisons with conventional surveillance strategies. Consequently, current evidence supports fusion imaging primarily as a problem-solving technique that complements established imaging pathways rather than replacing either CTA or CEUS.

Future prospective multicenter investigations employing standardized acquisition protocols, reproducible image registration techniques, and clinically meaningful outcome measures will be essential to better define the precise role of fusion imaging within evidence-based EVAR surveillance algorithms (Table 3).

Table 3. Incremental clinical value of CT–ultrasound fusion imaging compared with standalone CTA and CEUS. Comparison of the complementary strengths of CTA, CEUS, and CT–ultrasound fusion imaging during post-EVAR surveillance. Fusion imaging primarily provides incremental value by integrating anatomical and functional information rather than replacing either imaging modality.

Clinical Aspect	CTA	CEUS	CT–US Fusion Imaging
Anatomical overview	Excellent	Limited	Excellent
Hemodynamic assessment	Limited	Excellent	Excellent
Feeding vessel localization	Moderate	Moderate	Excellent
Correlation between anatomy and flow	Limited	Limited	Excellent
Guidance for intervention planning	Moderate	Moderate	Excellent
Radiation exposure	Yes	No	No additional radiation
Iodinated contrast	Required	Not required	Not required during examination
Problem-solving capability	Moderate	Moderate	High

6.3. Technical Workflow

The fusion imaging workflow is based on three main steps: dataset importation, spatial registration, and transducer tracking.

First, the pre-acquired CTA dataset is imported into the ultrasound platform or fusion workstation. This dataset provides the anatomical map of the aorta, endograft, aneurysm sac, iliac arteries, calcifications, thrombus, and collateral vessels.

Second, spatial registration aligns the CTA dataset with the patient's real-time anatomy. Registration may be performed manually using anatomical landmarks or semi-automatically/automatically depending on the system. Useful landmarks include the aorta, aortic bifurcation, iliac arteries, vertebral bodies, calcifications, and other recognizable anatomical structures [44].

Third, the ultrasound transducer is tracked in real time, usually with electromagnetic sensors. As the probe moves, the corresponding plane within the CTA dataset is displayed synchronously. During CEUS, the operator can observe microbubble enhancement in real time while simultaneously referencing the corresponding anatomical level on CTA [45].

6.4. Fusion Imaging as Anatomical Navigation

Fusion imaging should not be considered simple image superimposition. Its main value is anatomical navigation. By combining the dynamic sensitivity of ultrasound and CEUS with the spatial information of CTA, fusion imaging allows the operator to correlate flow with sac morphology, endograft position, mural thrombus, calcifications, and potential collateral vessels [46].

This is particularly useful in Type II endoleaks, where sac filling may be small, posterior, delayed, or difficult to localize using ultrasound alone. Fusion imaging may help clarify whether CEUS enhancement corresponds to posterior sac perfusion, lumbar collateral inflow, inferior mesenteric artery-related filling, or another source.

7. Clinical Applications and Illustrative Cases of CTA–CEUS Fusion Imaging After EVAR

DISCUSSION

Long-term imaging surveillance remains a cornerstone of EVAR management because successful aneurysm exclusion at the time of implantation does not eliminate the risk of late complications. Endoleaks, device migration, component separation, graft infection, and progressive aneurysm sac enlargement may develop months or even years after apparently successful treatment, making lifelong surveillance essential for maintaining procedural durability and preventing aneurysm rupture.

Among these complications, Type II endoleaks continue to represent the greatest diagnostic challenge. Their highly variable natural history, frequently intermittent flow patterns, and uncertain clinical significance require a surveillance strategy that extends beyond simple endoleak detection. Contemporary imaging increasingly aims to characterize aneurysm sac behavior, identify collateral inflow pathways, evaluate endoleak persistence over time, and support individualized therapeutic decision-making rather than relying solely on binary positive-or-negative imaging findings.

CTA remains the reference standard for comprehensive anatomical assessment because of its excellent spatial resolution, reproducibility, and ability to evaluate the endograft, aneurysm sac, branch vessels, and access routes simultaneously. However, repeated exposure to ionizing radiation and iodinated contrast media, together with the potential for underestimating delayed low-flow endoleaks, has progressively encouraged the integration of complementary imaging techniques into contemporary surveillance protocols.

In this context, CEUS has emerged as one of the most valuable adjunctive imaging modalities. Its ability to provide continuous real-time visualization of blood flow allows improved detection of slow-flow and delayed Type II endoleaks while avoiding both radiation exposure and nephrotoxic contrast agents. Nevertheless, CEUS should not be

regarded as a universal substitute for CTA. Instead, current evidence consistently supports a complementary multimodality strategy in which CTA provides comprehensive anatomical assessment while CEUS contributes dynamic hemodynamic characterization.

The principal contribution of CT-ultrasound fusion imaging lies precisely in this integration of anatomical and functional information. Rather than replacing existing imaging modalities, fusion imaging enhances interpretation by spatially correlating pre-acquired CTA datasets with real-time CEUS findings. This approach facilitates anatomical localization of endoleaks, improves identification of feeding collateral vessels, and increases diagnostic confidence in complex or equivocal cases. These characteristics are particularly valuable when planning secondary endovascular interventions or interpreting discordant findings between CTA and CEUS.

Importantly, currently available evidence does not demonstrate that fusion imaging substantially increases overall endoleak detection compared with expert-performed CEUS. Instead, its incremental value appears to reside in improved anatomical orientation, lesion localization, procedural planning, and multidisciplinary communication. Recognizing this distinction is essential to avoid overstating the current level of evidence while appropriately highlighting the unique strengths of fusion imaging within selected clinical scenarios.

Despite encouraging preliminary results, several limitations continue to restrict widespread implementation of CT-ultrasound fusion imaging. Most available studies originate from single institutions, include relatively small patient cohorts, and employ heterogeneous acquisition protocols, registration techniques, and outcome measures. Furthermore, operator experience remains a major determinant of examination quality, while differences in ultrasound equipment and image registration software limit direct comparison among published studies. These methodological limitations currently preclude robust quantitative assessment of the incremental diagnostic benefit of fusion imaging across diverse clinical settings.

Consequently, CT-ultrasound fusion imaging should presently be considered a highly valuable problem-solving technique within selected patients rather than a routine replacement for conventional surveillance pathways. Future evidence generated through prospective multicenter studies using standardized protocols and clinically meaningful outcome measures will be essential to determine its precise role within evidence-based EVAR follow-up algorithms.

7.1. Type II Endoleak Detection and Characterization

The most relevant diagnostic application of CT-CEUS fusion imaging after EVAR is the evaluation of suspected Type II endoleak. CEUS improves detection of slow-flow endoleaks, while CTA defines anatomy. Fusion imaging combines these advantages within a single examination [47].

In Type II endoleaks, fusion imaging may improve the confidence of endoleak localization and characterization. It allows the radiologist to determine whether an enhancing focus on CEUS corresponds to a specific region of the aneurysm sac and whether it is anatomically related to collateral vessels visible on CTA.

7.2. Equivocal CTA or CTA-Negative/CEUS-Positive Cases

Fusion imaging may be particularly valuable when CTA is equivocal or negative, but CEUS shows retrograde flow. In such cases, CEUS confirms hemodynamic activity, whereas the CTA dataset provides the anatomical reference needed to interpret the location and possible source of flow.

This scenario is common in Type II endoleaks and illustrates the rationale for fusion imaging: CEUS improves detection, CTA defines anatomy, and fusion imaging connects these two dimensions.

7.3. Follow-Up of Complex or Post-Treatment Cases

Fusion imaging may also be useful in complex post-treatment scenarios, including patients after sac embolization, patients with persistent or recurrent endoleaks, and patients with complex aneurysm sac anatomy. In such cases, prior treatments may alter the appearance of the aneurysm sac, and the integration of anatomical and dynamic information may improve diagnostic interpretation (Figures 10 and 11).

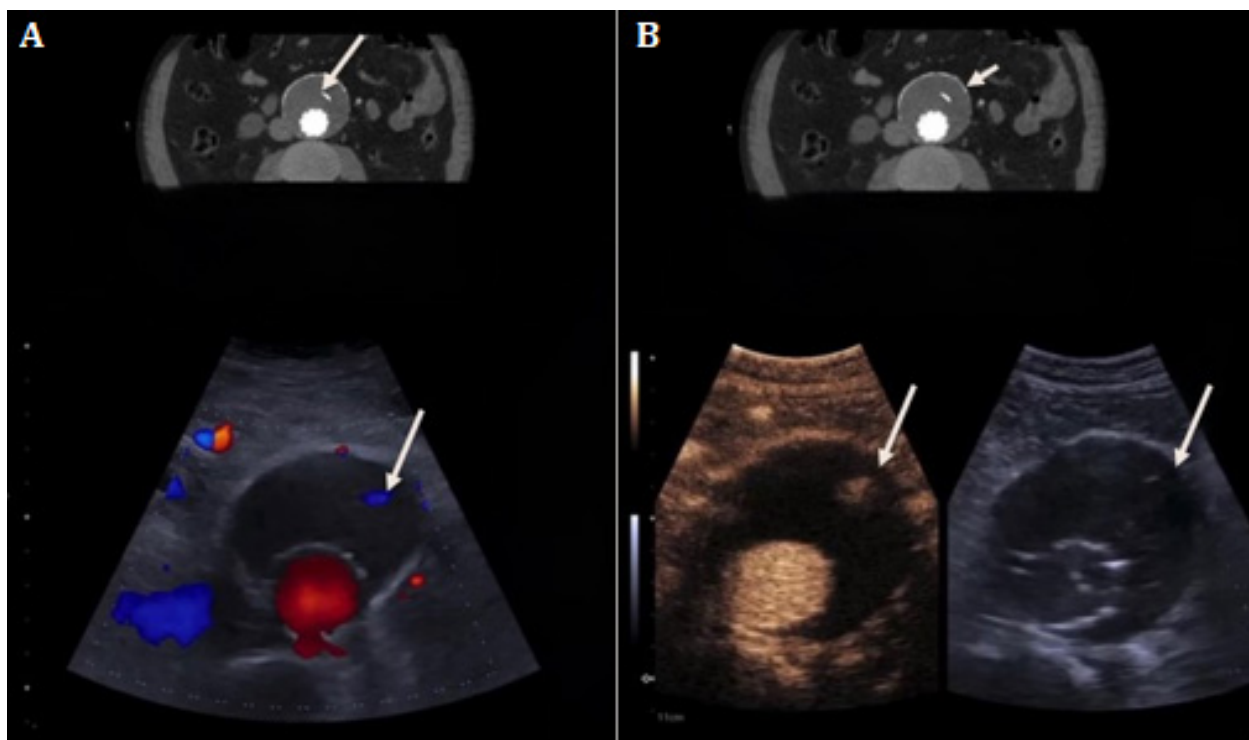


Figure 10. Type II endoleak detected during multimodality post-EVAR surveillance. A 77-year-old man previously treated with EVAR underwent follow-up evaluation with CTA, conventional ultrasound (A), CEUS, and fusion imaging (B). CTA demonstrated stable post-procedural findings, whereas CEUS revealed delayed arterial enhancement within the aneurysm sac, consistent with Type II endoleak. Fusion imaging facilitated spatial correlation between real-time CEUS findings and the pre-acquired CTA dataset, improving anatomical localization and diagnostic confidence. Images derived from anonymized institutional imaging material. The white arrow identifies the endoleak, which is consistently visualized across CT, ultrasound (US), and con-contrast-enhanced ultrasound (CEUS).

7.4. Limitations of Current Evidence

Although the available literature supports the growing role of CEUS and CT-ultrasound fusion imaging in post-EVAR surveillance, several limitations should be acknowledged. Much of the published evidence consists of retrospective or single-center observational studies with relatively limited sample sizes. Considerable heterogeneity exists regarding patient selection, follow-up intervals, ultrasound equipment, image registration methods, operator expertise, and reference standards, limiting direct comparison among studies and reducing the generalizability of reported diagnostic performance. Furthermore, relatively few prospective multicenter investigations have evaluated clinically relevant endpoints such as aneurysm sac growth, reintervention rates, rupture prevention,

or long-term patient outcomes. Consequently, although current evidence consistently supports the complementary role of fusion imaging, higher-quality prospective studies are still required before definitive recommendations regarding its routine incorporation into surveillance algorithms can be established.

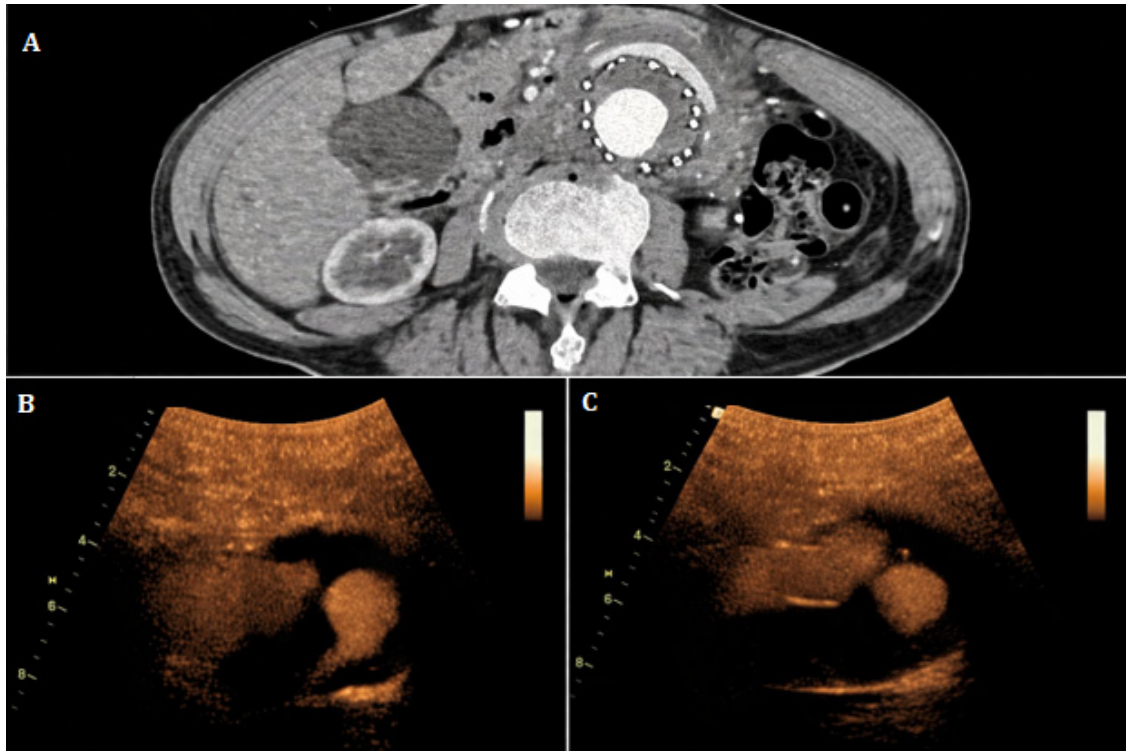


Figure 11. Persistent Type II endoleak after aneurysm sac embolization. A 74-year-old man underwent EVAR followed by endovascular sac embolization for treatment of a Type II endoleak. Follow-up CTA (A) demonstrated persistent periprosthetic enhancement, while B-mode ultrasound showed stable graft morphology and unchanged aneurysm sac size. CEUS (B,C) identified delayed posterior arterial filling, confirming persistent low-flow Type II endoleak. Fusion imaging improved correlation between flow dynamics and anatomical findings, supporting integrated post-treatment assessment. Images derived from anonymized institutional imaging material.

8. Imaging Pitfalls and Technical Limitations

Fusion imaging offers important diagnostic advantages, but its limitations must be clearly recognized. Overstating its value without acknowledging technical pitfalls would be inappropriate.

8.1. Registration Error

Accurate registration is essential. Even small misalignments between CTA and real-time ultrasound may affect interpretation, particularly when evaluating small endoleaks. Registration errors may result from differences in patient positioning, respiratory motion, anatomical deformation, or suboptimal landmark selection.

8.2. Respiratory Motion and Patient Movement

Respiratory motion may alter the position of the aneurysm sac relative to the abdominal wall and surrounding structures. Patient movement during the examination may also degrade registration accuracy. Rechecking registration during the examination is therefore important.

8.3. Temporal Mismatch Between CTA and Ultrasound

Fusion imaging often uses a CTA dataset acquired before the ultrasound examination. If the CTA is outdated, aneurysm sac size, thrombus distribution, endograft configuration, or collateral anatomy may have changed. This temporal mismatch may reduce the accuracy of fusion guidance.

8.4. Acoustic Window Limitations

Fusion imaging remains dependent on ultrasound quality. Obesity, bowel gas, abdominal scars, deep aortic position, and extensive calcifications may reduce image quality and limit CEUS assessment. Fusion imaging cannot overcome all limitations of ultrasound.

8.5. Operator Dependency and Learning Curve

Fusion imaging requires expertise in CTA interpretation, ultrasound scanning, CEUS technique, and registration workflow. It is therefore operator-dependent and requires structured training. A learning curve should be expected, particularly in complex post-EVAR anatomy.

8.6. Risk of Overconfidence

Fusion imaging may increase diagnostic confidence, but inaccurate registration or poor CEUS quality may produce misleading results. Findings should always be interpreted in the context of CTA, CEUS, aneurysm sac behavior, previous imaging, and clinical history.

9. Radiation and Contrast-Sparing Potential

One of the most relevant potential advantages of ultrasound-based surveillance strategies is reduction in cumulative radiation exposure. EVAR patients may undergo repeated imaging examinations over several years, and cumulative radiation burden is an important consideration in long-term follow-up. By using an already available CTA dataset as an anatomical roadmap during real-time ultrasound, fusion imaging may reduce the need for repeated CTA in selected cases [48,49].

Fusion imaging may also reduce additional iodinated contrast exposure. This is particularly relevant in patients with chronic kidney disease, contrast allergy, or other contraindications to iodinated contrast administration. CEUS uses microbubble contrast agents that are not nephrotoxic and do not expose patients to ionizing radiation.

However, the radiation- and contrast-sparing potential of fusion imaging should be interpreted with caution. Fusion imaging should not replace CTA when updated anatomical evaluation is required, when sac enlargement is unexplained, when graft complication is suspected, or when treatment planning is needed. Its role is best understood as an approach that optimizes the use of available information and may reduce unnecessary additional imaging in selected follow-up scenarios.

10. Future Perspectives

The future evolution of post-EVAR imaging surveillance will likely be driven by increasingly integrated, multimodal, and patient-centered diagnostic pathways. Rather than relying on a single imaging modality, future surveillance algorithms are expected to combine the complementary strengths of CTA, CEUS, and CT-ultrasound fusion imaging according to individual patient characteristics, aneurysm morphology, renal function, cumulative radiation exposure, and clinical risk profile.

Technological advances are expected to further improve CT-ultrasound fusion imaging. More accurate automatic image registration, electromagnetic tracking systems with reduced spatial error, three-dimensional ultrasound acquisition, and real-time deformable

registration algorithms may simplify image co-registration, reduce operator dependency, and improve reproducibility across different institutions.

Artificial intelligence (AI) also represents a promising area of development. Machine learning algorithms may facilitate automated image registration, improve endoleak detection, assist in the identification of feeding collateral vessels, and optimize image interpretation by integrating anatomical and hemodynamic information from multiple imaging modalities. Although these technologies remain largely investigational, they may contribute to more standardized and reproducible surveillance strategies in the coming years.

Quantitative imaging biomarkers may further enhance individualized follow-up. Beyond simple endoleak detection, future research should investigate objective parameters such as time–intensity curve analysis, quantitative perfusion metrics, aneurysm sac enhancement kinetics, and computational flow modeling to better characterize endoleak hemodynamics and predict aneurysm sac evolution. From a clinical perspective, future studies should prioritize prospective multicenter validation using standardized imaging protocols, reproducible registration techniques, and clinically meaningful outcome measures, including aneurysm sac growth, secondary intervention rates, rupture prevention, patient survival, and cost-effectiveness. Such investigations will be essential to define the precise role of CT–ultrasound fusion imaging within evidence-based EVAR surveillance algorithms and future international guideline recommendations (Table 4).

Table 4. Key messages for clinical practice.

Key Point	Clinical Implication
CTA remains the anatomical reference standard	Comprehensive evaluation of endograft integrity and aneurysm morphology
CEUS improves detection of low-flow Type II endoleaks	Reduces false-negative examinations in selected patients
Fusion imaging integrates anatomy and flow	Facilitates endoleak localization and interpretation
Fusion imaging is complementary, not a replacement	Best used as a problem-solving technique
Evidence remains limited	Prospective multicenter validation is required

11. Conclusions

CTA remains the cornerstone of anatomical assessment after EVAR, whereas CEUS provides valuable real-time hemodynamic information that substantially improves the detection and characterization of low-flow endoleaks, particularly Type II endoleaks. Rather than representing competing imaging modalities, CTA and CEUS should be regarded as complementary techniques within a multimodality surveillance strategy tailored to individual clinical scenarios.

CT–ultrasound fusion imaging further strengthens this complementary approach by integrating cross-sectional anatomical information with real-time functional assessment, thereby improving spatial orientation, anatomical localization of endoleaks, diagnostic confidence, and procedural planning in selected complex cases. Current evidence suggests that its principal contribution lies not in increasing overall endoleak detection, but in facilitating interpretation and supporting clinical decision-making when conventional imaging findings are inconclusive or anatomically challenging. Nevertheless, the current evidence base remains limited by relatively small, heterogeneous, predominantly single-center studies. Consequently, CT–ultrasound fusion imaging should presently be considered an advanced problem-solving technique that complements established surveillance pathways rather than replacing CTA or CEUS.

Future prospective multicenter investigations using standardized acquisition protocols, robust methodological designs, and clinically relevant outcome measures will be

essential to further define the role of CT–ultrasound fusion imaging within evidence-based post-EVAR surveillance and future international recommendations.

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Abbreviations

AAA	Abdominal aortic aneurysm
CEUS	Contrast-enhanced ultrasound
CTA	Computed tomography angiography
EVAR	Endovascular aneurysm repair
IMA	Inferior mesenteric artery
US	Ultrasound

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