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iREVIEWS

STATE-OF-THE-ART PAPER

Clinical Utility of Multimodality LA Imaging

Assessment of Size, Function, and Structure

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The reservoir, conduit, and contractile functions of the left atrium are integral to overall cardiac performance. Recent advances in cardiac imaging offer the accurate assessment of LA phasic functions and structure, using techniques such as 3-dimensional echocardiography, color tissue Doppler imaging, and speckle tracking, as well as cardiac computed tomography and magnetic resonance imaging. These new developments are particularly important in view of the increasing use of intervention involving the left atrium. This review article highlights and contrasts the imaging of the size, mechanics, and structure of the left atrium using multiple modalities. The authors discuss recent studies on the clinical applications of the various techniques in disease conditions. (J Am Coll Cardiol Img 2011;4:788–98) © 2011 by the American College of Cardiology Foundation

The left atrium (LA) plays an integral role in cardiac performance by modulating left ventricular (LV) filling with its reservoir, conduit, and contractile functions (Fig. 1). The LA acts as a volume sensor and barometer of diastolic burden, and communicates with the neurohormonal systems via its secretion of natriuretic peptides and its interactions with the sympathetic nervous system and renin-angiotensin-aldosterone systems. There is significant interplay between LA and LV function, such that events during each phase of "LA phasic function" are affected by factors from both the LA and LV.

Recent advances in pulmonary vein isolation for the treatment of atrial fibrillation have increased the interest in accurately imaging LA structure and function. With respect to the assessment of the LA, 2-dimensional echocardiography (2DE) and 3-dimensional echocardiography (3DE), cardiac computed tomography (CT), and cardiac magnetic resonance (CMR) imaging have distinctly different strengths and weaknesses, and are complementary in specific clinical scenarios. In this review, we discuss the role of multimodality imaging to assess LA size, function, and structure, with an emphasis on the relative merits of newer imaging techniques and how these may be applied in the various clinical settings. The main strengths and limitations for each modality are summarized in Table 1.

LA Size

LA size increases with conditions of pressure overload, such as mitral stenosis and increased LV filling pressures, and conditions of volume overload, such as mitral regurgitation, high output states, shunts, and fistulae. LA size reflects the average effect of LV filling pressures over time (1), making it a useful marker of both

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the chronicity and severity of LV diastolic dysfunction (2). Measuring the maximum LA volume at the time of mitral valve opening is now routinely performed with echocardiography, although it only represents a snapshot of LA function at a specific point of the cardiac cycle. Analogous to measuring not only the LV end-diastolic volume, but also LV end-systolic volume and hence, LV ejection fraction, incremental prognostic information may be obtained by assessing LA phasic volumes (maximum LA volume [LAmax], pre-atrial contraction LA volume [LApreA], and minimum LA volume [(LAmin]) and deriving LA stroke volumes (Table 2). Figure 1 summarizes the events that mark the phases of LA functions and their relationship with other events in the cardiac cycle. Because of the significant interplay between the LA and the LV, the various determinants of LA phasic functions need to be considered when interpreting these results.

Echocardiography—beyond maximum LA volume. Among the 3 modalities, echocardiography is most suited to measuring phasic LA volumes because it allows the assessment of individual LA function components and furthers our understanding of LA pathophysiology in various disease states. Eshoo et al. (3) measured LA phasic volumes in hypertensive patients using 2DE and found that the observed LA dilation in hypertensive patients (increased LAmax) was associated with augmentation of atrial contractile function (increased active LA stroke volume [LASV] and LA emptying fraction [LAEF]), but no significant change in atrial conduit function.

Measurement of LA phasic volumes using 2DE is time-consuming, and errors can arise from geometric assumptions of biplane volume calculations, as well as from difficulties with echocardiographic window and the timing of various atrial events. 3DE, with automated border detection, shows promise of improving this (4,5), due to the availability of the 3D dataset at different phases of the cardiac cycle. Also, 3DE displays acceptable temporal resolution, which is not easily achieved with cardiac CT or CMR (Fig. 2). LA volumes derived from 3DE show good agreement with CMR-derived volumes (6), and have a lower test–retest variability compared with 2DE (7) but tend to be higher than 2DE LA volumes (8).

Using 3DE, the phenomenon of LA reverse remodeling can be accurately documented, not only by improvement in LA static volumes, but also in LA phasic volumes and ejection fractions. After pulmonary vein isolation, atrial fibrillation patients demonstrate improved LA reservoir and contractile functions (total and active LAEF, respectively). The recovery of atrial contractile function post-ablation has been associated with a lower incidence of atrial fibrillation recurrence (9,10). Future research in the use of 3DE in monitoring LA phasic function after atrial fibrillation ablation may investigate how specific parameters of atrial function help determine the need for ongoing anticoagulation. Also, 3DE may reveal how repeated ablations exert deleterious effect on the various components of LA function, at which point further ablations may cease to improve overall cardiac efficiency.

In other clinical conditions, studies have demonstrated the power of 3DE in analyzing separate components of LA phasic volumes. In a small study of patients who had successful continuous positive airway pressure therapy for obstructive sleep apnea, there was an increase in LA passive ejection fraction and decrease in LA active ejection fraction, with no overall change in LAmax (11). This illustrates that the improvement in LA conduit function without overall change in LA reservoir function reflects improved LV diastolic function, rather than changes in intrinsic LA function. Although other studies investigated the changes in LA phasic volumes by 3DE in conditions such as mitral regurgitation (12), hypertrophic cardiomyopathy (13), and diastolic dysfunction (14), future studies will have to be performed with the view of demonstrating the incremental prognostic value of these new parameters over the conventional echocardiographic measure of LAmax.

Cardiac CT—beyond pulmonary vein anatomy. Cardiac CT acquires a 3D dataset that accurately depicts LA and pulmonary venous anatomy. As a result, cardiac CT has become the investigation of choice before and after atrial fibrillation ablation in many centers (Fig. 3). In this setting, its established utility includes:

- Pre-ablation diagnosis of pulmonary venous anatomy variations;
- Image integration of the cardiac CT-derived 3D images of the LA and pulmonary veins with the electrophysiologically acquired real-time electroanatomical mapping data during the ablation;

ABBREVIATIONS AND ACRONYMS

CMR = cardiac magnetic resonance
CT = computed tomography
LA = left atrium/atrial
LAEF = left atrial emptying fraction
LAmax = maximum left atrial volume
LAmin = minimum left atrial volume
LApreA = pre-atrial contraction left atrial volume
LASV = left atrial stroke volume
LGE = late gadolinium enhancement
LV = left ventricle/ventricular
SR = strain rate
2DE = 2-dimensional echocardiography
3D = 3-dimensional
3DE = 3-dimensional echocardiography

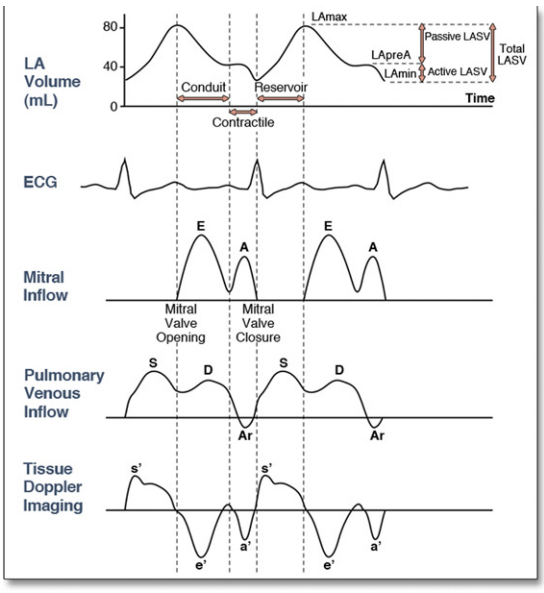

Figure 1. LA Phasic Functions

Left atrial (LA) phasic functions and their relationship with the cardiac cycle. Mitral inflow, pulmonary venous inflow, and tissue Doppler imaging at the mitral annulus are shown. LA volume increases during the reservoir phase to a maximum LA volume (LAmax), followed by 2 phases of emptying, conduit, and contractile phases, with the LA volume decreasing to the pre-atrial contraction LA volume (LApreA) and then the minimum LA volume (LAmin). Accordingly, total LA stroke volume (LASV) can be divided into passive and active components. ECG = electrocardiogram.

- Post-ablation diagnosis and surveillance of complications such as pulmonary vein stenosis.

With the acquired 3D dataset, LA volumes can be accurately measured using dedicated software with either manual tracing or threshold-based automatic border detection (15–18). This has been validated in comparative studies with both echocardiography (17) and CMR (18). Similar to echocardiography, LA remodeling after atrial fibrillation ablation can be demonstrated by cardiac CT. The post-ablation decrease in LA volume has been shown to predict recurrence of atrial fibrillation (19,20).

However, the routine use of cardiac CT solely for the purpose of assessing atrial size and function cannot be recommended, not only because of concerns over radiation exposure and the use of iodinated contrast in patients with renal impairment, but also because of issues unique to cardiac CT data acquisition. Traditionally, data acquisition is performed with retrospective helical scanning protocols, so that data are available throughout the cardiac cycle for reconstruction. LA phasic volumes can be measured, although in practice, the poor temporal resolution of CT (75 to 250 ms), which is as much as 10 times less than 2DE, may prevent accurate analysis. This is especially problematic for resolving the small difference between LApreA and LAmin, a change in volume that occurs within 1 PR interval of approximately 120 to 200 ms.

The increasing use of axial scanning protocols with prospective electrocardiogram gating to minimize radiation exposure means that data are only acquired at a certain phase of the cardiac cycle, usually set at mid-late ventricular diastole. As a result, phasic LA volumes cannot be measured, and the measured LA volume is different from the conventional measurement of LAmax at end-ventricular systole. Newer high-pitch helical prospective protocols may acquire images from a range of phases within a single cardiac cycle, rendering the dataset no longer reflective of a specified phase of the cardiac cycle.

CMR—beyond LV volume. CMR is the gold standard for measuring LV volumes and ejection fraction (21). Similar to the technique for the LV, LA size can be accurately measured with consecutive multislice breath-hold acquisitions of the LA using standard steady-state free precession sequences, followed by post-processing with either manual tracing of the atrial wall or automated border detection.

Studies have established normal ranges for LA phasic volumes as well as for ejection fractions using this method (22). The typical temporal resolution of steady-state free precession sequences of around 25 to 50 ms may not be as good as 2DE, but is sufficient for this purpose. Studies in patients with atrial fibrillation demonstrate CMR's ability to accurately document the changes of LA phasic volumes and LAEF after cardioversion (23) and pulmonary vein isolation (24,25). LA reverse remodeling after pulmonary vein isolation again has been associated with a lower rate of recurrence post-procedure (25). Head-to-head comparative studies with echocardiography have not been performed, although both modalities are well suited for measuring LA phasic volumes.

Some limitations unique to CMR are worth considering with respect to measuring LA volume. Acquisition of multislice image stacks to include the LA increases both scanning and post-processing times. The area-length method could be used, similar to that in 2DE. However, geometric assumptions in volume estimation negates

Table 1. Relative Strengths and Weaknesses of Various Imaging Modalities in the Evaluation of the LA

	Echocardiography	Cardiac CT	CMR
Technical considerations			
Temporal resolution*	2D = 10–20 ms 3D = 50–75 ms TDI = 5–10 ms Speckle = 10–20 ms	75–250 ms	25–50 ms
Spatial resolution*	2D = 0.5–1 mm 3D = 1–2 mm	0.5–2 mm	1–2 mm
Limitation with imaging window	Yes	No	No
True 3D dataset	Only with 3D	Yes	Selected sequences only
Real-time imaging	+++	−	+
Tissue characterization	+	+	+++
Availability	+++	++	+
Typical scan duration, min	30	10	30–50
Cost	Low	Moderate	High
Safety	Contrast	Radiation risk Iodinated contrast	Gadolinium contrast and renal failure Contraindications with pacemaker and defibrillators Hemodynamically stable patients only
Usefulness in the assessment of the left atrium			
LA size			
Static	+++	+++	+++
Phasic	+++	+	++
LA mechanics	+++	−	+
LA structure	+	+	+++
Current indications	First-line diagnostic evaluation and follow-up	Accurate 3D dataset for electroanatomic mapping Diagnosis and follow-up of pulmonary vein stenosis	Diagnostic evaluation and follow-up for patients with poor echocardiographic windows Accurate 3D dataset for electroanatomic mapping in patients with concern over radiation risk Diagnosis and follow-up of pulmonary vein stenosis in patients with concern over radiation risk
Potential indications	Serial monitoring of LA phasic volumes Detailed functional assessment of LA phasic function		Characterization of post atrial fibrillation ablation scarring Serial monitoring of LA phasic volumes

Values given here are approximations from commonly used techniques. *The actual temporal and spatial resolutions depend on the specific imaging parameters used in each modality. + = may be useful in selected clinical scenarios, but with significant limitations; ++ = useful modality but with some limitations; +++ = routinely performed now, or can be readily adopted in clinical practice; − = major limitation in the modality, making it difficult to be adopted in clinical practice; 2D = 2-dimensional; 3D = 3-dimensional; CMR = cardiac magnetic resonance; CT = computed tomography; LA = left atrium; TDI = tissue Doppler imaging.

the potential advantage of CMR over 2DE for this purpose and is especially problematic for the LA because of its complex 3D structure (26,27). 3D cine sequences could be designed but are intrinsically limited by the compromise between acquisition time, spatial and temporal resolution, and signal quality. Alternatively, gadolinium-enhanced magnetic resonance angiography can be used to measure LA volume, but this technique averages data through the cardiac cycle, so that differences in LA phasic volumes cannot be resolved (28). Respiratory navigator-gated electrocardiogram-gated 3D sequences obtain a 3D dataset of the LA with high spatial resolution, although it acquires data at a specific point of the cardiac cycle without the ability to measure LA phasic volumes.

LA Myocardial Mechanics

The study of LA myocardial mechanics is an emerging field that may provide new methods of accurately assessing LA phasic function. These techniques are under active research and have not been adopted in routine clinical practice. However, LA appendage emptying velocity by pulse Doppler is a commonly used measure of LA appendage mechanical function to predict the risk of atrial fibrillation recurrence post-cardioversion and the risk of future thromboembolism.

The requirement of measuring blood flow, tissue velocity, and tissue deformation with excellent temporal and spatial resolution makes echocardiography the imaging modality of choice. Cardiac CT is

Table 2. LA Phasic Volumes and Their Determinants

	LA Reservoir Function	LA Conduit Function	LA Contractile Function
LA stroke volumes	Total LASV = LAmax − LAmin Total LAEF = total LASV/LAmax LA expansion index = total LASV/LAmin	Passive LASV = LAmax − LApreA Passive LAEF = passive LASV/LAmax	Active LASV = LApreA − LAmin Active LAEF = active LASV/LApreA
Intrinsic determinants	LA active relaxation LA compliance	LA compliance	LA contractility
Extrinsic determinants	LV systolic function with apical displacement of mitral annulus Propagation of right ventricular pulse pressure through the pulmonary circulation Right ventricular stroke volume	LV relaxation and early filling Mechanical obstruction from the mitral valve	LV diastolic compliance

LA = left atrium; LAEF = left atrial ejection fraction; LAmax = maximum left atrial volume; LAmin = minimum left atrial volume; LApreA = pre-atrial contraction left atrial volume; LASV = left atrial stroke volume.

limited for studying myocardial mechanics especially in prospectively gated studies, and CMR also has significant limitations in this regard.

Conventional Doppler parameters of pulmonary venous inflow, transmitral flow, and mitral annular tissue velocity provide insight into LA mechanics. For instance, the pulmonary venous S, D, and A reversal waves correspond to LA reservoir, conduit, and contractile phases of the cardiac cycle, respectively. These parameters are not completely specific for LA mechanical function, but are affected by both LV diastolic and systolic performance. Nevertheless, multiple studies have documented changes in A-wave velocity and a′ in patients with atrial fibrillation following cardioversion or ablation as indicators of the initial deterioration and subsequent recovery of atrial contractile function (29–32). Although mitral A-wave velocity has been shown to predict atrial fibrillation recurrence after cardioversion (33), prognostic studies are sparse in this setting.

Strain imaging of the LA—how should this technique be adopted? Analogous to assessing LV mechanics by strain (ε) and strain rate (SR) imaging, measures of myocardial deformation have been increasingly adapted to study LA mechanics. Thomas and Popovic summarized the physics and clinical applications of LV strain imaging in a review article (34). Strain can be loosely defined as the change of dimension relative to the initial dimension, and SR is given by the instantaneous rate by which such change occurs. Negative strain occurs when myocardium contracts, and positive strain occurs when it lengthens.

Both echocardiographic methods of measuring strain and SR, 2-dimensional (2D) speckle tracking imaging (35–38) and color tissue Doppler imaging (39–42), have been adapted to measuring LA deformation. Speckle tracking calculates strain by tracking tissue deformation via characteristic myocardial speckles frame-by-frame, with SR given by the rate of such deformation. Color tissue Doppler imaging generates a spatial map of myocardial velocities, from which SR of the region of interest is derived, with strain calculated by integrating the SR data.

Typical LA strain and SR tracings by 2D speckle tracking and color tissue Doppler imaging are shown in Figures 4 and 5, respectively. In both methods, different measures of myocardial defor-

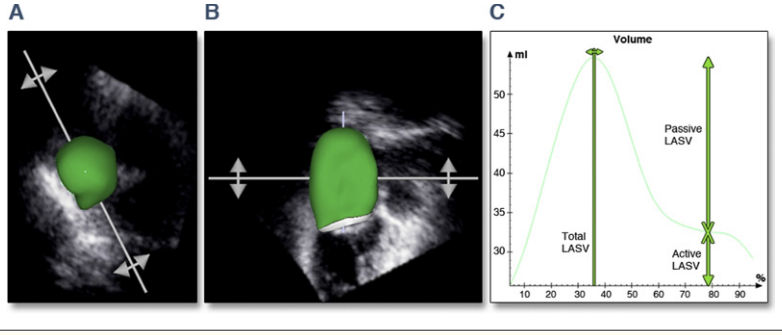

Figure 2. The Use of 3D Echocardiography in Measuring LA Phasic Volumes

Post-processing of the 3-dimensional (3D) dataset **(A and B)** permits the accurate calculation of the total, passive, and active left atrial stroke volume **(C)**. Abbreviations as in Figure 1.

mation, tissue velocity (V), ε, and SR can be derived at the 3 respective phases of the LA phasic cycle. Here, nomenclature becomes confusing, especially when LA strain and SR measurements are often labeled according to events of the LV, rather than events of the LA, because of resemblance with other Doppler parameters. A more consistent approach is outlined in Table 3. For V and SR, the "positive" phase corresponds to atrial filling, as myocardial lengthening corresponds to positive strain. The 2 stages of passive and active atrial emptying, are represented by "early negative" and "late negative," respectively. For strain timed to the start of the P-wave (atrial systole), active LA contraction is represented by the "negative" strain, whereas overall LA reservoir function is represented by "total" strain, the sum of strain components when the LA fills from the minimum LA volume to the maximum LA volume.

The advantage of analyzing LA myocardial mechanics with strain and SR imaging is the information that can be obtained about each component of LA phasic function. One could use this method to resolve the exact change in LA phasic function with different disease states and investigate the effect after treatment. Research in this field remains sparse but shows promise. In patients with atrial fibrillation undergoing cardioversion, indices of atrial active contraction ($V_{late\ neg}$ and $SR_{late\ neg}$) initially deteriorate but subsequently recover (43,44). Interestingly, a study of patients with atrial fibrillation undergoing atrial fibrillation ablation showed that the best predictors for maintenance of sinus rhythm were parameters of LA reservoir function (ε_{total}, SR_{pos}) rather than LA contractile function (ε_{neg}, $SR_{late\ neg}$) (45). Maintenance of sinus rhythm after cardioversion is also predicted by LA reservoir function (46). In a study of idiopathic and ischemic cardiomyopathy, LA reservoir function (ε_{total}) predicted a positive response to cardiac resynchronization therapy, although, of note, this study did not report strain and SR data for the other phases of LA functions, so the power of the various parameters cannot be compared fully (47). These studies highlight the prognostic power of new parameters and illustrate the importance and potential utility of considering each component in LA phasic functions separately. Further studies should clarify how best to interpret the data representing each stage and which ones have the best predictive power to alter clinical management.

The challenges with adapting strain imaging to the LA are somewhat similar to the ones applicable to the LV. One of the major difficulties is how best to present and summarize the vast numbers of parameters that are generated from the analysis of LA myocardial mechanics. Future studies will have to investigate the relative usefulness of various parameters in different disease conditions and concentrate on those with incremental diagnostic and prognostic value. Utility and value need to be proven before new techniques such as strain imaging can be adopted in routine clinical practice.

Unique challenges with LA strain imaging are due to the physiological differences between the LA and LV, so that reliability of such analysis may be suboptimal. Issues include the thinner LA wall, the complex LA motion during the cardiac cycle, regional LA differences in contraction (e.g., septum vs. lateral wall vs. near the pulmonary veins), higher signal noise from surrounding structures, and the location of the LA in

Figure 3. CT Assessment of Pulmonary Veins Pre- and Post-Pulmonary Vein Isolation

(A) Volume-rendered image of the left atrium (LA) viewing posteriorly, with the 3-dimensional dataset acquired by cardiac computed tomography (CT). This technique is commonly used for pre-ablation image integration with electroanatomical mapping. LA volume can also be measured with dedicated software and threshold-based automatic border detection. In this particular example, the right middle pulmonary vein **(white arrow)** drains directly and separately into the left atrium, which is a common variant. **(B to E)** Multiplanar reconstruction images of a 67-year-old patient 3 months after atrial fibrillation ablation, demonstrating severe left inferior pulmonary vein stenosis that was subsequently stented **(red arrow)**. Axial projections **(B,C)**, and sagittal projections **(D,E)** are shown. Post-stent images are shown in **C** and **E**. LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RIPV = right inferior pulmonary vein; RMPV = right middle pulmonary vein; RSPV = right superior pulmonary vein.

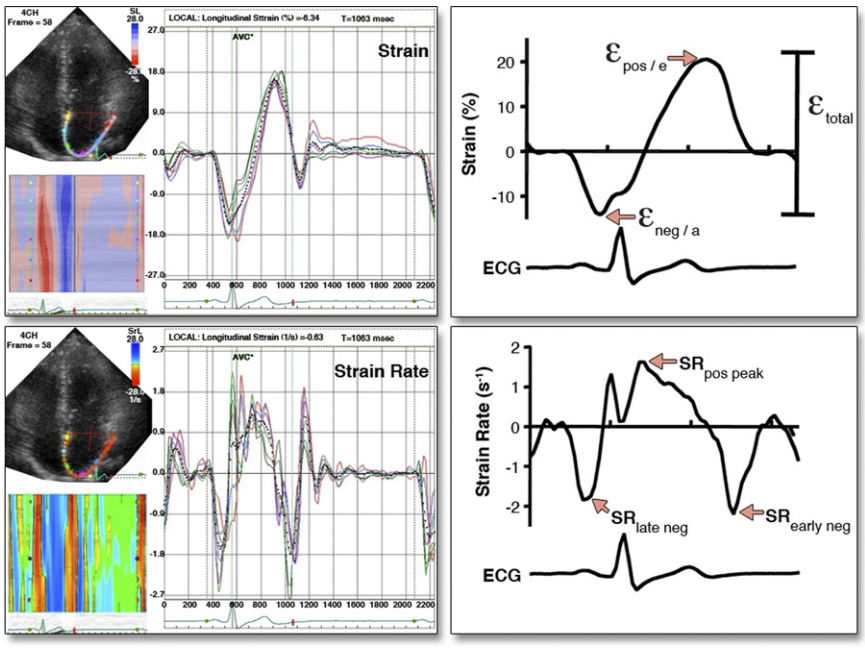

Figure 4. LA Strain Analysis by Speckle Tracking

Speckle tracking–derived LA global strain (ε) and strain rate (SR) (**left**), with the accompanying schematic diagram (**right**), are shown. neg = negative; pos = positive; other abbreviations as in Figure 1. Reproduced with permission from Saraiva et al. (35).

the far field of transthoracic echocardiogram. Current image analysis packages, which are validated only for the LV, will certainly require further optimization (48). Comparing 2D speckle tracking and color tissue Doppler imaging in LA analysis, 2D speckle tracking has the advantage of being angle independent, making strain measurements in walls not parallel to the ultrasound beam more reliable. However, the lower frame rate of 2D speckle tracking limits the temporal resolution of such analysis and is a more relevant issue for the LA than the LV because of poorer signal from LA, as discussed in the previous text.

LA Structure—Scar Imaging

The ability of CMR in tissue characterization and scar imaging with late gadolinium enhancement (LGE) is unique amongst the 3 imaging modalities discussed. There are emerging data for the noninvasive assessment of the location and extent of LA scarring following atrial fibrillation ablation, which is the most applicable clinical scenario for imaging LA structure. Techniques extend from the routinely used 2D inversion recovery gradient echo sequences following administration of gadolinium to 3D respiratory navigator-gated inversion recovery gradient echo sequences, which obtain a 3D dataset of the entire LA over several minutes (Fig. 6).

Studies of LA scar imaging in patients undergoing atrial fibrillation ablation have made several interesting observations. In general, there is good correlation between LGE and ablation sites from electroanatomic mapping data (49,50). However, in 1 study, 20% of intended ablation sites showed no evidence of LGE (49), suggesting that current ablation techniques may not be as effective as hoped. The completeness of circumferential pulmonary vein lesions and the total extent of LA scarring (50–53) were found to be predictive of atrial fibrillation recurrence.

The ability to image LA scarring post-ablation has immense implications for both the understanding of the pathophysiology of atrial fibrillation recurrence post-ablation and the refinement in ablation techniques. For instance, image integration with electroanatomical mapping data may enable targeted atrial ablation during redo-procedures. Studying patients with recurrence may also identify areas of the LA where it is most difficult to attain sufficient LA scar to achieve satisfactory electrical isolation. Alternatively, if one shows that atrial fibrillation recurrence is more closely correlated with the total extent of LA scarring rather than the location of scarring, it may support the alternative concept of "atrial debulking" in preventing atrial fibrillation recurrence, in which case, the current

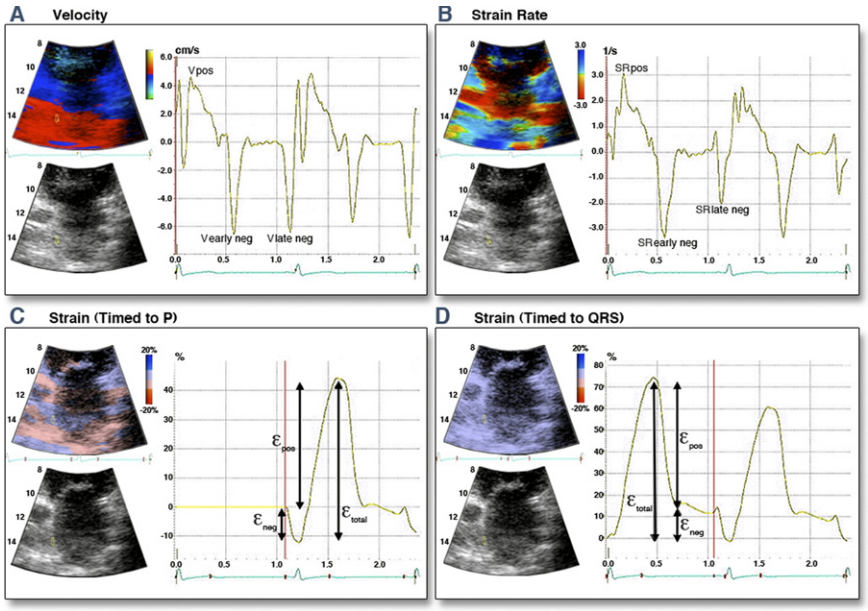

Figure 5. LA Strain Analysis of the Mid-Lateral Wall by Color Tissue Doppler Imaging

The imaging shows the velocity (V) **(A)**, strain rate **(B)**, and strain **(C and D)** curves. Various peaks can be identified from the velocity and strain rate curves according to the different phases in the cardiac cycle. The strain analysis on the **bottom left (C)** was timed to the start of atrial systole, whereas the strain analysis on the **bottom right (D)** was performed, timed to the start of ventricular systole. Abbreviations as in Figure 4.

focus of ablating the pulmonary vein ostia may have to be expanded to include more atrial tissues.

The major challenge of LA scar imaging with LGE remains that of spatial resolution. Autopsy studies showed that where the LA wall is the thinnest in the superior posterior aspect, mean LA transmural thickness (including epicardium and endocardium) measures 2.2 to 2.5 mm, and mean LA myocardial thickness measures 1.7 to 1.9 mm (54). LA wall thickness may also be less in those in chronic atrial fibrillation (55). The currently used 3D respiratory navigator-gated sequences have a spatial resolution of 1 to 2 mm (50–53). This suggests that the current spatial resolution of LGE imaging may have significant partial volume effects and not be sufficient to demonstrate LA wall scar reliably. Further studies are needed to validate and improve this technique.

Current Status and Future Directions

In this review, the assessment of LA size, myocardial mechanics, and structure by echocardiography,

Table 3. Tissue Velocity, Strain, and Strain Rate Parameters of the LA

	LA Reservoir Function	LA Conduit Function	LA Contractile Function
Preferred Nomenclature			
Events in the LA	**Atrial Filling**	**Passive Atrial Emptying**	**Active Atrial Systole**
V	V_{pos}	$V_{early\ neg}$	$V_{late\ neg}$
SR	SR_{pos}	$SR_{early\ neg}$	$SR_{late\ neg}$
ε	ε_{total}	ε_{pos}	ε_{neg}
Alternative Nomenclature, Named After Events in the LV			
Events in the LV	**Ventricular Systole**	**Ventricular Early Diastole**	**Ventricular Late Diastole**
V	V_s	V_e	V_a
SR	SR_s	SR_e	SR_a
ε	ε_s	ε_e	ε_a

a = atrial; d = diastolic; early neg = early negative; LA = left atrium; late neg = late negative; LV = left ventricle; pos = positive; s = systolic; SR = strain rate; V = velocity; ε = strain.

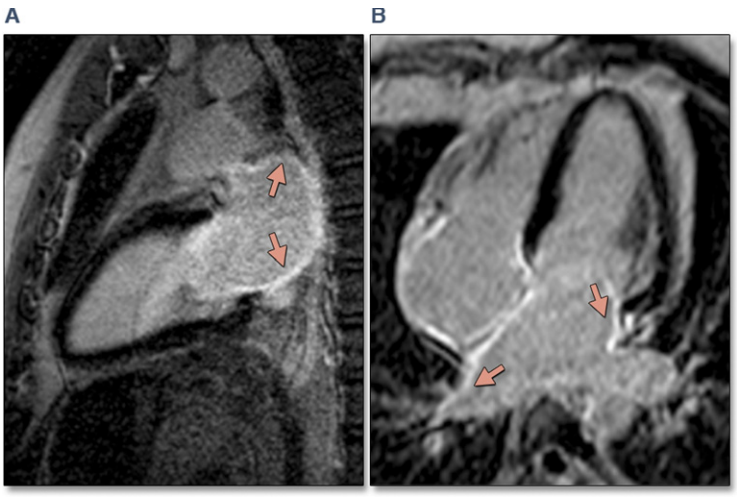

Figure 6. Two-Dimensional Inversion Recovery Gradient Echo Sequences of a Patient With Idiopathic Atrial Myopathy

Horizontal long-axis view **(A)** and 4-chambered view **(B)** images showed extensive delayed enhancement along the entire atrial wall, indicating scarring **(red arrows)**. Electrophysiology mapping study revealed undetectable left atrial voltage diffusely.

cardiac CT, and CMR are highlighted and contrasted. Assessing the LA is more challenging than the LV because of the complex physiology with the complementary interplay between LA and LV function, and hence, the numerous extrinsic and intrinsic factors that affect the various measurements of LA size and function.

Echocardiography remains the investigation of choice because of the wide availability. Dedicated LA function scans with newer echocardiographic techniques such as 3DE and strain imaging remain in the realm of active research, but potentially provide valuable information on both LA size and myocardial mechanics. Future studies will demonstrate how these parameters can be applied clinically in patients undergoing LA interventions such as catheter ablation, where it is prudent to monitor the effect of such intervention on LA phasic functions, and to understand how such alterations to LA function affect management decisions such as anticoagulation and redo procedures.

Cardiac CT remains the gold standard in obtaining a 3D dataset for image integration in electrophysiology procedures pre-atrial fibrillation ablation and in diagnosing complications from ablation such as pulmonary vein stenosis. Its more widespread application in studying LA size and function is largely limited by radiation exposure, which certainly prohibits its use in repeated routine follow-ups.

Currently, CMR is the least commonly performed of the 3 modalities for the LA, but shows great promise. Its ability to visualize the anatomy of the LA and assess function at an acceptable temporal resolution, combined with its unique ability of LA scar imaging makes CMR particularly useful for patients undergoing atrial fibrillation ablation. Further refinements in acquisition sequences are likely to improve image quality and make this technique applicable for more clinical indications.

In the era of cost containment, the use of multimodality imaging should concentrate on understanding specific clinical scenarios and comparing the relative strengths and limitations of each modality so that the best modality is chosen to answer specific clinical questions. Dedicated advanced LA imaging is mainly required in scenarios such as atrial fibrillation, especially in pre- and post-ablation patients where alterations in LA function are expected. In imaging studies performed for other conditions such as congestive heart failure and valvular heart disease where the LA is not the primary focus, refinement in advanced LA imaging may also provide new parameters with incremental prognostic information over existing techniques and ultimately improve management.

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REFERENCES

1. Appleton CP, Galloway JM, Gonzalez MS, Gaballa M, Basnight MA. Estimation of left ventricular filling pressures using two-dimensional and Doppler echocardiography in adult patients with cardiac disease. Additional value of analyzing left atrial size, left atrial ejection fraction and the difference in duration of pulmonary venous and mitral flow velocity at atrial contraction. J Am Coll Cardiol 1993;22:1972–82.
2. Tsang TS, Barnes ME, Gersh BJ, Bailey KR, Seward JB. Left atrial volume as a morphophysiologic expression of left ventricular diastolic dysfunction and relation to cardiovascular risk burden. Am J Cardiol 2002; 90:1284–9.
3. Eshoo S, Ross DL, Thomas L. Impact of mild hypertension on left atrial size and function. Circ Cardiovasc Imaging 2009;2:93–9.
4. Poutanen T, Jokinen E, Sairanen H, Tikanoja T. Left atrial and left ventricular function in healthy children and young adults assessed by three dimensional echocardiography. Heart 2003;89:544–9.
5. Anwar AM, Geleijnse ML, Soliman OI, Nemes A, ten Cate FJ. Left atrial Frank-Starling law assessed by real-time, three-dimensional echocardiographic left atrial volume changes. Heart 2007;93:1393–7.
6. Poutanen T, Ikonen A, Vainio P, Jokinen E, Tikanoja T. Left atrial volume assessed by transthoracic three dimensional echocardiography and magnetic resonance imaging: dynamic changes during the heart cycle in children. Heart 2000;83:537–42.
7. Jenkins C, Bricknell K, Marwick TH. Use of real-time three-dimensional echocardiography to measure left atrial volume: comparison with other echocardiographic techniques. J Am Soc Echocardiogr 2005;18:991–7.
8. Suh IW, Song JM, Lee EY, et al. Left atrial volume measured by real-time 3-dimensional echocardiography predicts clinical outcomes in patients with severe left ventricular dysfunction and in sinus rhythm. J Am Soc Echocardiogr 2008;21:439–45.
9. Delgado V, Vidal B, Sitges M, et al. Fate of left atrial function as determined by real-time three-dimensional echocardiography study after radiofrequency catheter ablation for the treatment of atrial fibrillation. Am J Cardiol 2008;101:1285–90.
10. Marsan NA, Tops LF, Holman ER, et al. Comparison of left atrial volumes and function by real-time three-dimensional echocardiography in patients having catheter ablation for atrial fibrillation with persistence of sinus rhythm versus recurrent atrial fibrillation three months later. Am J Cardiol 2008;102:847–53.
11. Oliveira W, Campos O, Cintra F, et al. Impact of continuous positive airway pressure treatment on left atrial volume and function in patients with obstructive sleep apnoea assessed by real-time three-dimensional echocardiography. Heart 2009;95:1872–8.
12. Saraiva RM, Yamano T, Matsumura Y, et al. Left atrial function assessed by real-time 3-dimensional echocardiography is related to right ventricular systolic pressure in chronic mitral regurgitation. Am Heart J 2009;158: 309–16.
13. Shin MS, Fukuda S, Song JM, et al. Relationship between left atrial and left ventricular function in hypertrophic cardiomyopathy: a real-time 3-dimensional echocardiographic study. J Am Soc Echocardiogr 2006; 19:796–801.
14. Murata M, Iwanaga S, Tamura Y, Kondo M, Kouyama K, Ogawa S. A real-time three-dimensional echocardiographic quantitative analysis of left atrial function in left ventricular diastolic dysfunction. Am J Cardiol 2008; 102:1097–102.
15. Lin FY, Devereux RB, Roman MJ, et al. Cardiac chamber volumes, function, and mass as determined by 64-multidetector row computed tomography: mean values among healthy adults free of hypertension and obesity. J Am Coll Cardiol Img 2008;1: 782–6.
16. Wolf F, Ourednicek P, Loewe C, et al. Evaluation of left atrial function by multidetector computed tomography before left atrial radiofrequency-catheter ablation: comparison of a manual and automated 3D volume segmentation method. Eur J Radiol 2010;75:e141–6.
17. Mahabadi AA, Truong QA, Schlett CL, et al. Axial area and anteroposterior diameter as estimates of left atrial size using computed tomography of the chest: comparison with 3-dimensional volume. J Cardiovasc Comput Tomogr 2010;4:49–54.
18. Wen Z, Zhang Z, Yu W, Fan Z, Du J, Lv B. Assessing the left atrial phasic volume and function with dual-source CT: comparison with 3T MRI. Int J Cardiovasc Imaging 2010;26 Suppl 1:83–92.
19. Helms AS, West JJ, Patel A, et al. Relation of left atrial volume from three-dimensional computed tomography to atrial fibrillation recurrence following ablation. Am J Cardiol 2009;103:989–93.
20. Tsao HM, Hu WC, Wu MH, et al. The impact of catheter ablation on the dynamic function of the left atrium in patients with atrial fibrillation: insights from four-dimensional computed tomographic images. J Cardiovasc Electrophysiol 2010;21:270–7.
21. Hundley WG, Bluemke DA, Finn JP, et al. ACCF/ACR/AHA/NASCI/SCMR 2010 expert consensus document on cardiovascular magnetic resonance: a report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. J Am Coll Cardiol 2010; 55:2614–62.
22. Hudsmith LE, Cheng AS, Tyler DJ, et al. Assessment of left atrial volumes at 1.5 Tesla and 3 Tesla using FLASH and SSFP cine imaging. J Cardiovasc Magn Reson 2007;9: 673–9.
23. Therkelsen SK, Groenning BA, Svendsen JH, Jensen GB. Atrial and ventricular volume and function evaluated by magnetic resonance imaging in patients with persistent atrial fibrillation before and after cardioversion. Am J Cardiol 2006;97:1213–9.
24. Wylie JV Jr., Peters DC, Essebag V, Manning WJ, Josephson ME, Hauser TH. Left atrial function and scar after catheter ablation of atrial fibrillation. Heart Rhythm 2008;5: 656–62.
25. Perea RJ, Tamborero D, Mont L, et al. Left atrial contractility is preserved after successful circumferential pulmonary vein ablation in patients with atrial fibrillation. J Cardiovasc Electrophysiol 2008;19:374–9.
26. Sievers B, Kirchberg S, Addo M, Bakan A, Brandts B, Trappe HJ. Assessment of left atrial volumes in sinus rhythm and atrial fibrillation using the biplane area-length method and cardiovascular magnetic resonance imaging with TrueFISP. J Cardiovasc Magn Reson 2004;6:855–63.
27. Hof IE, Velthuis BK, Van Driel VJ, Wittkampf FH, Hauer RN, Loh P. Left atrial volume and function assessment by magnetic resonance imaging. J Cardiovasc Electrophysiol 2010;21: 1247–50.
28. Montefusco A, Biasco L, Blandino A, et al. Left atrial volume at MRI is the main determinant of outcome after pulmonary vein isolation plus linear lesion ablation for paroxysmal-persistent atrial fibrillation. J Cardiovasc Med (Hagerstown) 2010;11:593–8.
29. Iuchi A, Oki T, Fukuda N, et al. Changes in transmitral and pulmonary venous flow velocity patterns after cardioversion of atrial fibrillation. Am Heart J 1996;131:270–5.

30. Verma A, Kilicaslan F, Adams JR, et al. Extensive ablation during pulmonary vein antrum isolation has no adverse impact on left atrial function: an echocardiography and cine computed tomography analysis. J Cardiovasc Electrophysiol 2006;17:741–6.
31. Donal E, Grimm RA, Yamada H, et al. Usefulness of Doppler assessment of pulmonary vein and left atrial appendage flow following pulmonary vein isolation of chronic atrial fibrillation in predicting recovery of left atrial function. Am J Cardiol 2005;95: 941–7.
32. Thomas L, Thomas SP, Hoy M, Boyd A, Schiller NB, Ross DL. Comparison of left atrial volume and function after linear ablation and after cardioversion for chronic atrial fibrillation. Am J Cardiol 2004;93:165–70.
33. Spiecker M, Bohm S, Borgel J, et al. Doppler echocardiographic prediction of recurrent atrial fibrillation following cardioversion. Int J Cardiol 2006;113: 161–6.
34. Thomas JD, Popovic ZB. Assessment of left ventricular function by cardiac ultrasound. J Am Coll Cardiol 2006; 48:2012–25.
35. Saraiva RM, Demirkol S, Buakhamsri A, et al. Left atrial strain measured by two-dimensional speckle tracking represents a new tool to evaluate left atrial function. J Am Soc Echocardiogr 2010;23:172–80.
36. Cameli M, Caputo M, Mondillo S, et al. Feasibility and reference values of left atrial longitudinal strain imaging by two-dimensional speckle tracking. Cardiovasc Ultrasound 2009;7:6.
37. Vianna-Pinton R, Moreno CA, Baxter CM, Lee KS, Tsang TS, Appleton CP. Two-dimensional speckle-tracking echocardiography of the left atrium: feasibility and regional contraction and relaxation differences in normal subjects. J Am Soc Echocardiogr 2009;22:299–305.
38. Kim DG, Lee KJ, Lee S, et al. Feasibility of two-dimensional global longitudinal strain and strain rate imaging for the assessment of left atrial function: a study in subjects with a low probability of cardiovascular disease and normal exercise capacity. Echocardiography 2009;26:1179–87.
39. Quintana M, Lindell P, Saha SK, et al. Assessment of atrial regional and global electromechanical function by tissue velocity echocardiography: a feasibility study on healthy individuals. Cardiovasc Ultrasound 2005;3:4.
40. Sirbu C, Herbots L, D'Hooge J, et al. Feasibility of strain and strain rate imaging for the assessment of regional left atrial deformation: a study in normal subjects. Eur J Echocardiogr 2006;7:199–208.
41. Thomas L, Levett K, Boyd A, Leung DY, Schiller NB, Ross DL. Changes in regional left atrial function with aging: evaluation by Doppler tissue imaging. Eur J Echocardiogr 2003;4: 92–100.
42. Zhang Q, Kum LC, Lee PW, et al. Effect of age and heart rate on atrial mechanical function assessed by Doppler tissue imaging in healthy individuals. J Am Soc Echocardiogr 2006;19:422–8.
43. Boyd AC, Schiller NB, Ross DL, Thomas L. Segmental atrial contraction in patients restored to sinus rhythm after cardioversion for chronic atrial fibrillation: a colour Doppler tissue imaging study. Eur J Echocardiogr 2008;9:12–7.
44. Thomas L, McKay T, Byth K, Marwick TH. Abnormalities of left atrial function after cardioversion: an atrial strain rate study. Heart 2007;93: 89–95.
45. Schneider C, Malisius R, Krause K, et al. Strain rate imaging for functional quantification of the left atrium: atrial deformation predicts the maintenance of sinus rhythm after catheter ablation of atrial fibrillation. Eur Heart J 2008; 29:1397–409.
46. Di Salvo G, Caso P, Lo Piccolo R, et al. Atrial myocardial deformation properties predict maintenance of sinus rhythm after external cardioversion of recent-onset lone atrial fibrillation: a color Doppler myocardial imaging and transthoracic and transesophageal echocardiographic study. Circulation 2005;112:387–95.
47. D'Andrea A, Caso P, Romano S, et al. Different effects of cardiac resynchronization therapy on left atrial function in patients with either idiopathic or ischaemic dilated cardiomyopathy: a two-dimensional speckle strain study. Eur Heart J 2007;28:2738–48.
48. Amundsen BH, Helle-Valle T, Edvardsen T, et al. Noninvasive myocardial strain measurement by speckle tracking echocardiography: validation against sonomicrometry and tagged magnetic resonance imaging. J Am Coll Cardiol 2006;47:789–93.
49. Taclas JE, Nezafat R, Wylie JV, et al. Relationship between intended sites of RF ablation and post-procedural scar in AF patients, using late gadolinium enhancement cardiovascular magnetic resonance. Heart Rhythm 2010;7: 489–96.
50. McGann CJ, Kholmovski EG, Oakes RS, et al. New magnetic resonance imaging-based method for defining the extent of left atrial wall injury after the ablation of atrial fibrillation. J Am Coll Cardiol 2008;52:1263–71.
51. Peters DC, Wylie JV, Hauser TH, et al. Recurrence of atrial fibrillation correlates with the extent of post-procedural late gadolinium enhancement: a pilot study. J Am Coll Cardiol Img 2009;2:308–16.
52. Oakes RS, Badger TJ, Kholmovski EG, et al. Detection and quantification of left atrial structural remodeling with delayed-enhancement magnetic resonance imaging in patients with atrial fibrillation. Circulation 2009; 119:1758–67.
53. Badger TJ, Daccarett M, Akoum NW, et al. Evaluation of left atrial lesions after initial and repeat atrial fibrillation ablation: lessons learned from delayed-enhancement MRI in repeat ablation procedures. Circ Arrhythm Electrophysiol 2010;3: 249–59.
54. Sanchez-Quintana D, Cabrera JA, Climent V, Farre J, Mendonca MC, Ho SY. Anatomic relations between the esophagus and left atrium and relevance for ablation of atrial fibrillation. Circulation 2005;112:1400–5.
55. Platonov PG, Ivanov V, Ho SY, Mitrofanova L. Left atrial posterior wall thickness in patients with and without atrial fibrillation: data from 298 consecutive autopsies. J Cardiovasc Electrophysiol 2008;19:689–92.

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