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iREVIEWS

STATE-OF-THE-ART PAPERS

The Left Atrial Appendage: Anatomy, Function, and Noninvasive Evaluation

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ABSTRACT

The left atrial appendage (LAA) is a finger-like extension originating from the main body of the left atrium. Atrial fibrillation (AF) is the most common clinically important cardiac arrhythmia, occurring in approximately 0.4% to 1% of the general population and increasing with age to >8% in those >80 years of age. In the presence of AF thrombus, formation often occurs within the LAA because of reduced contractility and stasis; thus, attention should be given to the LAA when evaluating and assessing patients with AF to determine the risk for cardioembolic complications. It is clinically important to understand LAA anatomy and function. It is also critical to choose the optimal imaging techniques to identify or exclude LAA thrombi in the setting of AF, before cardioversion, and with current and emerging transcatheter therapies, which include mitral balloon valvuloplasty, pulmonary vein isolation, MitraClip (Abbott Laboratories, Abbott Park, Illinois) valve repair, and the implantation of LAA occlusion and exclusion devices. In this review, we present the current data regarding LAA anatomy, LAA function, and LAA imaging using the currently available noninvasive imaging modalities. (J Am Coll Cardiol Img 2014;7:1251–65) © 2014 by the American College of Cardiology Foundation.

Atrial fibrillation (AF) occurs in approximately 0.4% to 1% of the general population, increasing with age to >8% in those >80 years of age, with prevalence projected to more than double by 2035 (1–3). In 1909, Welch (4) noted that cardiovascular stroke associated with AF was due to left atrial appendage (LAA) thrombi and that this was the most common site for thrombus formation in the setting of AF (5). Meticulous attention should be given to the LAA when evaluating patients with AF to determine the risk for cardioembolic complications, especially before proceeding with cardioversion. In addition, the development of new interventional transcatheter procedures for AF, mitral valve repair, atrial septal defect closure, and LAA occlusion may result in intentional or unintentional instrumentation of the LAA. Thus, it is now clinically important to understand LAA anatomy and the optimal imaging techniques to identify or exclude LAA thrombi.

LAA ANATOMY

The LAA derives from the primordial left atrium (LA), which is formed mainly by the adsorption of the primordial pulmonary veins and their branches (6). It is a finger-like projection from the main body of the LA. The junction is fairly well defined by a narrowing at the orifice of the appendage. There are considerable variations in its size, shape, and relationship with adjacent cardiac and extracardiac structures, which can be extremely relevant when interventional procedures are performed.

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ABBREVIATIONS AND ACRONYMS

AF = atrial fibrillation

CMR = cardiac magnetic resonance

ICE = intracardiac echocardiography

LA = left atrium

LAA = left atrial appendage

LV = left ventricular

MDCT = multidetector computed tomography

SEC = spontaneous echocardiographic contrast

SR = sinus rhythm

TEE = transesophageal echocardiography

2D = 2-dimensional

3D = 3-dimensional

In most hearts, the LAA extends between the anterior and the lateral walls of the LA, and its tip is directed anterosuperiorly, overlapping the left border of the right ventricular outflow tract or the pulmonary trunk and the main stem of the left coronary or the circumflex artery. It is not uncommon to find the tip of the LAA directed laterally and backward. However, in a small percent of hearts, the tip of the LAA passes behind the arterial pedicle to sit in the transverse pericardial sinus. The external appearance of the LAA is that of a slightly flattened tubular structure with crenellations, often with one or more bends and terminating in a pointed tip. Because of its slightly flattened shape, the lower surface usually overlies the left ventricle and the upper surface is beneath the fibrous pericardium. Internally (**Figure 1A**), the orifice of the appendage is usually oval, whereas round, triangular, and water-drop shapes are observed less frequently (7,8). The left lateral ridge separates the orifices of the left pulmonary veins from the LAA orifice, but the precise relationship between the level of the orifice and its distance to the venous orifices varies (9). The smooth muscular wall of the LA vestibule separates the orifice from the mitral annulus.

Most appendages have a well-defined orifice that leads to a neck region that opens to the body of the appendage. In a large study of postmortem hearts, Veinot et al. (10) defined lobes as protrusions from the main body with the tail portion also representing a lobe, whereas bends in the tail do not constitute more lobes. They found that 2 lobes were most common (54%), followed by 3 lobes (23%), 1 lobe (20%), and 4 lobes (3%), and noted there were no significant age- or sex-related differences in LAA morphologies. An increased number of lobes was associated with the presence of a thrombus independent of clinical risk and blood stasis (11). In a recent study using multidetector computed tomography (MDCT) and cardiac magnetic resonance (CMR), the shapes of the LAA in patients with drug-refractory AF were classified into 4 morphological types (**Figures 2 and 3**), with "chicken wing" being the most common (48%), followed by "cactus" (30%), "windsock" (19%), and "cauliflower" (3%) (12). The "cauliflower" morphology is most often associated with an embolic event. It is described as having a short overall length, more complex internal characteristics, a variable number of lobes with lack of a dominant lobe, and a more irregular shape of the orifice. The "cactus shape" has a dominant central lobe and secondary lobes arise from it superiorly and inferiorly, whereas the "windsock" has a dominant lobe as the primary structure and there are variations in the location and number of secondary or even tertiary lobes. The "chicken wing" has a dominant lobe that presents with an obvious bend in its proximal or middle part, folding back on itself at some distance from the orifice, and it may have secondary lobes. **Figure 4** demonstrates endocasts emphasizing that there can be overlap between the different morphologies when viewed from different angles. As elegantly demonstrated by Stöllberger et al. (13), the shape, lobes, and branches depend on the imaging plane.

Casts of the inner surface of the LAA reveal complex indentations made by the pectinate muscles that line the cavity of the appendage. The muscle bundles in the LAA do not ramify like the teeth of a comb. Instead, they have a feather-type-palm-leaf arrangement, especially at the borders between superior and inferior

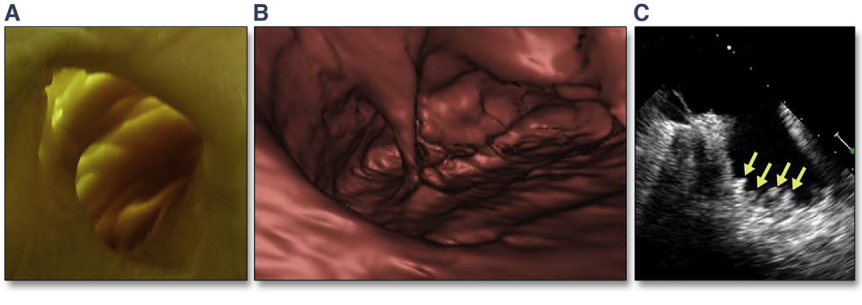

FIGURE 1 Orifice of the LAA and the Pectinate Muscles Within It

(A) The LAA imaged from within the LA in an explanted heart showing transilluminated thin walls between the pectinate muscles. **(B)** Corresponding computed tomography 3D reconstruction from within the LA. **(C)** 2D TEE; **arrows** point to the pectinate muscles. LA = left atrium; LAA = left atrial appendage; TEE = transesophageal echocardiography; 2D = 2-dimensional; 3D = 3-dimensional.

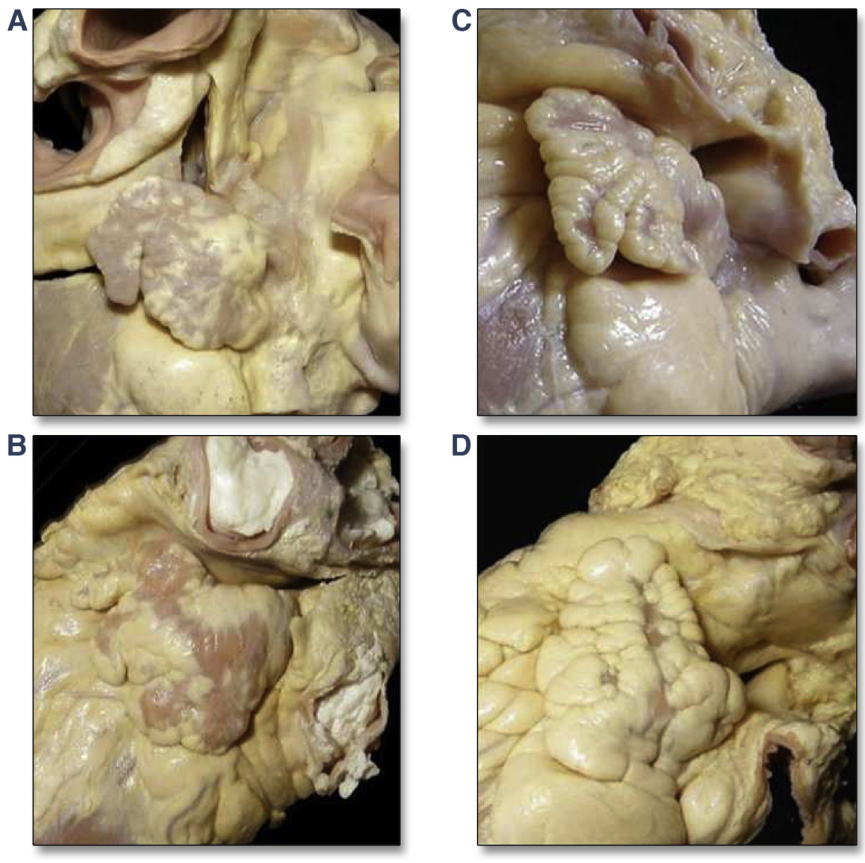

FIGURE 2 Anatomic Variants of LAA Morphology

Sample images taken from explanted hearts demonstrating different LAA morphologies **(top)**. **(A)** Chicken wing. **(B)** Windsock. **(C)** Cauliflower. **(D)** Cactus. Abbreviation as in Figure 1.

surfaces; are strap-like; or resemble a fan-type-palm-leaf arrangement near the border with the atrial vestibule (14). As shown in **Figure 5A**, the thicker muscle bundles may be mistaken for thrombi or intra-atrial masses (10). The remainder of the LAA wall in between the muscle bundles is paper-thin (**Figure 1A**).

Studies of heart specimens and casts from patients in sinus rhythm (SR) compared with those from patients with AF revealed structural remodeling of the LAA with dilation of the chamber and a reduction in the number of pectinate muscles (15,16).

LAA FUNCTION AND THROMBUS FORMATION

Normal contraction of the LAA during SR, as demonstrated in **Figure 6**, and adequate blood flow within the LAA lower the risk for formation of thrombi inside its cavity. Thrombus formation is more likely to occur within the LAA when reduced contractility and stasis ensue. As shown in **Figure 7**, during AF there is a decrease in LAA contractility and function, manifest as a decrease in Doppler velocities and dilation of the LAA (17,18). The remodeling process associated with AF causes the LAA to function as a static pouch, predisposing to stagnation and thrombosis. Limited data suggest that patients with significant left ventricular (LV) dysfunction and elevated LV end-diastolic pressures also may be at risk for an LAA thrombus formation in the absence of AF. Vigna et al. (19) found LAA thrombi in 8 of 58 patients with dilated cardiomyopathy who were in SR. Consequently, the risk of thrombus formation in the LAA seems to be related to impaired LAA function, reduced contractile function, and elevated filling pressures regardless of its cause. LAA thrombi are present in up to 14% of patients with acute (<3 days) AF (20). Moreover, thrombus formation may develop even in patients with AF who are receiving therapeutic anticoagulation therapy. A transesophageal echocardiography (TEE) study found that 1.6% of patients treated with anticoagulation for 1

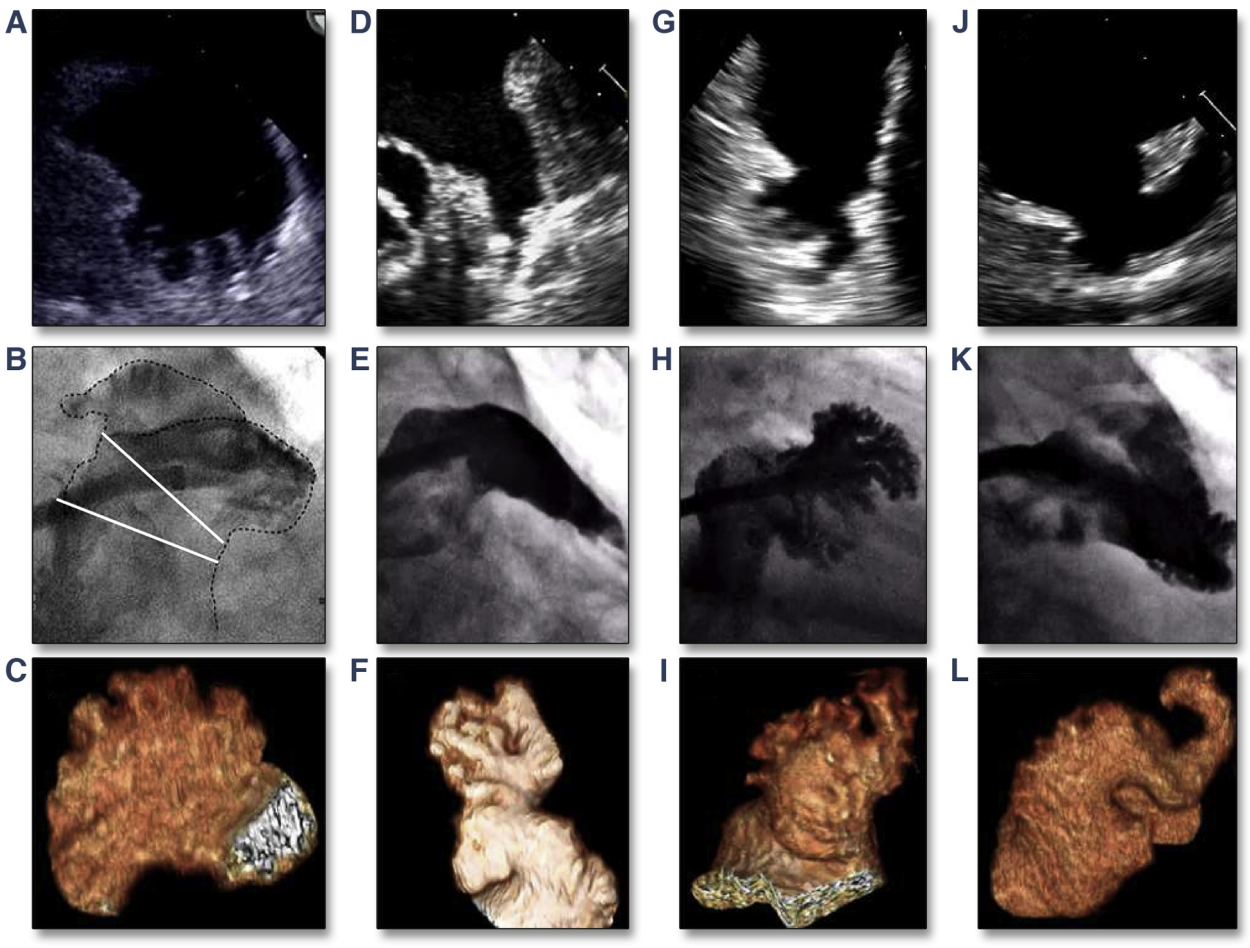

FIGURE 3 LAA: Morphologies and Modalities

The 4 different LAA morphologies as shown by TEE **(top)**, cine angiography **(middle)**, and 3D computed tomography **(bottom)**. Cauliflower **(A to C)**, windsock **(D to F)**, cactus **(G to I)**, and chicken wing **(J to L)**. Abbreviations as in Figure 1.

month had echocardiographic evidence of an LAA thrombus (21). These findings underscore the significant and important role of noninvasive imaging for detection of LAA thrombi.

In animal studies, removal of the LAA was found to decrease compliance of the LA, which was associated with significant changes in LV and LA filling and atrial function. Whether these effects of LAA removal are due to changes in LA geometry or to loss of a region with different distensibility is currently unknown, as well as the clinical implications (22).

NONINVASIVE IMAGING OF THE LAA FOR RISK ASSESSMENT

ECHOCARDIOGRAPHY. Although initial studies using transthoracic echocardiography demonstrated it to have limited ability for detection of LA and LAA thrombus formation (23,24), the use of harmonic imaging and administration of ultrasound contrast agents have enhanced the capability of transthoracic echocardiography to detect LAA thrombi (25,26).

TEE has made accurate assessment and imaging of the LAA possible, allowing the evaluation of LAA morphology and flow patterns within it. TEE is currently the most widely used and accepted modality to diagnose and exclude the presence of LAA thrombi. The sensitivity and specificity of TEE for detection of LAA thrombi when compared with intraoperative observations are 92% and 98%, respectively (27,28), with negative and positive predictive values of 100% and 86%, respectively (28). A complete TEE evaluation of the LAA should include imaging of the accompanying structures, such as the LA, LV, and mitral valve, along

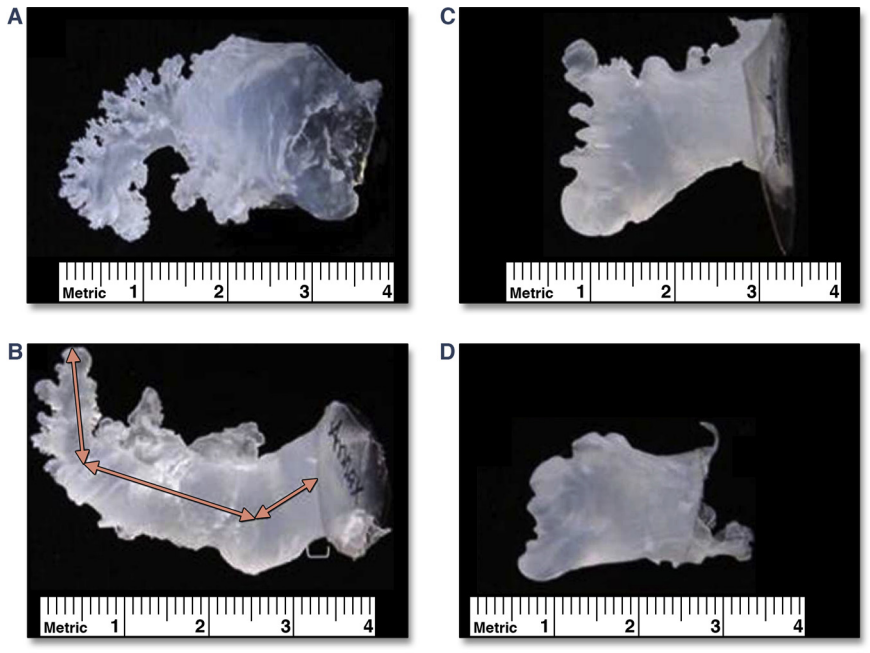

FIGURE 4 Endocasts Obtained From 2 Explanted Hearts Showing the Different LAA Intraluminal Morphologies

(A) Chicken wing. **(B)** Windsock. **(C)** Cauliflower. **(D)** Cactus. **A, B** and **C, D** are pairs of the same casts but viewed from different perspectives showing the overlap that exists regarding LAA morphology. Abbreviation as in **Figure 1**.

with a detailed assessment of LAA morphology, contraction, and flow velocities using 2-dimensional (2D) and 3-dimensional (3D) echocardiography. Exclusion of LAA thrombi using TEE can also allow early, and safe, cardioversion avoiding the need for prolonged anticoagulation therapy prior to cardioversion (29). The different aspects used for echocardiographic evaluation of LAA anatomy, function, and flow are further detailed in **Table 1**.

2D AND 3D ECHOCARDIOGRAPHY. As shown in **Figure 8**, TEE imaging of the LAA is best obtained using a multiplane approach in both the long-axis and the short-axis views, as well as with the use of 3D imaging. In cases in which LAA images are suboptimal, ultrasound contrast agents are useful to enhance visualization of the LAA. The use of contrast eliminates many of the artifacts and generally demonstrates complete opacification of the LAA or reveals filling defects in its body (30,31). Although patients with dense spontaneous echocardiographic contrast (SEC) seen within the LAA have a stroke rate of 18.2% per year if untreated with warfarin and a 4.5% per year stroke risk with adjusted-dose warfarin, the presence of an LAA thrombus triples the overall rate of stroke (32).

Table 2 and **Figure 5** list and demonstrate the different findings that can be encountered during echocardiographic evaluation of the LAA. Because of the complex anatomic features of thrombi, they can be difficult to detect and thus missed. Conversely, overdiagnosis of thrombi can result from misinterpretation of acoustic shadowing from the ligament of Marshall or misinterpretation of pectinate muscles as thrombi (**Figures 5A and 5B**). Whether the presence of sludge or dense SEC within the LAA should be regarded equivalently as the presence of a thrombus is controversial (33).

Imaging with 3D TEE is a relatively recent development that improves assessment of LAA anatomy. Although 2D TEE provides higher-resolution images because of a better frame rate, 3D TEE allows a more comprehensive assessment of the LAA by overcoming some of the limitations associated with 2D imaging, such as inadequate imaging planes. In addition, 3D TEE provides better separation and differentiation between adjacent structures, along with a more complete and comprehensive evaluation of the LAA, its complex morphology, and the surrounding structures (25,34,35). Data are still limited regarding the sensitivity and specificity of 3D TEE for detecting LAA thrombi. However, with recent advances in percutaneous device therapy for LAA closure, 3D TEE has become important to guide device delivery into the

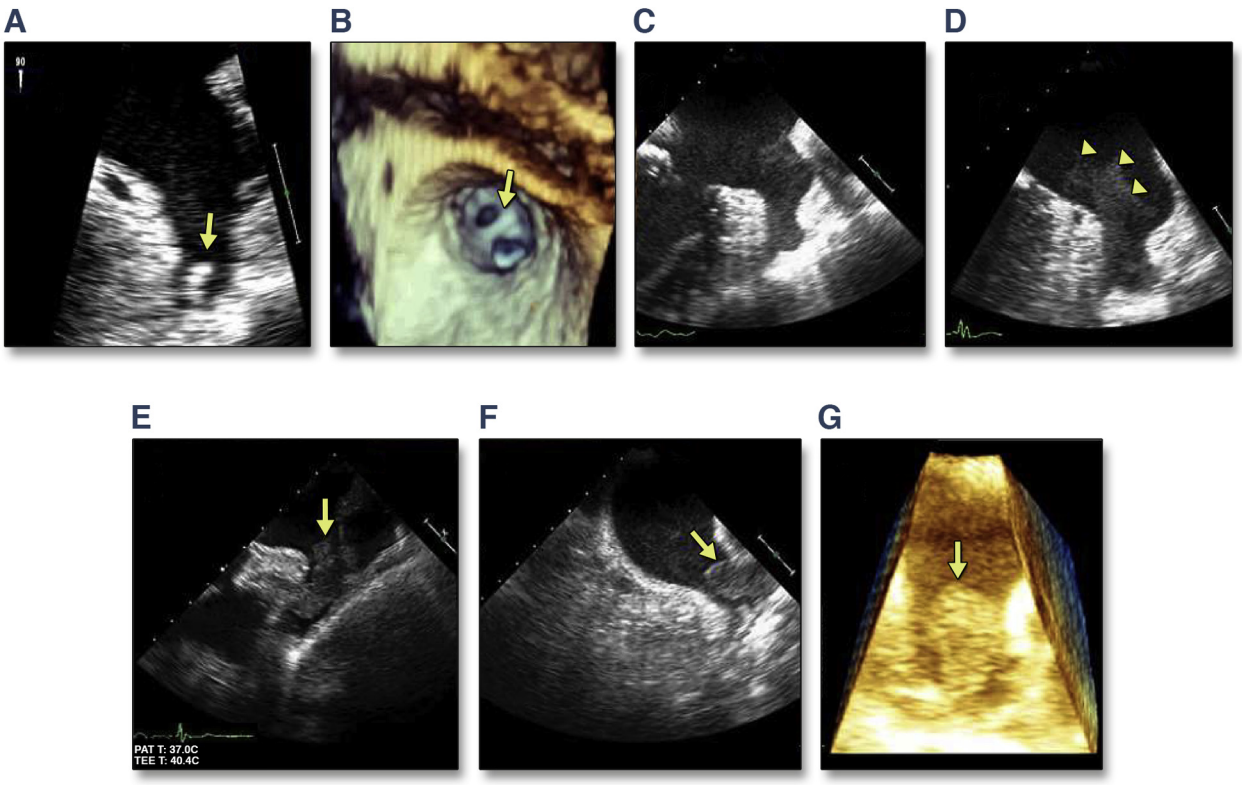

FIGURE 5 Abnormal TEE Findings Within the LAA

(A) The presence of a large pectinate muscle can sometimes be confused for an LAA thrombus. **(B)** In this case, the pectinate muscle is better defined by 3D TEE. **(C)** SEC is seen in the LAA. **(D)** A more echo-dense, amorphous finding consistent with sludge is seen within the LAA **(arrowheads)**. Zero-degree **(E)** and 95° **(F)** views and 3D imaging **(G)** show a thrombus within the LAA **(arrows)**. SEC = spontaneous echocardiographic contrast; other abbreviations as in Figure 1.

LAA. Table 3 details the potential advantages of 3D echocardiography compared with 2D echocardiography for LAA and LA evaluation (18,35-43).

Intracardiac echocardiography (ICE) can provide an alternative imaging method when TEE is not obtainable. ICE can provide multiple views and detailed imaging of the LAA (44) to reliably diagnose the presence of thrombi (45). Although ICE is less sensitive compared with TEE for thrombus detection (46), it can serve as a complementary method, especially when equivocal TEE findings merit further evaluation. However, because ICE is an invasive procedure, its use is limited in daily practice and is mainly reserved for the catheterization laboratory during planned interventional cardiac procedures.

DOPPLER. Because the LAA is generally multilobed, it can be difficult to visualize in its entirety, even with 3D imaging. In addition, TEE has limited sensitivity for identification of small thrombi or thrombi within a side lobe. Thus, the absence of visualizing an LAA thrombus does not equate with the absence of an LAA thrombus. To better assess the LAA and the risk of thromboembolism, functional assessment of the LAA using Doppler echocardiography is routinely used (47). Evaluation of LAA Doppler velocities is requisite to help exclude LAA thrombi. In SR, the LAA is usually a highly contractile muscular sac that obliterates its apex during atrial systole. This can be seen by TEE and confirmed by pulsed and color flow Doppler. The LAA velocity and color flow in SR are concordant with LAA reduction in size, reflecting true contraction, whereas in AF this normal pattern is usually replaced by a chaotic one of varying velocities (Figure 9). Flow in the appendage should be assessed after optimally aligning the pulsed-wave Doppler signal with the LAA flow using color flow imaging, with the sampling done at the site where maximal flow velocities are obtained (usually in the proximal third of the appendage) (47). In normal subjects, without known cardiac abnormalities, LAA contraction is biphasic

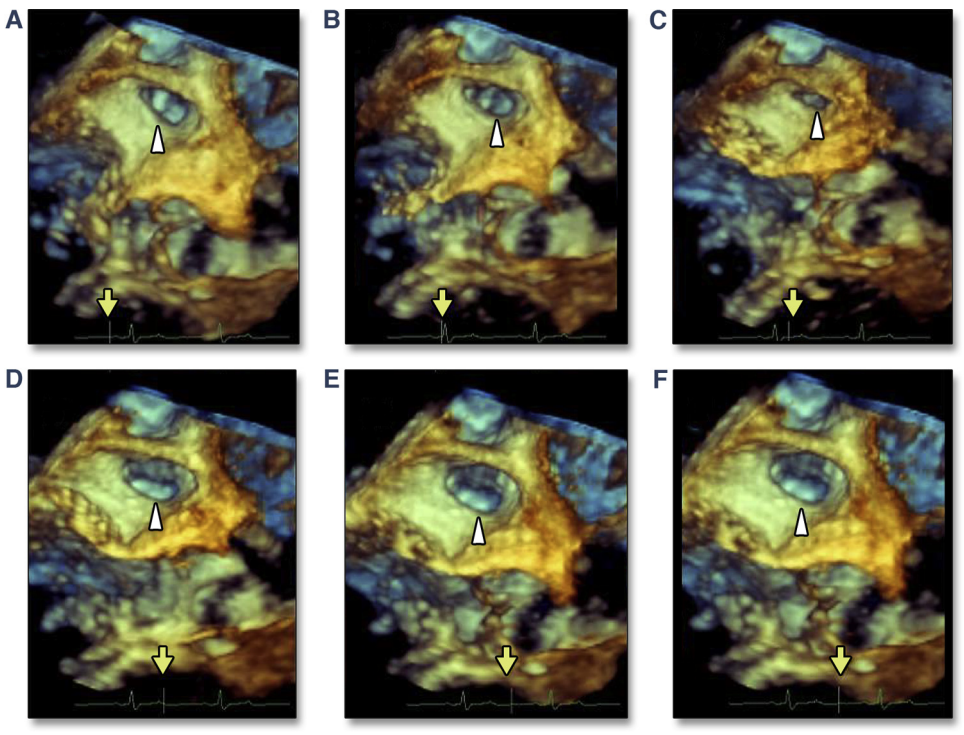

FIGURE 6 Change in Size of the LAA During the Cardiac Cycle in a Patient in SR

In this patient in SR, the LAA **(arrowhead)** can be seen in varying sizes during the different phases **(A to F)** of the cardiac cycle (**yellow arrow** pointing to time frame of cycle). SR = sinus rhythm; other abbreviation as in Figure 1.

with velocities ranging from 50 ± 6 cm/s to 83 ± 25 cm/s with filling velocities ranging from 46 ± 12 cm/s to 60 ± 19 cm/s (48-52). Decreased velocities in patients in SR can be observed in the presence of elevated LA pressure (51). In patients with AF, flow signals from the LAA are highly variable with a sawtooth pattern or the absence of identifiable flow waves (48,53), although they tend to have lower velocities during ventricular systole (when the LAA contracts against a closed mitral valve) with increasing heart rate reducing the peak flow velocity (54). Velocities were found to be highest in subjects in SR, intermediate in subjects with paroxysmal AF and atrial flutter, and lowest in subjects with chronic AF (55-58). Velocities <40 cm/s are associated with a higher risk of stroke and the presence of SEC (59), with decreasing velocities of <20 cm/s associated with the identification of thrombus within the LAA and a higher incidence of thromboembolic events (32,48,50,55,60). The presence of velocities <40 cm/s requires meticulous evaluation of the LAA before cardioversion or device intervention involving the LA and LAA. In addition, as shown in Figure 10, setting the color Doppler to a low Nyquist limit can aid in visualizing flow and help detect or exclude the presence of a thrombus. Absence of color flow in the LAA's distal tip or side lobes may indicate the absence of flow because of the lack of filling from a thrombus. Although a decrease in LAA function has been demonstrated in patients with AF, atrial flutter, or SR (50,53,55,61), its significance has been widely evaluated only in the setting of AF. In patients in SR, the presence of SEC has a greater association with stroke risk than reduced LAA emptying velocities (62). The role of LAA dysfunction for predicting embolic events in patients in SR has not been widely addressed. When Doppler signals are suboptimal, the use of a microbubble contrast agent enhances detection of LAA Doppler flow velocities (63). A useful algorithm detailing the approach for the evaluation of the LAA is shown in Figure 11.

ADDITIONAL PARAMETERS. Doukky et al. (64) found that E/e' and e' velocities are independently associated with an LAA thrombus in patients with

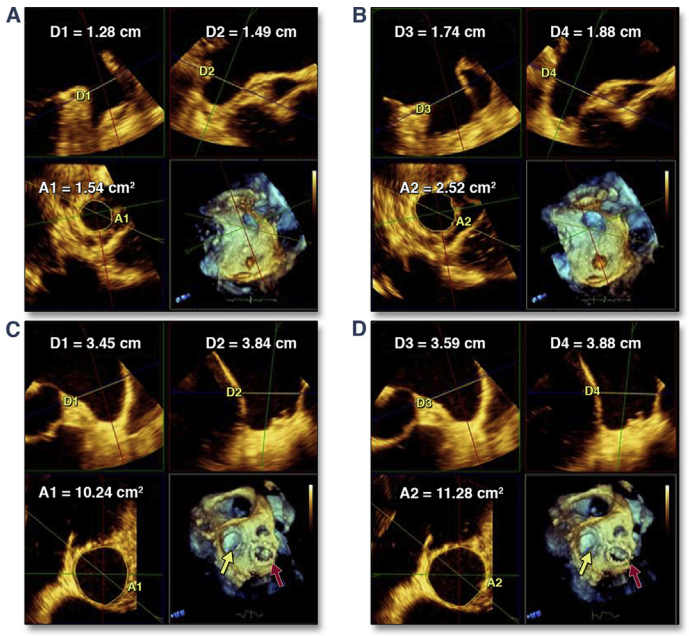

FIGURE 7 Diameter and Area Changes of the LAA Orifice During the Cardiac Cycle

(Top) A patient in normal SR who had LAA contractility. Systole **(A)** and diastole **(B)**. **(Bottom)** A patient with long-lasting AF. Systole **(C)** and diastole **(D)**. Note the difference in area between systole and diastole in the patients in SR opposed to the minimal change in the area in the patient in AF where there is considerably reduced contractility. In this patient in AF, the LAA orifice is markedly enlarged; note that a 32-mm Carpentier ring in the mitral position **(bottom right in C and D, red arrow)** is visually smaller in diameter than the LAA orifice **(yellow arrow)**. AF is associated with structural remodeling of the LAA, which includes dilation of the chamber and reduction in pectinate muscles (not shown). AF = atrial fibrillation; SR = sinus rhythm; other abbreviation as in Figure 1.

nonvalvular AF, supporting the physiologic plausibility that LV diastolic dysfunction and LA elevated filling pressure also may contribute to stasis leading to LAA thrombus formation in patients with AF.

A limited number of studies evaluated the use of tissue Doppler imaging for evaluation of the LAA before cardioversion. Patients with an LAA thrombus demonstrated the lowest LAA contraction velocities (65); thus, tissue Doppler imaging can be complementary to flow velocities when evaluating the LAA (66,67). Compromised LAA contractile fraction, measured by speckle tracking (strain-based methods), seems to be an independent determinant of LAA thrombus (68). A reduced strain rate was found to correlate with LAA emptying velocities after cardioversion (69). At present, these methods have not been extensively validated or routinely adopted.

LAA FUNCTION AND TEE ASSESSMENT POST-CARDIOVERSION. Post-cardioversion temporary stunning, paradoxical reduction in LAA flow velocities, and worsening mechanical function of both the LA (70–72) and the LAA (72–78) can appear, predisposing to the appearance of SEC and thrombus formation, highlighting the need for adequate anticoagulation therapy before and after cardioversion. LAA stunning post-cardioversion occurs whether conversion to SR is spontaneous (73) or associated with direct current cardioversion, either external (71,74,77,79) or low-dose internal (75), or pharmacological cardioversion (74,79). Despite there being higher flow velocities in the LAA in most patients with

TABLE 1 Different Echocardiography Modalities Evaluated When Using Echocardiography to Assess the LAA

Echocardiographic Modality	Parameters Evaluated	Comments
2D and 3D echocardiography	Visual assessment for the presence of thrombi or other pathologies within the LAA as noted in Table 2.	If there is inadequate visualization or artifacts, ultrasound contrast agents can enhance visualization. ICE can serve as a complementary method for evaluation.
Spectral Doppler	Evaluation of flow in the LAA using pulsed-wave Doppler: Velocities >40 cm/s are suggestive of adequate flow within the appendage and a low risk for thrombus formation. Color Doppler to a low Nyquist limit can aid in visualization of flow within the LAA.	Easily performed, highly reproducible, and carries relevant clinical implications. When Doppler signal is limited, microbubble contrast agent enhances visualization of contractility indices.
Tissue Doppler and strain imaging	Limited studies. E/e' and e' velocity were found to be independently associated with an LAA thrombus in patients with nonvalvular AF. Compromised LAA contractile fraction, measured by speckle-tracking, strain-based methods, was an independent determinant of LAA thrombus.	Not routinely used.

AF = atrial fibrillation; ICE = intracardiac echocardiography; LAA = left atrial appendage; 2D = 2-dimensional; 3D = 3-dimensional.

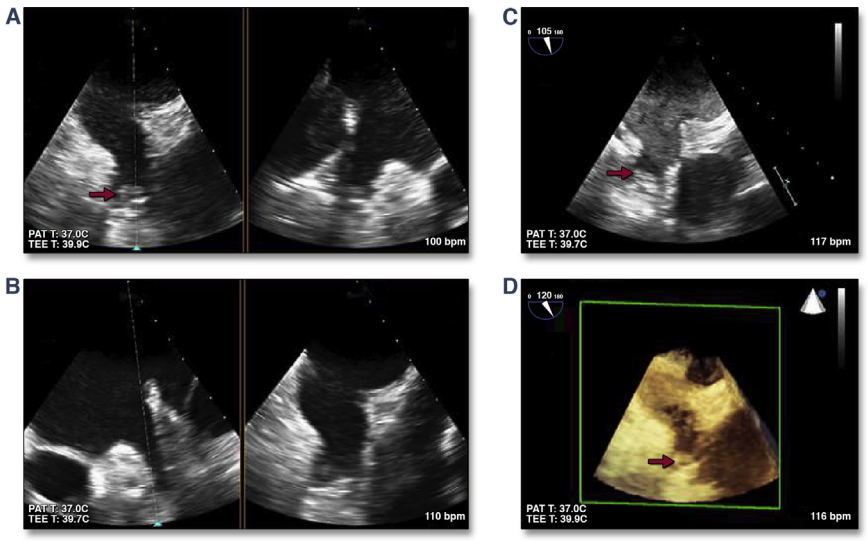

FIGURE 8 TEE Imaging of the LAA

TEE images in **(A, B)** 2D X-plane view demonstrating a finding suspicious of a thrombus **(arrow)**. **(C)** With the use of contrast, a thrombus is now clearly demonstrated, as well as in the 3D view **(D)** (Online Videos 1, 2, and 3). Abbreviations as in **Figure 1**.

atrial flutter, stunning also occurs after conversion of atrial flutter to SR (78). Stunning usually resolves within several days after cardioversion to SR (72). The total energy used for electrical cardioversion has no effect on the mechanical function of the LA or LAA (76). These findings support the concept that mechanisms other than the electrical shock itself are responsible for stunning. As shown in **Figure 9**, the occurrence of stunning post-cardioversion (defined as LAA peak late diastolic emptying velocities <20 cm/s) (80) is not uniform. High LAA flow velocities post-cardioversion can identify patients with a greater likelihood of maintaining normal SR at 1 year post-cardioversion (81). However, the presence of low LAA flow velocities after cardioversion are of limited value in identifying those who will develop a recurrence of AF within 1 year (81).

ADDITIONAL NONINVASIVE IMAGING MODALITIES. Although TEE is the most widely used method for evaluation of the LAA, MDCT and CMR are emerging as valuable modalities for imaging and assessment of

TABLE 2 Transesophageal Echocardiographic Evaluation of the LAA

	Pathophysiology	Echocardiographic Appearance	Treatment	Figure
SEC	Low blood flow velocities. Composed of activated platelets and leukocytes or aggregated red blood cells.	Swirling echodensity within the atrium.	Anticoagulation does not reduce SEC but reduces the development of LAA thrombus. Cardioversion is acceptable. SEC can initially increase, but eventually decreases after cardioversion.	5C
Sludge	Low blood flow velocities.	Viscous, gelatinous morphology, not well formed. Represents an intermediate stage between SEC and formed thrombus.	Anticoagulation. Cardioversion in the setting of sludge is controversial and associated with a higher risk of thrombus being present.	5D
Thrombus	Low blood flow velocities.	Organized formed thrombus.	Anticoagulation. Cardioversion contraindicated with this finding.	5E, F
Pectinate muscle	Part of the normal LAA morphology.		No treatments, normal finding.	5A, B

LAA = left atrial appendage; SEC = spontaneous echocardiographic contrast.

TABLE 3 Potential Advantages of 3D Echocardiography Compared With 2D Echocardiography for LAA Evaluation

3D TEE can be helpful in differentiating a thrombus from other findings, such as pectinate muscles within the LAA (35).
3D echocardiography is superior to 2D echocardiography for assessment of thrombus mobility and differentiation between the thrombus and the myocardium (36).
3D echocardiography is superior to 2D echocardiography for delineation of the changes in thrombi structure (e.g., calcification, degeneration, or lysis) (36).
3D echocardiography measurements of maximum thrombus diameter showed better interobserver agreement than 2D echocardiography (36).
LAA volume calculation and volume-derived ejection fraction can be obtained by 3D echocardiography only (36,42).
3D TEE renders additional information compared with 2D TEE regarding type and site of intracardiac masses, surface features, and spatial relationship to surrounding structures (37).
3D echocardiography (transthoracic echocardiography [TTE]/TEE) is superior to 2D echocardiography (TTE/TEE) in the adequate visualization of the entire LAA (38).
The LAA orifice area is measured more precisely by 3D TEE using enface views; 3D measurements correlated well with MDCT values, whereas 2D TEE underestimates the LAA orifice area (18,39).
2D TTE/TEE probably underestimates the dimensions of intracardiac masses, compared with 3D TTE/TEE, regardless of the size, location, and cause of the mass (37,40).
An excellent correlation on volume measurement between 3D TEE and surgically removed masses has been demonstrated (41).
3D TEE is superior to 2D TEE in visualizing the LAA orifice in relation to surrounding structures (e.g., mitral valve, left upper pulmonary vein) (43).

LAA = left atrial appendage; MDCT = multidetector computed tomography; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography; 2D = 2-dimensional; 3D = 3-dimensional.

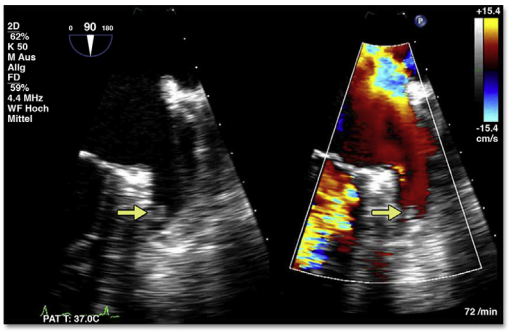

FIGURE 10 Lowering of the Nyquist to Aid in Thrombus Detection

In this patient, there was a suspicion for a thrombus in the LAA **(arrow)**. By using color Doppler and reduction of the Nyquist limit to 15 cm/s, a color flow filling defect supporting the diagnosis of an LAA thrombus is observed (Online Video 4). Abbreviation as in Figure 1.

the LAA anatomy and function. Table 4 summarizes the main strengths and limitations of each of the noninvasive imaging modalities. MDCT and CMR are likely to have an increasing role in the pre- and

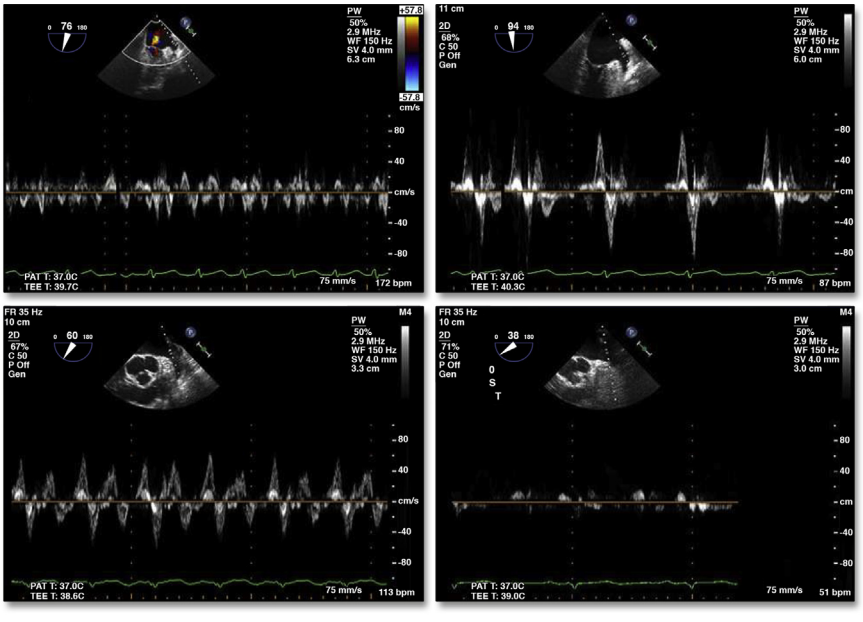

FIGURE 9 LAA Velocities Pre- and Post-Cardioversion

(Top) In this patient in AF, pre-cardioversion LAA velocities **(left)** are approximately 35 cm/s. Post-cardioversion **(right)**, in SR, LAA velocities increased to 80 cm/s. **(Bottom)** Pre-cardioversion, LAA velocities **(left)** were approximately 50 cm/s with LAA velocities decreasing to <20 cm/s post-cardioversion while the patient is in SR **(right)**, reflecting LAA stunning. AF = atrial fibrillation; SR = sinus rhythm; other abbreviation as in Figure 1.

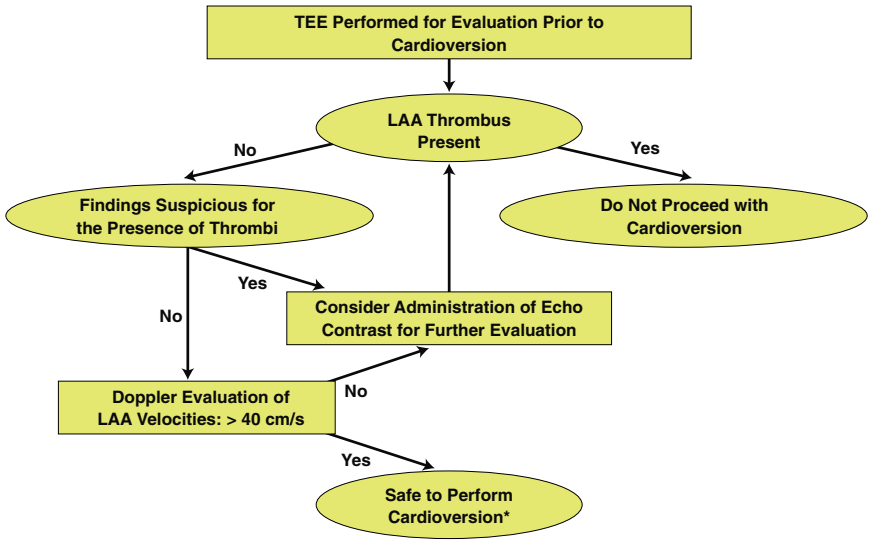

FIGURE 11 Schematic Approach for TEE Evaluation of the LAA Before Cardioversion

*Safe if no other contraindications exist for the patient. TEE refers to 2D TEE, but 3D TEE should be used, if available, to increase sensitivity and specificity of findings. Abbreviations as in Figure 1.

post-procedural evaluation of the LAA when their imaging resolution improves to allow for accurate determination and exclusion of thrombus.

MDCT. MDCT generates 3D volumetric data of the entire heart, which can be reconstructed along different planes and cardiac phases to provide accurate assessment of LAA anatomy (**Figure 3**). Current advances in MDCT now permit high spatial and temporal resolution, 3D imaging, and quantitative assessment to permit successful identification of LAA thrombi and nondense clearing SEC as seen by TEE (82–85). In the largest series to date of 402 patients, MDCT had a negative predictive value and a sensitivity of 100% for excluding LAA thrombi when compared with TEE (86). The reported positive predictive value of MDCT ranges from 41% to 92% depending on the method used for acquisition of data (87). A positive MDCT scan is not highly specific for the presence of a thrombus, and thus the high rate of false-positive test results and poor interobserver variability (88) are major limitations for accurate detection of thrombi by MDCT. The sensitivity and specificity, and the positive and negative predictive value can be enhanced when delayed imaging, a method used to differentiate between poor LAA filling and SEC or thrombus, is used (87). Limitations of MDCT include the following: 1) LAA mechanical function is not routinely evaluated, unless retrospective gating is used to assess dynamic function; however, this method is associated with significantly higher radiation doses (89); 2) radiation and the use of iodine-based contrast media; and 3) significantly lower temporal resolution than TEE.

CMR. CMR is an alternative, noninvasive imaging modality for those cases in which TEE is not possible, namely, in patients with esophageal pathology and unsuccessful TEE probe insertion. However, this

TABLE 4 Comparison of the Different Imaging Modalities for Assessment of the LAA

	TEE	MDCT	CMR
Sensitivity/specificity for LAA thrombi detection	92%–100%/ 98%–99%	96%/92%	67%/44%
Spatial resolution	0.2–0.5 mm	0.4 mm	1–2 mm
Temporal resolution	20–33 ms	70–105 ms	30–50 ms
3D volume rendering	Yes (with 3D)	Yes	Yes
Contrast required	No*	Yes	No*
Ionizing radiation	No	Yes	No
Special considerations	Widely available, provides real-time assessment Semi-invasive	Noninvasive, dynamic assessment of LA function Cannot be performed real-time during procedures Limited availability	Noninvasive, cannot be performed real-time during procedures Limited availability Cannot be performed in patients with pacemakers

*Contrast may be used to enhance visualization of a thrombus in equivocal cases.
CMR = cardiac magnetic resonance; LA = left atrium; other abbreviations as in Table 3.

modality has been evaluated in a limited number of studies. CMR accurately visualizes LAA size and function, and has the potential to detect thrombus in patients with AF (90). In a CMR study, patients with a history of stroke had larger LAA mean volumes than control subjects (28.8 ± 13.5 cm^3 vs. 21.7 ± 8.27 cm^3, p = 0.002), with the highest risk found in patients with an LAA volume >34 cm^3 (multivariable odds ratio: 7.11, p = 0.003) (90). The sensitivity and specificity of CMR to identify the presence of possible LAA thrombus are similar to those of MDCT. Ohyama et al. (91) evaluated CMR and TEE for the detection of LAA thrombi and found a high concordance between the modalities, with all 16 patients with thrombus being correctly identified; however, there were 3 false-positive CMR cases (negative predictive value: 100%, positive predictive value: 84%). In a study by Rathi et al. (92), 97 patients with AF underwent TEE and CMR. They found 100% concordance between these modalities for detection of LAA thrombi. Akoum et al. (93) evaluated the use of late gadolinium enhancement to quantify atrial fibrosis. They demonstrated that atrial fibrosis on CMR was independently associated with LAA thrombi and spontaneous contrast. This might provide an additional risk stratification method beyond clinical parameters (93).

CMR can measure blood flow using velocity-encoded techniques. A small study (N = 30) comparing CMR velocity-encoded technique to assess LAA emptying velocities was compared with TEE (94). A good correlation was found between CMR and TEE emptying measurements (r = 0.61, p < 0.0001). However, there was a mean underestimation of 10 ± 15 cm/s for peak A-wave velocities by velocity-encoded CMR compared with TEE. Although CMR has several advantages compared with MDCT and TEE, such as lack of exposure to iodine contrast and radiation, as well as not necessitating the passage of a probe, there are still several limitations that limit its widespread use, such as lower spatial resolution, prolonged examination duration, dependence on breath holds, and inability to be performed in patients with implanted cardiac devices.

DEVICE THERAPY FOR LAA EXCLUSION

LAA device closure is an evolving treatment strategy to prevent embolic events in patients with nonvalvular AF (95). There are currently 2 strategies available for percutaneous LAA closure: LAA occlusion and LAA exclusion. Occlusion refers to the placement of an intravascular device into the LAA percutaneously, through a venous access, and exclusion refers to exclusion of LAA from circulation by applying an external ligature. The 2 most commonly used devices for LAA occlusion are the Watchman Device (Boston Scientific Corp., Natick, Massachusetts) and the Amplatzer Cardiac Plug (St. Jude Medical, Inc., St. Paul, Minnesota). Currently, there is only one device for LAA exclusion: the LARIAT snare device (SentreHEART Inc., Redwood City, California), which uses a ligation suture for exclusion of the LAA. Noninvasive imaging modalities, including 2D and 3D TEE, and MDCT aid in the assessment of the LAA anatomy, the orifice, and the "landing zone" diameters for determining suitability for device implantation. 3D TEE has been shown to correlate better than 2D TEE for assessment of LAA orifice size when compared with MDCT (18), which has been shown to accurately assess both anatomy and orifice sizing, making it a useful tool during the pre-procedural planning period in select populations. MDCT provides valuable information about the shape of the LAA and for defining its relationships with surrounding critical structures, such as the left upper pulmonary vein and the left circumflex artery (7). **Table 5** compares MDCT and TEE and highlights the strengths of each modality. Newer imaging modalities incorporating fusion/integrated imaging would increase the confidence and anatomic awareness, assist in guidance, and increase procedural efficiency (96).

TABLE 5 Comparison Between MDCT and TEE for Evaluation of the LAA Including Assessment of Patients for Percutaneous LAA Closure

	MDCT	TEE
LAA thrombus detection	+	2D/3D ++
Assessment of LAA function	+	+++
LAA orifice size	++	2D + 3D ++
LAA morphology	++	2D + 3D ++
Evaluation of intracardiac structures	+++	2D + 3D +++
Evaluation of extracardiac structures	+++	-
Intraprocedural guidance	-	2D ++ 3D +++

Abbreviations as in Table 3.

CONCLUSIONS

The LAA, the most common site for thrombus formation in the setting of chronic or paroxysmal AF, is a complex structure. Multiplane 2D and 3D TEE with spectral and color Doppler, as well as echocardiographic contrast agents, are useful to identify and exclude LAA thrombi. The nonuniform anatomy of the LAA requires a multiparameter approach

for the evaluation and detection of thrombi, and for the adequate assessment before novel device therapy, which is rapidly evolving. New transcatheter techniques make it a requisite to identify the presence of LAA thrombi to prevent systemic thromboembolism.

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KEY WORDS anatomy, function, left atrial appendage, noninvasive imaging, thromboembolism

APPENDIX For supplemental videos and their legends, please see the online version of this article.