Atrial fibrillation (AF) is the most commonly encountered arrhythmia in clinical practice, with an overall prevalence of 0.4% in the general population (1). Recent advances in technology and in the understanding of the pathophysiology of AF have led to more definitive and potentially curative therapeutic approaches. Echocardiography has a well-established role in the assessment of cardiac structure and function, risk stratification, and has become an essential part of the guidelines for management of AF (2). The development of intracardiac echocardiography has led to real-time guidance of percutaneous interventions, including radiofrequency ablation and left atrial appendage closure procedures for patients with AF. Other imaging modalities, including computed tomography and magnetic resonance angiography, have allowed for more accurate measurement and better understanding of the cardiac anatomy. In this work, we review the impact of various imaging modalities in the evaluation and management of AF.

**ROLE OF ECHOCARDIOGRAPHY IN AF**

**Transthoracic echocardiography.** Transthoracic echocardiography (Tables 1 and 2) identifies conditions that predispose patients to AF. This information can influence the subsequent management strategies; a structurally normal heart may suggest a triggered mechanism for AF that may be amenable to radiofrequency (RF) ablation whereas the presence of severe mitral stenosis makes long-term maintenance of normal sinus rhythm (NSR) unlikely. Left ventricular (LV) systolic function helps to guide the choice of pharmacologic therapy for rate and rhythm control in chronic AF.

The size of the left atrium (LA) can be readily assessed by transthoracic echocardiography. Sustained AF can lead to progressive increase in LA size, termed atrial remodeling. This remodeling may be reversed with the restoration of NSR. Diameter measurements of the LA may not be reflective of the true extent of LA enlargement as measured by LA volume (3,4). Increased LA volume is associated with a low probability of successful cardioversion for chronic AF or maintenance of NSR (5–7).

Disordered atrial contractions in AF result in a 20% to 30% reduction in stroke volume and cardiac output, which is further accentuated in those patients with heart disease. The ratio of peak early transmitral velocity (E) to early diastolic annular (Ea) velocity (the E/Ea ratio) has been shown to reliably estimate LV filling pressures in patients with AF (8). Cardioversion may lead to improved LV filling because of synchronized atrial activity and function. Van Gelder et al. (9) found that improvement in ejection fraction and peak oxygen consumption lag behind improvement in atrial function after cardioversion. The improved ventricular function after conversion to NSR leads ultimately to improved exercise tolerance, less fatigue, resolution of dyspnea and chest discomfort, and overall decreased morbidity (9,10).

Atrial mechanical function is difficult to assess in patients with AF. Upon conversion to NSR, one can reassess the
velocity and duration of transmitral atrial wave and pulmo-
nary venous atrial reversal using pulsed-wave Doppler, as
well as the mitral late diastolic annular velocity from tissue
Doppler imaging. During AF, early transmitral velocities
are abnormal and reduced. Atrial stunning has been doc-
umented with spontaneous and pharmacological cardiover-
sion (11). Depending on the duration of AF and degree of
atrial stunning, the peak transmitral atrial wave velocity may
remain reduced for up to 4 weeks after successful cardio-
version, which is the basis for the anticoagulation guidelines
after conversion (12).

In our experience, atrial volume diminishes and mechani-
cal function improves or is unchanged after isolation of the
pulmonary vein (PV). On the other hand, procedures
targeting the anterior and anterolateral aspects of the LA
may result in decreased LA function (13). Recently, LV
function has been shown to improve with PV isolation in
patients with AF and heart failure (14,15).

Transesophageal echocardiography. Transesophageal
echocardiography (TEE) is the modality of choice for
detecting LA or left atrial appendage (LAA) thrombi with
a sensitivity and specificity of approximately 95% to 100%
(11) (Fig. 1). In patients with pre-existing thrombus, TEE
should be used to confirm thrombus resolution before
attempts at cardioversion. Varying degrees of blood stasis
have been described, ranging from spontaneous echo con-
trast (SEC) to “sludge.” Spontaneous echo contrast, iden-
tified as swirling echodensity, reflects increased erythrocyte
aggregation, the presence of fibrinogen, and a low flow state
and is associated with later development of thrombus and
with systemic embolization (8,11). Sludge is a viscid
echodensity in the LA or LAA without clear thrombus
formation. Sludge represents thrombus in situ that is a stage
farther along the continuum toward thrombus formation. A
negative correlation between peak LAA emptying velocity
and SEC highlights the relation of LAA dysfunction to
thrombus formation (16–18). It is important to note that
anticoagulation does not influence the presence of SEC
because it does not change the underlying hemodynamic
abnormalities.

The finding of thrombus on TEE portends a very poor
outcome. In one observational study, it was associated with
an embolic risk of up to 10.4% per year and a death risk of
15.8% in a series of patients, most of whom were receiving
oral anticoagulation (19). Despite the sensitivity of multi-
plane TEE being >95%, thrombi <2 mm may still be
missed, given the complex morphology of multilobed LAA.
The percentage of thrombus resolution after 4 to 6 weeks of
anticoagulation has varied widely from 5% to 90% (20–23).
It is generally accepted that 20% of thrombus may still be
present.

The mechanical function of LAA is best assessed using
TEE. Low LAA emptying velocities (<20 cm/s) correlate
strongly with the presence of SEC and thrombus formation
(24,25), whereas LAA emptying velocities >40 cm/s pre-
dict greater likelihood of sustained NSR 1 year after
cardioversion (19). In AF without thrombus, LAA appears
to passively empty and fill with multiple small fibrillatory
contractions that do not contribute to LV filling. There is
decreased or no demonstrable flow observed in those with
thrombus. In contrast, LAA function during NSR has the
normal characteristic pattern of emptying, resulting in a
well-defined, pulsed-wave Doppler signal (26,27).

Transesophageal echocardiography-guided cardioversion.
The ACUTE (Assessment of Cardioversion Using
Transesophageal Echocardiography) trial (28) compared
a TEE-guided strategy combined with short-term anti-
coagulation using a conventional 3-week oral anticoagu-
lation precardioversion strategy. Although there was a
significant difference in the composite end point of major
and minor bleeding and a shorter time to cardioversion,
there was no difference in the composite end point of
stroke, transient ischemic attack, and peripheral embo-
lish. The ACUTE II pilot trial compared TEE-guided
cardioversion using low molecular weight heparin with
intravenous unfractionated heparin in 155 patients and

Table 1. Echocardiography in Atrial Fibrillation

<table>
<thead>
<tr>
<th>TTE</th>
<th>TEE</th>
<th>ICE</th>
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<tr>
<td>General anatomy of cardiac structures</td>
<td>More detailed assessment of valve structure and function</td>
<td>Interventional anatomic assessment</td>
</tr>
<tr>
<td>Assessment of LV function, valve function</td>
<td>Assessment of pulmonary vein flows, LAA emptying velocity</td>
<td>Guidance during left atrial ablation</td>
</tr>
<tr>
<td>Assessment of chamber size</td>
<td>Detection of thrombotic left atrial milieu</td>
<td>Avoidance and detection of complications</td>
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ICE = intracardiac echocardiography; LAA = left atrial appendage; LV = left ventricular; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography.
showed similar safety and efficacy with a lower length of stay and more sinus rhythm in the low molecular weight heparin group (29). Kinnaird et al. (30) also used TEE to evaluate the PVs before and after RF ablation.

**Intracardiac echocardiography.** Intracardiac echocardiography (ICE) is an essential tool for safe trans-septal access, identification of anatomical structures relevant to the ablation, placement, navigation of the circular mapping catheter, titrating energy delivery during ablation, and the early diagnosis of complications (31,32).

Traditional fluoroscopic landmarks occasionally might be misleading when there is distortion of the atrial or septal anatomy in conditions such as LA dilation, interatrial septal aneurysm, and previous cardiac surgery, thereby increasing the risk of complications. The use of ICE allows a safer approach for trans-septal puncture and facilitates earlier administration of heparin to prevent clot formation on the trans-septal sheath that can be visualized by ICE. Compared with pulmonary venography, ICE has shown greater accuracy to define the antrum. Correct identification of the anatomy is important to allow for the appropriately sized catheter selection and proper vein treatment due to significant variation, including a common vestibule of the left PVs and additional small branches (33,34).

Intracardiac echocardiography can be used to evaluate catheter movement during lesion delivery without the need for intermittent fluoroscopy and is helpful in monitoring the catheter-tissue interface during energy delivery (35). Conventionally, temperature, power, and impedance are monitored and RF energy discontinued if they are greater than the safety thresholds. Using ICE, we have learned that RF delivery generates microbubbles. By guiding our ablation titrating power output to limit microbubble formation, we have seen improved success rates and reduced risk of complications, including thromboembolic episodes (36). The use of ICE guidance in such a way may also prevent atrioesophageal fistulas.

The esophagus has a variable relationship to the PVs and posterior LA wall. Visualization of this thin-walled structure can be enhanced by the ingestion of a carbonated beverage. Identification of the esophageal relationship can prevent occurrence of atrioesophageal fistulas by either controlling or avoiding energy delivery during ablation in this region (37).

Postablation PV narrowing can be quantified with diameter measurement and Doppler flow measurements to assess for flow turbulence. An increase in flow after ablation is likely a marker of extensive swelling, which could theoretically lead to chronic PV stenosis. However, Saad et al. (38) studied PV flow before and after PV ostial isolation and showed that although there were acute changes in the postablation diastolic flows, they do not appear to be strong predictors for chronic PV stenosis. Intracardiac echocardiography can also be used for intracardiac Doppler assessment of LA contraction and for prediction of success after PV isolation (39,40).

**Magnetic resonance angiography and multidetector CT.** Evolving techniques in catheter ablation of AF have led to the expansion of the knowledge of LA anatomy (41–44). Understanding the morphological characteristics of LA in detail can achieve a more efficient and successful ablation and prevent potential complications. Noninvasive imaging modalities, including MRA and multidetector computed tomography (MDCT), can depict the PVs and LA and provide a valuable road map before the catheter ablation of AF (45–51). The advantages of cardiac CT/
MRA are: 1) imaging the anatomic characteristics of the PV and LA preprocedurally; 2) assessing the anatomic relationship of the LA, esophagus, and adjacent vascular structures; 3) understanding the morphological remodeling of PV and LA in AF; and 4) detecting postprocedural complications. Examples of variations in LA anatomy are depicted in Figures 2 and 3. Figure 2 shows an unusual variant of the LA with a roof pouch, and Figure 3 demonstrates a case of an unusually low LAA. Avoidance of both structures during ablation may be critical in preventing complications.

**Anatomy of the PVs.** The interventional therapy of AF has been focused on the interruption of electric conduction by isolating the AF initiators of PVs from LA tissues. The detailed information of PV anatomy and the relationship between PV and LA is mandatory for the mapping and ablation procedures.

The PV ostia are ellipsoid with a longer superior-inferior dimension, and the funnel-shaped ostia are frequently noted in patients in AF (46). The right superior PV is close to the superior vena cava or right atrium, and the right inferior PV
projects horizontally. The left superior PV is in close vicinity to the descending aorta. These observations are essential for the trans-septal procedure, placement of a circular mapping catheter, and the application of energy around or outside the PV ostia.

**Morphology patterns of PV trees.** Although the morphologies of PVs have a certain basic pattern, they are more variable than arteries. Variations of PVs can be readily demonstrated by cardiac CT/MRA (Table 3). The variability can substantially influence the success rate of catheter ablation if the variant veins are inadequately treated. Several studies reported the existence of supernumerary right PVs, with the incidence ranging from 18% to 29% (45,48,51–54) (Fig. 4A). Tsao et al. (47) used MRA to demonstrate the PV variant of a discrete right middle PV with an independent orifice rather than the typical 2 PV ostia in the right side. The ectopic focus originating from the right middle PV could initiate AF, which is cured by catheter ablation of right middle PV. In addition, a significantly longer distance between the PV ostium and first branch was demonstrated for left versus right PVs (44). Perez-Lugones el al. (54) showed that multiple ramifications and early branching of the right inferior PV were observed in the study, which might explain the low incidence of firing of the right inferior PV.

A common trunk of left or right PVs also was imaged using CT/MRA. A common ostium is found more frequently on the left-sided PVs (6% to 35%) and results in a broad PV-atrial junction (Fig. 4B). The common left PV is a consistent origin of arrhythmogenic ectopy (55). Localization of the true PV atrial junction in these patients can be more accurately determined with the assistance of the 3-dimensional images before mapping and ablation procedures.

**Table 3. Anatomic Variations of Pulmonary Veins (PVs)**

<table>
<thead>
<tr>
<th>Supernumerary PVs</th>
<th>Right</th>
<th>18%–29%</th>
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<tbody>
<tr>
<td>Common ostium of Right PVs</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>Common ostium of Left PVs</td>
<td>3%–35%</td>
<td></td>
</tr>
<tr>
<td>Early branching of right inferior PV</td>
<td>66%–99%</td>
<td></td>
</tr>
<tr>
<td>“Right top” PV</td>
<td>3%</td>
<td></td>
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</table>

Anatomic relationship between LA and adjacent structures. Atrioesophageal fistulas have been reported during intraoperative RF ablation of AF using the endocardial approach, percutaneous PV isolation, and LA ablation (56–59). An atrioesophageal fistula can cause an air embolism with a stroke, mediastinitis, or gastrointestinal bleeding and is associated with a high rate of mortality. Understanding the anatomic relationship of the esophagus and PV/LA provides useful information for avoiding esophageal injury during the catheter ablation. Several studies have demonstrated the close relationship of the posterior LA, coronary sinus, PVs, and esophagus by CT scan (Figs. 5A to 5C) (60–63). Although the peristalsis and dynamic movement of the esophagus was suspected to influence the results, the anatomic parameters of the relationship of the esophagus, PVs, and LA posterior wall are useful in determining the location of the ablation lesions in the LA and to understand the possible risk of esophageal injury.

The close proximity of the LA roof and right pulmonary artery was also revealed by CT imaging (Fig. 6A). Although there were no reported cases of injury to the right pulmonary artery, it may be that another structure could be damaged when more powerful energy sources are introduced to make a deep lesion in the LA roof. It is likely that the cooling effect of the rapid blood flow may protect the right pulmonary artery from heat injury. However, to avoid the potential hazard of right pulmonary artery injury, the ablation at the LA roof (especially near the right superior PV orifice where the distance to the right pulmonary artery was the shortest compared to the other parts of the roof) should be performed with care.

In addition, the very close vicinity between the LAA orifice and proximal left circumflex artery was demonstrated by CT images (Fig. 6B). Takahashi et al. (63) reported a case wherein the left circumflex coronary artery was acutely occluded during ablation within the coronary sinus. Due to energy applications around the LAA that have been recently proposed to increase the success rate in treating persistent AF, ablation near the anterior base of the LAA orifice must be conducted with caution to avoid any risk of injury to the left circumflex artery.

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**Figure 4.** (A) Supernumerary right pulmonary veins (PVs) (arrows). (B) Broad PV-atrial junction. LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein.
Morphological remodeling of PVs and LA in patients with AF. The ostial geometries of PVs have been comprehensively evaluated by the use of CT and MRA. Tsao et al. (64,65) first reported the different sizes of PVs among controlled AF, paroxysmal AF, and chronic AF patients by MRA images. Furthermore, the significant dilatation of both superior PVs with simultaneous LA enlargement was demonstrated among patients with paroxysmal AF and chronic AF. After successful ablation of arrhythmogenic PV, the dilated (nonablated) PVs could regress during long-term follow-up (65). Several reports demonstrated the morphological remodeling and reverse remodeling process of LA and PVs in patients in AF (66–68).

Detection of complications after catheter ablation. The feasibility and safety of catheter ablation of the PVs and LA have been well documented. However, the procedure-related major complications, including cerebral emboli, PV stenosis, and pericardial effusion with tamponade, could occasionally be encountered. The use of MRA and CT can detect PV stenosis after ablation of AF (69–72). Acquired PV stenosis after PV ablation was a major concern when RF energy was applied around or inside the PV ostia. Although a single PV stenosis can be asymptomatic, the severity of clinical symptoms may be related to the numbers and stenotic degree of the involved veins. The use of MDCT and MRA can effectively delineate the lesions and provide the information for justification of treatment (70–72). The ROTEA (Role of TEE in Pulmonary Vein Ablation: Comparison with Computed Tomography) study is an ongoing prospective study assessing the incidence of PV stenosis detected by TEE compared with MDCT.

Conclusions. Echocardiography continues to be the foundation of clinical management of AF. TEE continues to be the gold standard to exclude LAA thrombus pre-procedurally; however, MDCT is increasingly being used to exclude thrombus and shows excellent negative predictive value (73). However, successful catheter ablation of AF highly depends on understanding the LA and PV anatomy. Advances in imaging technology have improved the quality
of ICE and CT/MRA, providing crucial information for electrophysiologists to perform ablations within the LA. Familiarity with the normal and variant patterns of PVs, the important landmarks within the LA, and the topographic relationship of the LA and the surrounding structures is important before the ablation procedure.

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