Current Cardiology Reports (2026) 28:27
https://doi.org/10.1007/s11886-026-02349-5

REVIEW

Multimodality Imaging for Left Atrial Appendage Occlusion Devices

Alvin Ho[1] · Leila Alizadeh[2] · Alan F Vainrib[1] · Richard Ro[1] · Daniel Bamira[1] · Robin S. Freedberg[1] · Muhamed Saric[1]

Received: 9 December 2025 / Accepted: 12 February 2026

Abstract

Purpose of Review This review summarizes the current and evolving landscape of multimodality imaging for percutaneous endocardial left atrial appendage occlusion (LAAO) across three phases: preprocedural planning, periprocedural guidance, and postprocedural follow-up.

Recent Findings Transesophageal echocardiography (TEE) remains the primary imaging modality to assess the left atrial appendage (LAA) in all three phases of clinical care surrounding LAAO, though many innovations have led to the rise of cardiac computed tomography (CCT) and intracardiac echocardiography (ICE) as powerful adjuncts and alternatives to TEE. Advances in CCT technology such as fusion imaging and three-dimensional (3D) modeling have contributed to the emergence of CCT as an alternative to TEE for preprocedural evaluation. Intraprocedurally, real-time 3D ICE offers similar real-time guidance to TEE with similar procedural efficacy while employing a simplified workflow that can reduce procedural times and staffing needs. Post-procedural assessment with TEE or CCT is essential for evaluating device stability and complications such as peridevice leak or device-related thrombus.

Summary Multimodality imaging of LAAO is a rapidly evolving field, and thoughtful integration of TEE, CCT, and ICE is critical to optimize LAAO outcomes and minimize procedural complications.

Keywords Left atrial appendage · Left atrial appendage occlusion · Echocardiography · Cardiac computed tomography · Intracardiac echocardiography · Multimodality imaging

Introduction

The left atrial appendage (LAA) is the most common site of thrombus formation in patients with atrial fibrillation (AF) [1] and has emerged as a therapeutic target in the field of AF management. Anticoagulation is the preferred medical treatment to mitigate stroke risk in AF, but many patients may not tolerate or have contraindications to prolonged oral anticoagulation. For this subset of patients, left atrial appendage occlusion (LAAO) has emerged as an important therapeutic option for prevention of thromboembolic events.

✉ Alvin Ho
alvin.ho@nyulangone.org

[1] Leon H. Charney Division of Cardiology, NYU Grossman School of Medicine, NYU Langone Health, New York, NY, USA

[2] The Zena and Michael A. Wiener Cardiovascular Institute, Icahn School of Medicine at Mount Sinai Mount Sinai Hospital, New York, NY, USA

The first surgical LAAO was described in 1949 by Madden, which involved complete resection of the appendage [2]. Since then, several techniques have been developed for LAAO, including excision, stapler occlusion, epicardial suture ligation, and endocardial implants. Stapler occlusion devices directly obstruct flow into the appendage and may be deployed during open cardiac surgery or through a thoracoscopic approach. These devices include the AtriClip (AtriCure, Mason, Ohio, USA), TigerPaw Pro (Getinge, Gothenburg, Sweden), and Penditure systems (Medtronic, Dublin, Ireland). The Lariat system (previously SentreHEART, now AtriCure) is a suture inserted via epicardial puncture and looped around the neck of the LAA. This causes mechanical obstruction of blood flow between the appendage and the left atrium, as well as local ischemia, tissue necrosis, and eventual resorption of the appendage [3].

The first percutaneous endocardial occlusion device was first introduced by Sievert et al. in 2002 with the PLAATO device (previously Appriva Medical, now Medtronic, Dublin, Ireland) [4]. Percutaneous LAAO endocardial device development has advanced significantly in the last two

Published online: 25 February 2026

decades, and the PLAATO device has since been withdrawn from the market in favor of newer models such as the Watchman devices (Boston Scientific, Natick, MA, United States) and the Amplatzer devices (Abbott Medical, Plymouth, MN, United States). Numerous large-scale studies have consistently demonstrated the efficacy of percutaneous LAAO with these newer devices in significantly reducing the risk of systemic embolism and stroke [5–10]. The PROTECT-AF and PREVAIL trials demonstrated that implantation of the Watchman 2.5 device was noninferior to warfarin for reducing thromboembolic events in patients with nonvalvular AF [11, 12]. Subsequently, the AMULET IDE trial demonstrated noninferiority between the Amplatzer Amulet and Watchman devices for safety and effectiveness of stroke prevention [13]. The PRAGUE-17 trial demonstrated non-inferiority between both types of LAAO and direct oral anticoagulants in preventing thromboembolic events and cardiovascular mortality at a median of 3.5 years, with a trend toward a reduction in nonprocedural bleeding events [14].

There are two major families of endocardial left atrial appendage occlusion devices: plug-based devices and disk/lobe devices. Plug-based devices (e.g. the Watchman family) rely on a proximal anchor which expands laterally to occlude the LAA. On the other hand, disk/lobe devices (e.g. the Amplatzer family) are characterized by a two-part system. The lobe is placed in the LAA cavity in a similar fashion to plug-based devices, and a separate disc covers and seals the LAA ostium against the lobe. Currently, the Watchman FLX Pro and Amplatzer Amulet are the most widely used devices and are the only two endocardial LAA devices with FDA approval for use in the United States. Several other devices have received CE mark approval for use in the European Economic Area, including the LAmbre (Lifetech Scientific, Shenzhen, China), Occlutech LAA Occluder (Occlutech, Helsingborg, Sweden), and Ultraseal (Cardia, Eagan, Minnesota, United States). The remainder of this review will focus on the role of cardiac imaging for the Watchman and Amplatzer families of LAAO devices.

As this innovative procedure has evolved, so has the role of multimodality cardiac imaging. Advancements in imaging techniques have become integral to each phase of the LAAO process — preprocedural planning, intra-procedural guidance, and post-procedural surveillance (Fig. 1). Transesophageal echocardiography (TEE) has been the cornerstone of cardiac imaging of percutaneous LAAO procedures since their inception in the early 2000s. In the early 2010s,

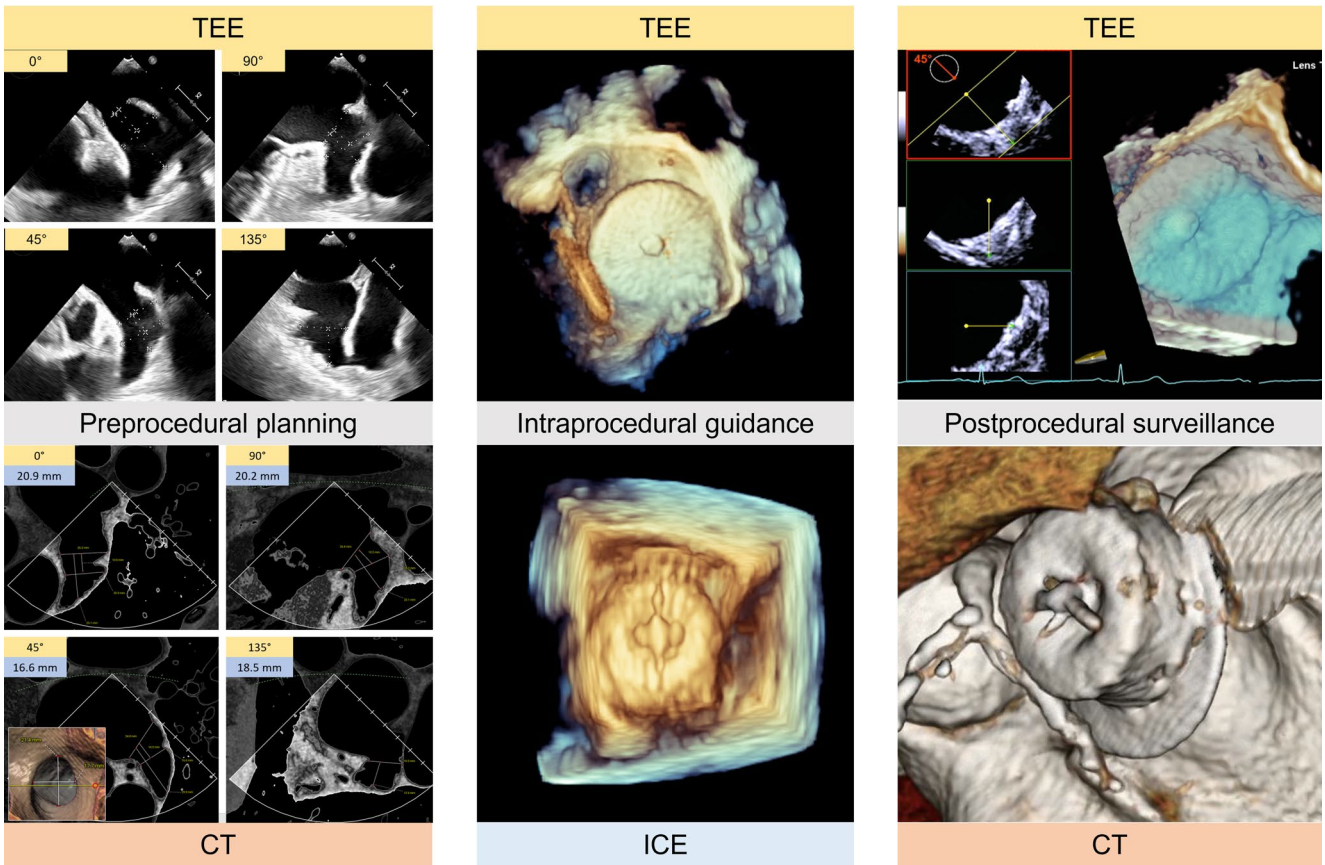

Fig. 1 Multimodality imaging of left atrial appendage occlusion across three phases of care. **Key**: CT, computed tomography; ICE, intracardiac echocardiography; TEE, transesophageal echocardiography

cardiac computed tomography (CCT) was introduced as an adjunct to TEE for preprocedural planning and postprocedural assessment and has since become a standalone alternative to TEE in these contexts. Intraprocedural guidance has also progressed with the introduction of intracardiac echocardiography (ICE), particularly with real-time 3D ICE catheters capable of generating volumetric datasets that allow for approximations of the 3D TEE views. Careful consideration of the distinct advantages and limitations of each of the imaging modalities is important for optimizing clinical outcomes.

In this review, we summarize the role of multimodality cardiac imaging for LAAO, focusing on the distinct advantages and limitations of each modality across each phase of the LAAO process. In addition, we discuss the latest advances and knowledge gaps in this field.

Preprocedural Planning

Three-dimensional transesophageal echocardiography (3D TEE) and CCT are essential for thorough preprocedural evaluation and planning. The major goals of preprocedural assessment include evaluation for spontaneous echo contrast or thrombus, sizing of the LAA, and identification of LAA morphology to inform device selection.

Spontaneous echo contrast refers to increased echogenicity in the cardiac chambers as a result of blood flow stasis. Low shear conditions promote the accumulation of plasma proteins, particularly fibrinogen, leading to rouleaux formation of erythrocytes. The size of the erythrocyte clusters creates ultrasound backscatter which manifests as "smoke" or sludge depending on the extent of aggregation [15, 16]. The presence of spontaneous echo contrast indicates blood stasis and is strongly associated with increased risk of thrombus formation and subsequent thromboembolic events [17].

TEE

On TEE, the LAA is evaluated in four key views in 45-degree increments (0°, 45°, 90°, and 135°). Color flow Doppler is used to assess for spontaneous echo contrast or thrombus, with positive findings including smoke or sludge within the LA or LAA and reduced or absent color flow within the LAA. Pulse wave Doppler is another helpful adjunct to assess risk of thrombi, as LAA emptying velocity $\leq$ 20 cm/s has been shown to be associated with a significantly increased risk of thrombus formation or spontaneous echo contrast. In contrast, emptying velocities > 40 cm/s are associated with a lower risk of embolic events [18–20]. Importantly, the pectinate muscles in the LAA are often seen as hyperechoic structures along the LAA apex and should not be mistaken for thrombus.

LAA sizing and LAAO device selection is based on the landing zone diameter. For plug-based devices, the LAA landing zone is measured from the left circumflex artery to 2 mm from the tip of the limbus. For disk/lobe devices, the LAA anatomic orifice is first measured from the mitral annulus to the tip of the limbus. Subsequently, the lobe landing zone is measured 10–12 mm distal to the LAA orifice. For all types of LAAO devices, the depth of the LAA should also be measured in an orthogonal line from the LAA orifice.

LAA morphology exhibits substantial variability, primarily characterized by the number of appendage lobes and their relative spatial configuration. Wang et al. originally described four general categories of LAA morphology: chicken wing, cactus, windsock, and cauliflower [16]. Since then, advances in 3D TEE technology such as multiplanar reconstruction (MPR), photorealistic imaging, and light source manipulation (e.g. TrueVue/GlassVue, Philips Medical Systems, Best, the Netherlands), along with the tilt-up-and-turn-left (TUPLE) maneuver, have enabled more precise characterization of the LAA anatomy. These techniques have revealed a much greater spectrum of morphological variation than previously recognized [21]. In practice, LAA morphology is crucial in device selection and is an important predictor of thromboembolic risk. In multivariable analyses, chicken wing morphology was associated with the lowest risk of thromboembolic events in patients with AF, even after controlling for CHA_2DS_2-VASc score, gender, and AF type [22, 23].

CCT

CCT with MPR has emerged as an alternative primary imaging modality for preprocedural assessment in LAAO. Compared with TEE, CCT offers superior visualization of complex LAA anatomy and is particularly advantageous in patients with contraindications to esophageal instrumentation. In addition, CCT provides comparable spatial resolution for 3D evaluation of LAA dimensions and morphology, with most protocols using a reconstructed slice thickness of 0.5–0.75 mm [24]. With a TEE transducer utilizing 4–7 MHz, spatial resolution may approach 0.2–0.4 mm [25], although TEE may be prone to increased interoperator variability. In addition, CCT offers excellent evaluation for thrombus with a pooled sensitivity of 98–100% and specificity of 99–100% compared to TEE [26, 27]. Due to these benefits, CCT is increasingly utilized as a non-invasive modality for preprocedural planning, enabling workflows where TEE or ICE is reserved for intraprocedural guidance.

Standardized CT acquisition protocols may vary across scanning systems but generally follow a biphasic scan

framework. The first phase involves a prospective electrocardiographically gated scan acquisition during systole, defined as 30–60% of the R-R interval, with most protocols using a reconstructed slice thickness of < 1 mm to optimize 3D visualization. This high-resolution dataset provides detailed 3D information on LAA morphology, ostial diameter, and depth for accurate device sizing. 3D reconstruction techniques can also generate simulated TEE images at traditional angles (0°, 45°, 90°, and 135°) to assist with intraprocedural guidance. The delayed phase is obtained 30 to 180 s later to help reliably differentiate slow flow from true filling defects. Meta-analyses have shown that this biphasic protocol carries a high positive predictive value (92%) and a high negative predictive value (96–100%) for detecting LAA thrombi [26].

Comparative studies have consistently shown that LAA dimensions such as ostial diameter and depth are larger on CCT compared to TEE, with a standardized mean difference of 0.3 mm in mean ostial diameter and 0.7 mm in maximal ostial diameter [28]. Despite these discrepancies, device selection and sizing accuracy remain largely consistent between modalities. This may be due in part to the overlapping size ranges of commercially available LAAO devices, which provide tolerance for minor 1–2 mm differences in sizing measurements. Notably, the incorporation of 3D modeling with CCT has been shown to improve the accuracy of device sizing compared with conventional two-dimensional (2D) TEE.

Advanced software applications are emerging that utilize CCT data sets to further enhance procedural planning. The PREDICT-LAA trial found that use of CT simulation-based planning via an artificial intelligence-enabled computational model, FEops HEARTguide, was associated with a lower incidence of peridevice leak (PDL) and device-related thrombus (DRT) compared to conventional planning approaches. In addition, this model was reported to decrease procedural time, the number of closure devices used, and number of device repositionings [29]. In other studies, 3D printed models generated from CCT data have been shown to improve transeptal puncture site selection and accuracy of device sizing compared to traditional methods [30].

Intraprocedural Guidance

TEE with fluoroscopy remains the current cornerstone of intraprocedural imaging guidance of LAAO, although intracardiac echocardiography (ICE) is increasingly being adopted as a suitable alternative. The primary objectives of intraprocedural imaging are to exclude the presence of thrombus, confirm LAA landing zone diameter and depth, guide transeptal puncture, and verify device positioning and stability.

TEE

As described previously, the standard four TEE views are used to exclude spontaneous echo contrast and thrombus in the LAA, as well as measure LAA dimensions and depth. Once femoral access is obtained, TEE is used to visualize the interatrial septum in multiple planes to guide transeptal puncture. The optimal location for transeptal puncture varies with LAA anatomy but is typically located in the posteroinferior septum, facilitating coaxial alignment of the LAAO delivery system with the LAA.

Each LAA occlusion device has its own set of imaging criteria for evaluating device placement. For Watchman devices, the PASS (Position, Anchoring, Size/Compression, Seal) criteria are applied: (1) positioning of the shoulders of the device at or distal to the LAA ostium, (2) adequate anchoring of the device as demonstrated by the tug test, (3) device compression to 10–30% of its original size, and (4) adequate seal as shown by the device spanning the ostium without evidence of peridevice leak. Notably, the presence of color flow immediately after the procedure may not accurately reflect PDL, as transient residual flow can occur prior to device endothelialization [31, 32].

For Amulet devices, the CLOSE (Circumflex, Lobe, Orientation, Separation, Elliptical) criteria are used: (1) at least two-thirds of the device lobe lies distal to the left circumflex artery, (2) the lobe of the device is compressed and assumes a tire-shaped configuration with good apposition to the LAA wall, (3) the device is oriented coaxially to the LAA, (4) separation of the disc and lobe confirmed by the tug test, and (5) an elliptical (concave) shape of the disc when placed under tension.

ICE

ICE, used in conjunction with fluoroscopy. is emerging as a practical alternative to TEE for intraprocedural guidance during percutaneous LAAO device placement. 2D ICE was first introduced in the early 2000s and initially applied to relatively straightforward interventional cardiac procedures, such as closure of atrial septal defect or patent foramen ovale as well as transeptal puncture [33]. The introduction of real-time 3D ICE probes in the 2010s represented a major technological advance that improved imaging quality to a degree that enabled the expansion of the use of ICE to more complex structural interventions, including LAAO device implantation.

A key advantage of ICE is the opportunity to simplify procedural logistics, as the interventionalist can manipulate both the ICE and interventional catheters. This approach potentially obviates the need for general anesthesia or a dedicated echocardiographer to handle the TEE probe, allowing for more streamlined workflows.

Despite these advantages, TEE provides superior spatial and temporal resolution due to fundamental differences in design between the two probes. The limited diameter of ICE catheters restricts the number of imaging elements, with contemporary 3D ICE probes containing up to 840 imaging elements compared to 2,500 elements on typical 3D ICE probes. In addition, ICE catheters use a rectangular matrix array, featuring more elements along the long axis of the catheter and fewer along its short axis. This configuration results in degradation of spatial resolution of the imaging sector orthogonal to the long axis of the ICE catheter – a phenomenon that is not present in TEE imaging. As a result of these limitations, it is currently recommended for pre-procedural LAA sizing to be done with either TEE or CT, with ICE reserved for intraprocedural guidance. Nevertheless, ongoing advances in ICE technology and real-time 3D imaging have yielded comparable procedural outcomes relative to traditional TEE-guided LAAO [34].

The procedural workflow for ICE-guided LAAO begins after femoral venous access is obtained. The ICE catheter is inserted in the right femoral vein and advanced into the right atrium. The interatrial septum is visualized in multiple planes or with real-time 3D imaging to evaluate the superior-inferior and anterior-posterior portions and guide transeptal puncture. The ICE catheter may then be positioned in the pulmonary artery for a posterior view of the LAA or advanced through the interatrial septum into the LA. Within the LA, three standard ICE views are obtained that correspond to conventional TEE planes: the mid-LA view (resembling the 45° TEE view), the supramitral view (resembling the 90° TEE view), and the left superior pulmonary vein view (resembling the 135° TEE view). Notably, there is no ICE equivalent for the 0° view on TEE. These views allow for assessment of spontaneous echo contrast or thrombus, LAA size measurements, and evaluation of device positioning according to the PASS or CLOSE criteria. After confirmation of successful device deployment, an evaluation for pericardial effusion and examination of the iatrogenic ASD should be performed before removal of the ICE catheter.

Several studies have found no significant difference in PDL or DRT rates when using ICE compared to TEE for procedural guidance [35]. Meta-analyses demonstrated that ICE is associated with marginally higher procedural success compared to TEE. However, ICE was also associated with a higher rate of pericardial effusion and residual iatrogenic ASD compared to TEE [36]. It should be noted that the risk of procedural complications may be due in part to the steep learning curve associated with adoption of ICE-guided LAAO, as operators with more than 30 cases of experience had significantly fewer pericardial effusion complications and faster procedural time [35]. Some studies have demonstrated the feasibility of ICE-only guided LAAO without the use of fluoroscopy [37], which would further simplify workflow and reduce cumulative dose of radiation for patients and proceduralists.

Presently, both TEE and ICE are recommended modalities for intraprocedural guidance for LAAO. The choice between each modality varies by institution and depends on factors such as procedural efficiency, workflow logistics, complication risk, and cost considerations. While TEE remains the reference standard due to widespread operator familiarity and its superior spatial and temporal resolution, real-time 3D ICE provides satisfactory visualization of relevant structures and offers a minimally invasive approach without the need for general anesthesia or esophageal intubation. Studies have shown a decrease in procedural time with ICE compared to TEE [38], and the avoidance of general anesthesia is associated with shorter recovery times and higher rates of same-day discharge. However, this economic benefit is offset by the high cost of single-use 3D ICE catheters.

Postprocedural Follow-up

Predischarge Imaging

Transthoracic echocardiography (TTE) or chest radiograph is typically the first-line imaging modality used to confirm device stability and exclude immediate postprocedural complications, such as pericardial effusion or device embolization. Although the device position may be assessed in standard TTE views, visualization of LAA usually remains limited, and comparison with TEE or ICE findings is challenging. Therefore, the final post-release TEE or ICE images obtained during the procedure are used as the reference standard for subsequent follow-up studies. In cases where device position or stability is uncertain, TEE or cardiac CT should be performed promptly to exclude complications.

Surveillance Imaging

The Society for Cardiovascular Angiography and Interventions/Heart Rhythm Society (SCAI/HRS) and the American Society of Echocardiography (ASE) recommend routine post-procedural follow-up imaging with either TEE or CCT at 45–90 days post-implant with a focus on detection of PDL or DRT [39, 40]. If either PDL or DRT is identified, further surveillance imaging is recommended at 45- to 90-day intervals. Given the high incidence of delayed-onset DRT after 180 days post-implant, some experts recommend additional routine follow up imaging at 1 year post-implant [32].

Peridevice Leaks

Peridevice leaks (PDLs) are common, though the incidence varies significantly depending on imaging modality. Follow up imaging with TEE at 45 days post-implant demonstrated PDL in 26% to 39% of patients, whereas CCT detected PDLs in up to 61% of patients [31, 41]. There was no difference between the two modalities in detection of clinically significant PDLs, defined as a vena contracta > 5 mm, whereas CCT has greater sensitivity for detecting smaller PDLs < 5 mm [42]. Notably, the original definition of clinically significant PDL was arbitrarily defined in the initial pivotal trials for LAAO [10, 11, 13, 42], though more recent studies with long-term follow up data suggest that any size PDL is associated with higher thromboembolic risk [43–45]. Similarly, the finding of LAA patency within 3 months, especially when associated with a large PDL, portends higher rates of adverse events [46, 47].

Optimal management of PDL is challenging and remains an area of active investigation. Large PDLs > 5 mm may be referred for closure via endovascular coiling, plugs, or radiofrequency ablation, though there is limited data on long-term outcomes regarding stroke prevention following these interventions [48]. Regarding medical management, continuing anticoagulation after discovery of a PDL seems reasonable to prevent thromboembolic events. However, current guidelines make no recommendation for or against prolonged anticoagulation in this clinical scenario due to a lack of demonstrated benefit in available studies [43, 44].

Device-related Thrombus

Device-related thrombus (DRT) is another important complication of LAAO involving the formation of thrombus on the atrial surface of the LAAO device after implantation. Expert consensus statements describe the TEE findings of DRT as an independently mobile echo density in contact with the LAAO device that is not explained by healing or artifact. One recent meta-analysis found a pooled incidence of DRT in 3.8% of patients post-LAAO [49]. DRT also occurs at variable times after implantation, with over one-third of DRTs detected after 180 days [50]. Several predictors of DRT have been identified, including advanced age, higher CHA_2DS_2-VASc score, prior stroke or transient ischemic attack, and deep device implantation [51]. With disk/lobe devices, DRT may develop on the superior aspect of the device between the disk and pulmonary vein ridge, especially in cases of deep implantation in which the pulmonary vein ridge remains uncovered [52]. Interestingly, neither LAA morphology nor duration of anticoagulation after implantation was associated with DRT occurrence [51].

The rise of CCT for post-procedural imaging has led to an increased detection of hypoattenuated thickening (HAT) on the LAAO device, which is an entity that appears radiographically similar to DRT but has unclear clinical significance. HAT has been reported to occur in 12–24% among all patients undergoing LAAO [53]. The exact pathophysiology of HAT remains under investigation; current literature describes a spectrum from low-grade HAT representing benign endothelialization of the LAAO device to high-grade HAT with clinical consequences similar to DRT [54].

Management of this condition is particularly challenging as patients undergoing LAAO typically already have a contraindication to prolonged oral anticoagulation. Current guidelines suggest 3–6 months of oral anticoagulation if tolerated by the patient [39]. However, further research is needed to determine the optimal cessation period for oral anticoagulation after detection of DRT, as well as the optimal management strategy for different grades of HAT.

Future Directions and Conclusions

The changing landscape of multimodality imaging across all three phases of LAAO care reflects the rapid advances in technology used to improve outcomes. Preprocedural planning with TEE or CCT is essential for determining LAA size, morphology, and ruling out thrombus. Intraprocedural guidance with fluoroscopy alongside either TEE or ICE is critical for precise transeptal puncture and device placement. Finally, postprocedural surveillance with TEE or CCT is important for the evaluation of device stability and detection of PDL and DRT. The increasing adoption of ICE and artificial intelligence-based CT software to existing TEE workflows is expected to further improve procedural efficiency and enhance long-term clinical outcomes.

Key References

- Jain, Renuka et al. “Multimodality Imaging in Evaluating and Guiding Percutaneous Left Atrial Appendage Occlusion.” Journal of the American Society of Echocardiography : official publication of the American Society of Echocardiography, S0894-7317(25)00397-9. 25 Jul. 2025. https://doi.org/10.1016/j.echo.2025.07.009
  - This article provides the most recent guidelines for the use of multimodality imaging for procedural planning, intraprocedural guidance, and follow up of percutaneous left atrial appendage occlusion.

- Serpa, Frans et al. "Intracardiac vs transesophageal echocardiography for left atrial appendage occlusion: An updated systematic review and meta-analysis." Heart rhythm vol. 22,3 (2025): 786-795. https://doi.org/10.1016/j.hrthm.2024.08.027
  - Findings from this study suggest that ICE is a feasible alternative to TEE for intraprocedural guidance of LAAO with similar procedural success rates, though with higher complication rates of pericardial effusion that are mitigated with greater operator experience.

- Cepas-Guillén, Pedro et al. "Imaging assessment after percutaneous left atrial appendage closure: from immediate to long-term follow-up." European heart journal. Cardiovascular Imaging vol. 26,6 (2025): 993-1006. https://doi.org/10.1093/ehjci/jeaf078
  - This study reviews the importance of assessing for peridevice leak and device-related thrombus after LAAO implantation, summarizes gradation schemes for each complication, and highlights the strengths and limitations of TEE and CCT for evaluation of each complication.

Author Contributions AH: Literature review, writing, revision of manuscript, figure preparation. LA: Literature review, writing, revision of manuscript. AV, RR, DB, RF: critical review of manuscript. MS: project supervision, final approval.

Funding The authors did not receive support from any organization for the submitted work.

Data Availability No datasets were generated or analyzed for this study.

Declarations

Human and Animal Rights and Informed Consent No animal or human subjects by the authors were used in this study.

Competing interests Dr. Saric is a member of the speakers bureaus of Abbott, Boston Scientific, Medtronic, and Philips, and the advisory board of Siemens. All other authors have reported that they have no competing interests relevant to the contents of this paper to disclose.

References

1. Blackshear JL, Odell JA. Appendage obliteration to reduce stroke in cardiac surgical patients with atrial fibrillation. Ann Thorac Surg. 1996;61(2):755–9.
2. Madden JL. Resection of the left auricular appendix; a prophylaxis for recurrent arterial emboli. J Am Med Assoc. 1949;140(9):769–72.
3. Turagam MK, Velagapudi P, Kar S, Holmes D, Reddy VY, Refaat MM, et al. Cardiovascular therapies targeting left atrial appendage. J Am Coll Cardiol. 2018;72(4):448–63.
4. Sievert H, Lesh MD, Trepels T, Omran H, Bartorelli A, Della Bella P, et al. Percutaneous left atrial appendage transcatheter occlusion to prevent stroke in high-risk patients with atrial fibrillation: early clinical experience. Circulation. 2002;105(16):1887–9.
5. Asmarats L, Rodes-Cabau J. Percutaneous left atrial appendage closure: current devices and clinical outcomes. Circ Cardiovasc Interv. 2017;10(11):e005359.
6. Glikson M, Wolff R, Hindricks G, Mandrola J, Camm AJ, Lip GYH, et al. EHRA/EAPCI expert consensus statement on catheter-based left atrial appendage occlusion - an update. EuroIntervention. 2020;15(13):1133–80.
7. Freeman JV, Varosy P, Price MJ, Slotwiner D, Kusumoto FM, Rammohan C, et al. The NCDR left atrial appendage occlusion registry. J Am Coll Cardiol. 2020;75(13):1503–18.
8. Hindricks G, Potpara T, Dagres N, Arbelo E, Bax JJ, Blomstrom-Lundqvist C, et al. Corrigendum to: 2020 ESC guidelines for the diagnosis and management of atrial fibrillation developed in collaboration with the European association for Cardio-Thoracic surgery (EACTS): the task force for the diagnosis and management of atrial fibrillation of the European society of cardiology (ESC) developed with the special contribution of the European heart rhythm association (EHRA) of the ESC. Eur Heart J. 2021;42(40):4194.
9. Jung RG, Simard T, Killu A, Harris AA, Hohmann SF, Holmes DR, et al. Learning curve and outcomes of left atrial appendage closure. JACC Cardiovasc Interv. 2021;14(24):2750–2.
10. Alkhouli M, Ellis CR, Daniels M, Coylewright M, Nielsen-Kudsk JE, Holmes DR. Left atrial appendage occlusion: current advances and remaining challenges. JACC Adv. 2022;1(5):100136.
11. Holmes DR, Reddy VY, Turi ZG, Doshi SK, Sievert H, Buchbinder M, et al. Percutaneous closure of the left atrial appendage versus warfarin therapy for prevention of stroke in patients with atrial fibrillation: a randomised non-inferiority trial. Lancet. 2009;374(9689):534–42.
12. Holmes DR Jr., Kar S, Price MJ, Whisenant B, Sievert H, Doshi SK, et al. Prospective randomized evaluation of the watchman left atrial appendage closure device in patients with atrial fibrillation versus long-term warfarin therapy: the PREVAIL trial. J Am Coll Cardiol. 2014;64(1):1–12.
13. Lakkireddy D, Thaler D, Ellis CR, Swarup V, Sondergaard L, Carroll J, et al. Amplatzer amulet left atrial appendage occluder versus watchman device for stroke prophylaxis (Amulet IDE): A Randomized, controlled trial. Circulation. 2021;144(19):1543–52.
14. Osmancik P, Herman D, Neuzil P, Hala P, Taborsky M, Kala P, et al. Left atrial appendage closure versus direct oral anticoagulants in High-Risk patients with atrial fibrillation. J Am Coll Cardiol. 2020;75(25):3122–35.
15. Merino A, Hauptman P, Badimon L, Badimon JJ, Cohen M, Fuster V, et al. Echocardiographic smoke is produced by an interaction of erythrocytes and plasma proteins modulated by shear forces. J Am Coll Cardiol. 1992;20(7):1661–8.
16. Wang Y, Di Biase L, Horton RP, Nguyen T, Morhanty P, Natale A. Left atrial appendage studied by computed tomography to help planning for appendage closure device placement. J Cardiovasc Electrophysiol. 2010;21(9):973–82.

17. Bernhardt P, Schmidt H, Hammerstingl C, Luderitz B, Omran H. Patients with atrial fibrillation and dense spontaneous echo contrast at high risk a prospective and serial follow-up over 12 months with transesophageal echocardiography and cerebral magnetic resonance imaging. J Am Coll Cardiol. 2005;45(11):1807–12.
18. Goldman ME, Pearce LA, Hart RG, Zabalgoitia M, Asinger RW, Safford R, et al. Pathophysiologic correlates of thromboembolism in nonvalvular atrial fibrillation: I. Reduced flow velocity in the left atrial appendage (The stroke prevention in atrial fibrillation [SPAF-III] study). J Am Soc Echocardiogr. 1999;12(12):1080–7.
19. Handke M, Harloff A, Hetzel A, Olschewski M, Bode C, Geibel A. Left atrial appendage flow velocity as a quantitative surrogate parameter for thromboembolic risk: determinants and relationship to spontaneous Echocontrast and thrombus formation–a transesophageal echocardiographic study in 500 patients with cerebral ischemia. J Am Soc Echocardiogr. 2005;18(12):1366–72.
20. Hahn RT, Saric M, Faletra FF, Garg R, Gillam LD, Horton K, et al. Recommended standards for the performance of transesophageal echocardiographic screening for structural heart intervention: from the American society of echocardiography. J Am Soc Echocardiogr. 2022;35(1):1–76.
21. Negrotto SM, Lugo RM, Metawee M, Kanagasundram AN, Chidsey G, Baker MT, et al. Left atrial appendage morphology predicts the formation of left atrial appendage thrombus. J Cardiovasc Electrophysiol. 2021;32(4):1044–52.
22. Hayes DE, Bamira D, Vainrib AF, Freedberg RS, Aizer A, Chinitz LA, et al. Left atrial appendage Tilt-Up-and-Turn-Left maneuver: A novel Three-Dimensional transesophageal echocardiography imaging maneuver to characterize the left atrial appendage and to improve transcatheter closure guidance. CASE (Phila). 2023;7(10):391–5.
23. Di Biase L, Santangeli P, Anselmino M, Mohanty P, Salvetti I, Gili S, et al. Does the left atrial appendage morphology correlate with the risk of stroke in patients with atrial fibrillation? Results from a multicenter study. J Am Coll Cardiol. 2012;60(6):531–8.
24. Korsholm K, Berti S, Iriart X, Saw J, Wang DD, Cochet H, et al. Expert recommendations on cardiac computed tomography for planning transcatheter left atrial appendage occlusion. JACC Cardiovasc Interv. 2020;13(3):277–92.
25. Kubota T, Kawasaki M, Takasugi N, Takeyama U, Ishihara Y, Okubo M, et al. Evaluation of left atrial degeneration for the prediction of atrial fibrillation: usefulness of integrated backscatter transesophageal echocardiography. JACC Cardiovasc Imaging. 2009;2(9):1039–47.
26. Romero J, Husain SA, Kelesidis I, Sanz J, Medina HM, Garcia MJ. Detection of left atrial appendage thrombus by cardiac computed tomography in patients with atrial fibrillation: a meta-analysis. Circ Cardiovasc Imaging. 2013;6(2):185–94.
27. Ghozy S, Liu M, Kobeissi H, Mortezaei A, Amoukhteh M, Abbas AS, et al. Cardiac CT vs echocardiography for intracardiac thrombus detection in ischemic stroke: A systematic review and Meta-Analysis of 43 studies. Neurology. 2024;103(7):e209771.
28. Sattar Y, Kompella R, Ahmad B, Aamir M, Suleiman AM, Zghouzi M, et al. Comparison of left atrial appendage parameters using computed tomography vs. transesophageal echocardiography for watchman device implantation: a systematic review & meta-analysis. Expert Rev Cardiovasc Ther. 2022;20(2):151–60.
29. De Backer O, Iriart X, Kefer J, Nielsen-Kudsk JE, Aminian A, Rosseel L, et al. Impact of computational modeling on transcatheter left atrial appendage closure efficiency and outcomes. JACC Cardiovasc Interv. 2023;16(6):655–66.
30. Obasare E, Mainigi SK, Morris DL, Slipczuk L, Goykhman I, Friend E, et al. CT based 3D printing is superior to transesophageal echocardiography for pre-procedure planning in left atrial appendage device closure. Int J Cardiovasc Imaging. 2018;34(5):821–31.
31. Bhuta S, Carlen A, Savona SJ, Augostini RS, Kalbfleisch SJ, Houmsse M, et al. Incidence and Temporal evolution of delayed peridevice leak after left atrial appendage closure. Heart Rhythm. 2024;21(11):2118–25.
32. Cepas-Guillen P, Holmes DR Jr., Cavalcante J, Freixa X, O'Hara G, Beaudoin J, et al. Imaging assessment after percutaneous left atrial appendage closure: from immediate to long-term follow-up. Eur Heart J Cardiovasc Imaging. 2025;26(6):993–1006.
33. Alkhouli M, Hijazi ZM, Holmes DR Jr., Rihal CS, Wiegers SE. Intracardiac echocardiography in structural heart disease interventions. JACC Cardiovasc Interv. 2018;11(21):2133–47.
34. Sularz A, Chavez Ponce A, Al-Abcha A, Simard T, Killu AM, Doshi SK, et al. Safety and feasibility of 3D intracardiac echocardiography in guiding left atrial appendage occlusion with WATCHMAN FLX. JACC Adv. 2025;4(2):101570.
35. Ferro EG, Alkhouli M, Nair DG, Kapadia SR, Hsu JC, Gibson DN, et al. Intracardiac vs transesophageal echocardiography for left atrial appendage occlusion with watchman FLX in the U.S. JACC Clin Electrophysiol. 2023;9(12):2587–99.
36. Serpa F, Rivera A, Fernandes JM, Braga MAP, Araujo B, Ferreira Felix I, et al. Intracardiac vs transesophageal echocardiography for left atrial appendage occlusion: an updated systematic review and meta-analysis. Heart Rhythm. 2025;22(3):786–95.
37. Flautt T, Da-Wariboko A, Lador A, Patel A, Guevara M, Valderrabano M. Left atrial appendage occlusion without fluoroscopy: optimization by 4D intracardiac echocardiography. JACC Cardiovasc Interv. 2022;15(15):1592–4.
38. Berti S, Pastormerlo LE, Santoro G, Brscic E, Montorfano M, Vignali L, et al. Intracardiac versus transesophageal echocardiographic guidance for left atrial appendage occlusion: the LAAO Italian multicenter registry. JACC Cardiovasc Interv. 2018;11(11):1086–92.
39. Saw J, Holmes DR, Cavalcante JL, Freeman JV, Goldsweig AM, Kavinsky CJ, et al. SCAI/HRS expert consensus statement on transcatheter left atrial appendage closure. J Soc Cardiovasc Angiogr Interv. 2023;2(3):100577.
40. Jain R, Wessly P, Saric M, Richardson K, Garcia-Sayan E, Addetia K et al. Multimodality imaging in evaluating and guiding percutaneous left atrial appendage occlusion. J Am Soc Echocardiogr. 2025;38(12):1198–218.
41. Korsholm K, Jensen JM, Norgaard BL, Samaras A, Saw J, Berti S, et al. Peridevice leak following amplatzer left atrial appendage occlusion: cardiac computed tomography classification and clinical outcomes. JACC Cardiovasc Interv. 2021;14(1):83–93.
42. Viles-Gonzalez JF, Kar S, Douglas P, Dukkipati S, Feldman T, Horton R, et al. The clinical impact of incomplete left atrial appendage closure with the watchman device in patients with atrial fibrillation: a PROTECT AF (Percutaneous closure of the left atrial appendage versus warfarin therapy for prevention of stroke in patients with atrial Fibrillation) substudy. J Am Coll Cardiol. 2012;59(10):923–9.
43. Alkhouli M, Du C, Killu A, Simard T, Noseworthy PA, Friedman PA, et al. Clinical impact of residual leaks following left atrial appendage occlusion: insights from the NCDR LAAO registry. JACC Clin Electrophysiol. 2022;8(6):766–78.
44. Dukkipati SR, Holmes DR Jr., Doshi SK, Kar S, Singh SM, Gibson D, et al. Impact of peridevice leak on 5-Year outcomes after left atrial appendage closure. J Am Coll Cardiol. 2022;80(5):469–83.
45. Samaras A, Papazoglou AS, Balomenakis C, Bekiaridou A, Moysidis DV, Patsiou V, et al. Residual leaks following percutaneous left atrial appendage occlusion and outcomes: a meta-analysis. Eur Heart J. 2024;45(3):214–29.
46. Chen M, Yao PC, Fei ZT, Wang QS, Yu YC, Zhang PP, et al. Prognostic impact of left atrial appendage patency after device closure. Circ Cardiovasc Interv. 2024;17(5):e013579.
47. Jacquemyn X, Sa MP, Korsholm K, Nielsen-Kudsk JE, Iriart X, Saw J, et al. Outcomes of left atrial appendage patency after

device closure detected by cardiac CT: A Meta-Analysis. JACC Cardiovasc Imaging; 2025.
48. Alkhouli M, De Backer O, Ellis CR, Nielsen-Kudsk JE, Sievert H, Natale A, et al. Peridevice leak after left atrial appendage occlusion: Incidence, Mechanisms, clinical Impact, and management. JACC Cardiovasc Interv. 2023;16(6):627–42.
49. Alkhouli M, Busu T, Shah K, Osman M, Alqahtani F, Raybuck B. Incidence and clinical impact of Device-Related thrombus following percutaneous left atrial appendage occlusion: A Meta-Analysis. JACC Clin Electrophysiol. 2018;4(12):1629–37.
50. Simard T, Jung RG, Lehenbauer K, Piayda K, Pracon R, Jackson GG, et al. Predictors of Device-Related thrombus following percutaneous left atrial appendage occlusion. J Am Coll Cardiol. 2021;78(4):297–device313.
51. Alkhouli M, Alarouri H, Kramer A, Korsholm K, Collins J, De Backer O, et al. Device-Related thrombus after left atrial appendage occlusion: clinical Impact, Predictors, Classification, and management. JACC Cardiovasc Interv. 2023;16(22):2695–707.
52. Aminian A, Schmidt B, Mazzone P, Berti S, Fischer S, Montorfano M, et al. Incidence, Characterization, and clinical impact of Device-Related thrombus following left atrial appendage occlusion in the prospective global AMPLATZER amulet observational study. JACC Cardiovasc Interv. 2019;12(11):1003–14.
53. Korsholm K, Jensen JM, Norgaard BL, Nielsen-Kudsk JE. Detection of Device-Related thrombosis following left atrial appendage occlusion: A comparison between cardiac computed tomography and transesophageal echocardiography. Circ Cardiovasc Interv. 2019;12(9):e008112.
54. Korsholm K, Iriart X, Saw J, Wang DD, Berti S, Galea R, et al. Position statement on cardiac computed tomography following left atrial appendage occlusion. JACC Cardiovasc Interv. 2024;17(15):1747–64.