Multimodality imaging to guide cardiac interventional procedures
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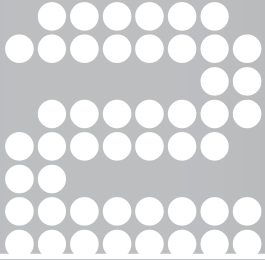
Multi-modality imaging to assess left atrial size, anatomy and function

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INTRODUCTION

The left atrium (LA) anterior-posterior diameter was one of the first standardized echocardiographic parameters. However, the clinical importance of LA size assessment has been neglected for a long time. Recent population-based studies have demonstrated the prognostic value of LA size for long-term outcome. Furthermore, with new dedicated techniques such as tissue Doppler imaging, it has become feasible to assess (regional) LA function. In addition, the introduction of catheter ablation procedures has changed the treatment of patients with drug-refractory atrial fibrillation (AF) dramatically. New image integration systems have become available for these catheter ablation procedures. With the use of image integration systems, a real anatomical 'roadmap' of the LA is provided for catheter ablation procedures. All these factors may explain the renewed interest in LA anatomy.

In the present manuscript, the importance of assessment of LA size and LA anatomy is discussed. Furthermore, the various imaging modalities that are available for the non-invasive visualization of the LA will be reviewed. In addition, the role of these imaging techniques in catheter ablation procedures for AF will be discussed.

CAUSES AND MECHANISMS OF LA DILATATION

In large population-based studies, it has been demonstrated that LA size is an important predictor of cardiovascular outcome (1-3). Tsang et al (3) recently demonstrated that a larger indexed LA volume predicted a higher risk of cardiovascular events after adjustment for age, gender and other covariates. Patients with a severely increased left atrium (≥40 ml/m^2) had the highest risk for the development of cardiovascular events (hazard ratio 6.6) (3).

Left atrium dilatation can occur in a broad spectrum of cardiovascular diseases including hypertension, left ventricular dysfunction, mitral valve disease and AF. In general, two major conditions are associated with LA dilatation: pressure overload and volume overload (4). LA volume overload frequently occurs in the setting of mitral regurgitation. Pressure overload is most frequently caused by an increased LA afterload, secondary to mitral valve disease or LV dysfunction (4). Pritchett et al (5) demonstrated a close correlation between LA volume and the severity of diastolic dysfunction after adjusting for the presence of covariates including age, gender, cardiovascular disease, ejection fraction and left ventricular mass. Accordingly, it has been suggested that whereas LA volumes represent long-term exposure to elevated pressures, Doppler measures of filling pressures rather represent the actual LV filling pressures at one point in time (6).

Atrial fibrillation is another important factor associated with LA dilatation. Atrial fibrillation is the most commonly encountered cardiac arrhythmia, and the association of LA enlargement and AF has been well recognized (1,7-10). However, whether AF causes LA dilatation or vice

versa still remains controversial. Several studies suggest that LA enlargement may cause AF (1,7,8). In the Framingham Heart Study (7), M-mode derived LA size was an independent risk factor for development of AF. More recently, Tsang et al (1) demonstrated that LA volume (assessed with a modified biplane method) was a strong predictor of AF, incremental to clinical risk factors (1). However, other studies have revealed that LA enlargement may be the consequence of AF (9,10). Dittrich et al (10) demonstrated that AF was an independent predictor of LA size in a large cohort study with 3465 patients with AF.

THE IMPORTANCE OF LA SIZE AND ANATOMY ASSESSMENT

Assessment of LA size is important since it has been shown to provide strong prognostic information. The incremental value of LA size over conventional risk factors has been demonstrated in several studies (3,11-13). In the Framingham Heart study (13) it was demonstrated that LA enlargement was a significant predictor of death in both men and women. The relative risk of death per 10 mm increment in LA size was 1.3 for men (95% CI 1.0-1.5) and 1.4 for women (95% CI 1.1-1.7).

In particular, assessment of LA size is important in patients with AF. The guidelines on management of patients with AF recommend a standard 2-dimensional and Doppler echocardiogram, with assessment of LA size and function, in the clinical evaluation of all patients with AF (14). Osranek et al (12) demonstrated the predictive value of LA dilatation in patients with lone AF. In this population-based study with a median follow-up of 27 years, it was noted that in patients with lone AF, LA volume was a strong predictor of adverse events (cerebrovascular event/ acute myocardial infarction/ heart failure hospitalization/ death), independent of age and clinical risk factors (12).

The assessment of LA anatomy is important in the setting of catheter ablation procedures for AF. Although there is still debate concerning the best ablation strategy and the exact lesion set, knowledge on LA and pulmonary vein anatomy is mandatory, both before and during the ablation procedure. Both anatomical (15) and in vivo studies with different imaging modalities (16-18) have shown that LA and pulmonary vein anatomy is highly variable. Different non-invasive imaging modalities are available for assessment of LA size and anatomy. The various techniques and their clinical relevance/ applications will be discussed in the following paragraphs.

## MULTI-MODALITY IMAGING OF THE LEFT ATRIUM

Echocardiography

For assessment of LA size various echocardiographic techniques are available, including transthoracic, transesophageal and intracardiac echocardiography. Transthoracic echocardiography is most commonly used in daily clinical practice to assess LA size. Both transesophageal and intracardiac echocardiography are mainly used during interventions for AF, such as cardioversion (transesophageal echocardiography) and catheter ablation procedures (intracardiac echocardiography).

Transthoracic echocardiography Feigenbaum was the first to demonstrate the correlation between LA dimension assessed with one-dimensional M-mode echocardiography and angiographic LA size (19). Afterwards, the development of two-dimensional echocardiography has expanded the insight in LA size and morphology. Nowadays, various established parameters for assessment of LA size are available (20). The LA anteroposterior diameter of the left atrium as assessed with M-mode is most commonly used in daily clinical practice and in large studies. However, it is not sufficient to determine true LA size, since M-mode represents only one dimension of the LA (21). In particular in LA enlargement, which may result in an asymmetrical geometry of the LA, M-mode echocardiography may underestimate LA size. Therefore, optimal assessment of LA size should include LA volume measurements (20,21). Various methods for the assessment of LA volume with two-dimensional echocardiography are available, including the cubical method, area-length method, ellipsoid method, and Modified Simpson's rule (Table 1 and Figure 1). In a prospective study including 631 patients (22), it was demonstrated that the biplane area-length method and the biplane Simpson's method compared closely (mean LA volume 39 ± 14 ml/m^2 and 38 ± 13 ml/m^2, correlation coefficient 0.98) , whereas the ellipsoid method systematically underestimated LA volume (mean LA volume 32 ± 14 ml/m^2). Recently,

Table 1. Methods for left atrial volume quantification with two-dimensional echocardiography

Method	Parameter	View	Equation	Assumption
Cube	Anterior-Posterior diameter (APD)	PSLAX	4/3 π (APD/2)3	LA has a spherical shape
Ellipsoid	Anterior-Posterior diameter (APD)	PSLAX	4/3 π (APD/2)(D1/2)	LA has an ellipsoid
	LA transversal diameter (D1)	4CH	(L/2)	geometry
	LA length (L)	4CH		
Area-length	LA area planimetry (A2C)	2CH	8/3 π [(A4C)(A2C)/L]	LA has an ellipsoid
	LA area planimetry (A4C)	4CH		geometry
	LA length (L)	2CH or		
		4CH		
Modified Simpson's rule	LA planimetry	2CH 4CH	Summation of discs	Total volume can be calculated from sum of smaller volumes

LA = left atrium; PSLAX = parasternal long-axis; 2CH = 2-chamber view; 4CH = 4-chamber view
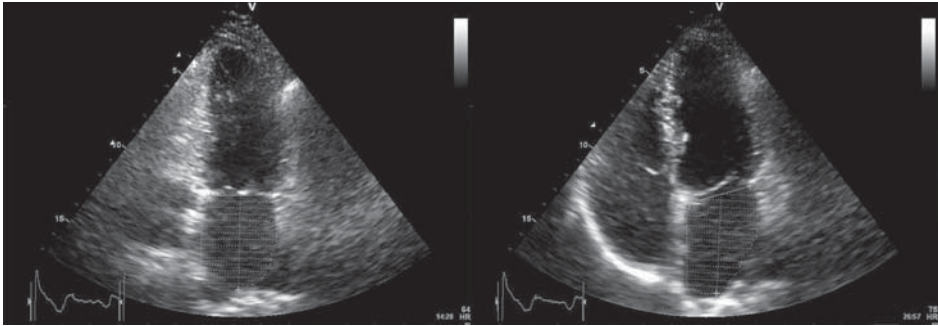
Figure 1. Measurement of LA volumes with transthoracic echocardiography using the modified biplane Simpson's rule. The maximum LA volume is assessed during ventricular systole in the apical 2-chamber (left panel) and apical 4-chamber (right panel) views. Maximal LA volume was 46 ml, minimal LA volume was 22 ml, resulting in an LA ejection fraction of 53%.

three-dimensional echocardiography has been introduced (Figure 2). A number of studies have demonstrated the feasibility of three-dimensional echocardiography for the assessment of LA volumes (23,24), and it has been validated against magnetic resonance imaging (25). Jenkins et al (23) have demonstrated that three-dimensional echocardiography allows accurate LA volume assessment, with a low test-retest variation, and a lower intra-and inter-observer variability as compared to two-dimensional echocardiography. However, there still remain some technical limitations such as the spatial and temporal resolution. In addition, since a relatively constant RR interval is needed, three-dimensional echocardiography may not be feasible in patients with AF and a high ventricular response rate.

Transesophageal echocardiography Transesophageal echocardiography (TEE) provides good views on the LA and the left atrial appendage (LAA). However, visualizing the complete left atrium to determine LA size with TEE may be hampered by the close proximity of the probe to the LA and the variable position of the esophagus to the posterior LA. As a result, measurements of LA size with TEE have not been standardized. Only few studies have compared the assessment of LA size with TEE and TTE. Block et al (26) assessed different LA dimensions with TEE and TTE in 109 patients. The authors noted that the 30- to 60-degree short-axis equivalent at the level of the aortic valve was the only view in which the entire LA dimension could be reliably obtained. Although TEE slightly underestimated LA size, it provided good correlation with TTE (26).

TEE is considered the procedure of choice for assessment of thrombi in the LA cavity or LAA. It can detect thrombi with a high degree of sensitivity and specificity varying from 93 - 100% (27). In addition, TEE is helpful in assessment of LAA emptying velocities, which are correlated with thrombus formation (velocities <20 cm/s) and with maintenance of sinus rhythm after cardioversion (velocities >40 cm/s) (28). Furthermore, TEE may be of great value in performing transseptal punctures in AF ablation procedures.
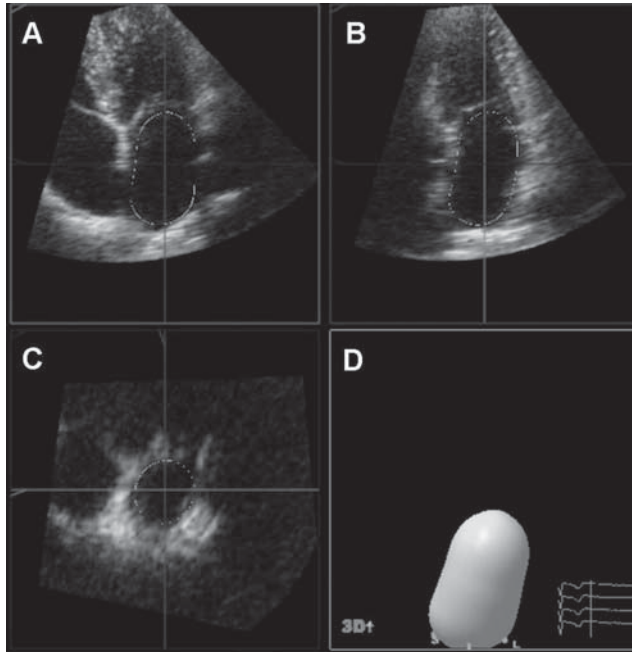
Figure 2. Real-time three-dimensional echocardiogram for the assessment of LA volumes. Panels A to C represent the coronal, sagittal and transverse planes, respectively. With the use of a 5-point tracing algorithm, LA volumes can be obtained throughout the cardiac cycle, represented by the 'shell' in panel D. In this example, LA maximum volume was 53 ml.
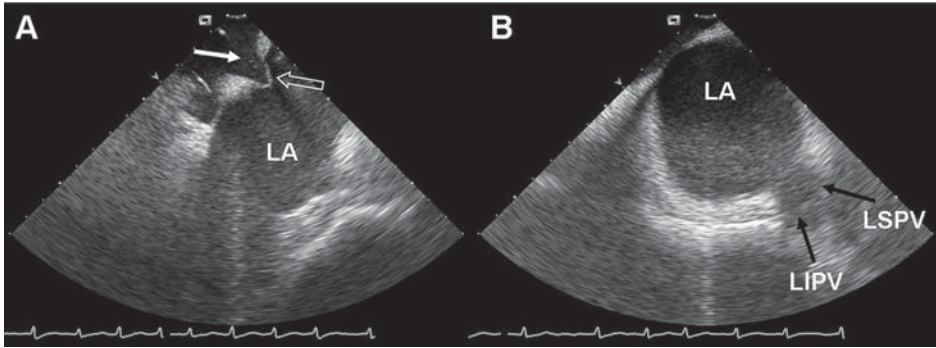
Intracardiac echocardiography Intracardiac echocardiography (ICE) is only used during interventional procedures, such as percutaneous closure of atrial septal defects and catheter ablation procedures. Therefore, no standardized measurements of LA size or volume are available. During these interventional procedures, ICE can accurately visualize LA anatomy and related structures (29). Furthermore, it allows visualization of intracardiac devices and catheters, and it is helpful in monitoring potential complications during catheter ablation procedures (30). Examples of intracardiac echocardiograms are shown in Figure 3.

In addition, the Doppler capacities of ICE allow for monitoring of pulmonary vein narrowing and may predict the recurrence of AF after ablation (31). Furthermore, LA function can be assessed with ICE. Rotter et al (32) demonstrated a good correlation between ICE and TEE for measurement of mitral E wave velocity (correlation coefficient 0.759, mean difference 6.9 cm/s) and LAA emptying velocity (correlation coefficient 0.991, mean difference 0.7 cm/s). Although ICE is limited by the monoplane character and the lack of standardized measurements of LA size, it is a valuable tool for interventional procedures.

Multi-slice computed tomography

The application of multi-slice computed tomography (MSCT) in cardiac imaging has rapidly expanded in the past few years. Since MSCT has an excellent spatial and temporal resolution,

Figure 3. Intracardiac echocardiography during a catheter ablation procedure for AF. Panel A: The transseptal puncture is guided by ICE to gain access to the LA. The white arrow indicates the transseptal sheath aimed at the fossa ovalis, which is the preferred site for the transeptal puncture. The 'tenting' of the septum (open arrow) indicates stable contact of the sheath with the fossa ovalis. Panel B: The anatomy of the pulmonary veins can be assessed with ICE during the ablation procedure. In this patient, the left inferior pulmonary vein (LIPV) and the left superior pulmonary vein (LSPV) have a single insertion in the LA, a so-called 'common ostium' of the left-sided pulmonary veins.

it can accurately quantify LA volumes, by using the modified Simpson's method (33). However, because of the radiation exposure and the use of contrast agents, MSCT is not routinely used for the assessment of LA size.

For AF ablation procedures, MSCT is a valuable tool to depict LA anatomy (34). With the use of volume-rendered reconstructions, MSCT can provide detailed information on LA and pulmonary vein anatomy (Figure 4). Since LA and pulmonary vein anatomy is highly variable, MSCT may offer a 'road-map' for ablation. The exact role of MSCT in ablation procedures is discussed in one of the following paragraphs.

Magnetic resonance imaging

Magnetic resonance imaging (MRI) is considered the most accurate technique for the non-invasive assessment of atrial volumes, because of the high spatial resolution and the excellent myocardial border detection. Detailed information of LA size and volumes throughout the cardiac cycle can be acquired with MRI (Figure 5). Anderson et al (35) recently reported findings on LA dimensions and LA area assessed with MRI in 20 healthy controls and in 20 patients with cardiomyopathy. It was noted that a LA systolic area <24 cm^2 was the upper 95th percentile of the normal range, and best discriminated normal from abnormal hearts (35). Similar to MSCT, a modified Simpson's method can be used to determine LA volumes. However, due to its relatively long acquisition times and the cumbersome data analysis, LA volume assessment with MRI is not performed in daily clinical practice. MRI can provide detailed information on LA and pulmonary vein anatomy before catheter ablation procedures, and is a useful tool in the follow-up of patients after the ablation procedure. This will be discussed in more depth in one of the following paragraphs.

Several studies have compared the value of the different imaging modalities for the assessment of LA size and volumes (23-26,36). Two-dimensional transthoracic echocardiography
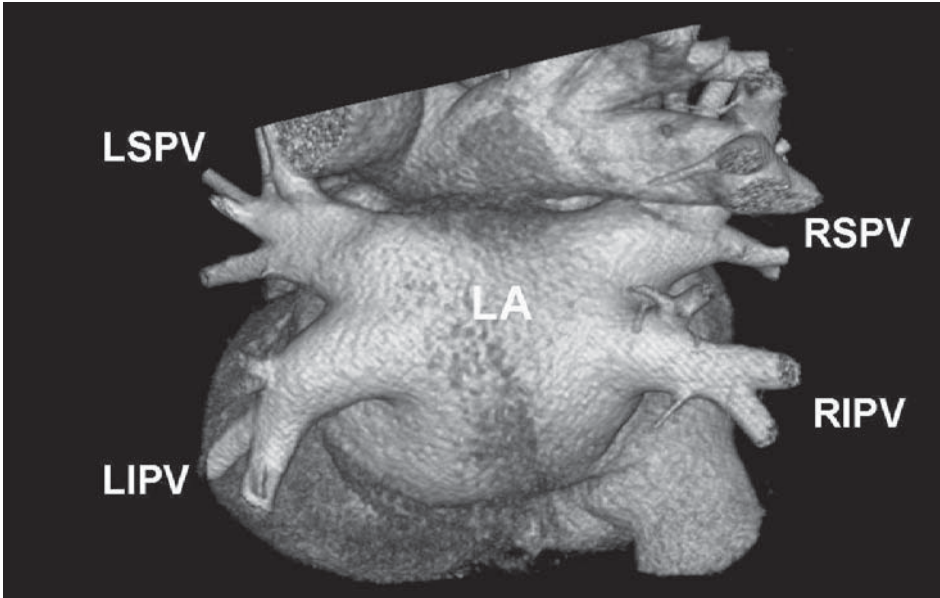
Figure 4. Volume-rendered three-dimensional reconstruction of a 64-slice MSCT scan. The dorsal view clearly demonstrates the anatomy of the LA and pulmonary veins. In this patient, normal pulmonary vein anatomy is present including four pulmonary veins, all with their own insertion into the LA. LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein.

(using the biplane methods) may underestimate true LA size, as compared with computed tomography (36) or magnetic resonance (25). However, these three-dimensional techniques are not preferred for LA size assessment in daily clinical practice. In this respect, new three-dimensional echocardiography is a promising technique that is widely available and provides accurate information on LA size (24).
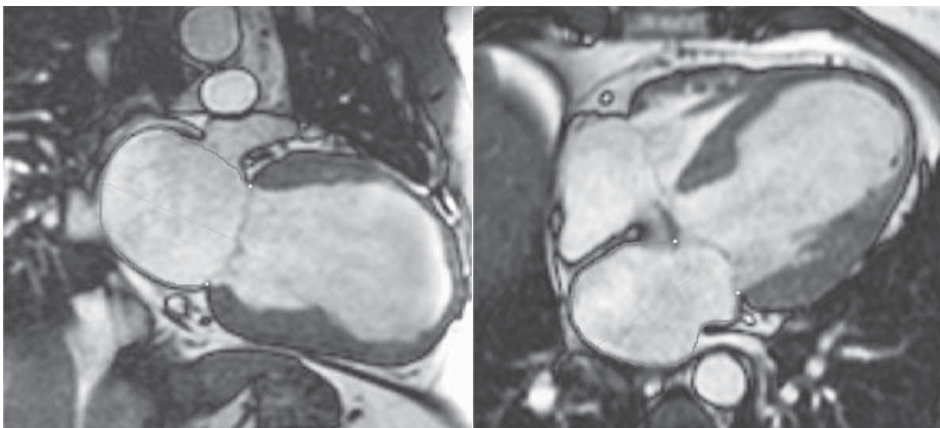
Figure 5. Assessment of LA volumes with MRI. The 2-chamber (left panel) and the 4-chamber (right panel) views are used to delineate the endocardial border of the LA, as well as the maximal diameter.
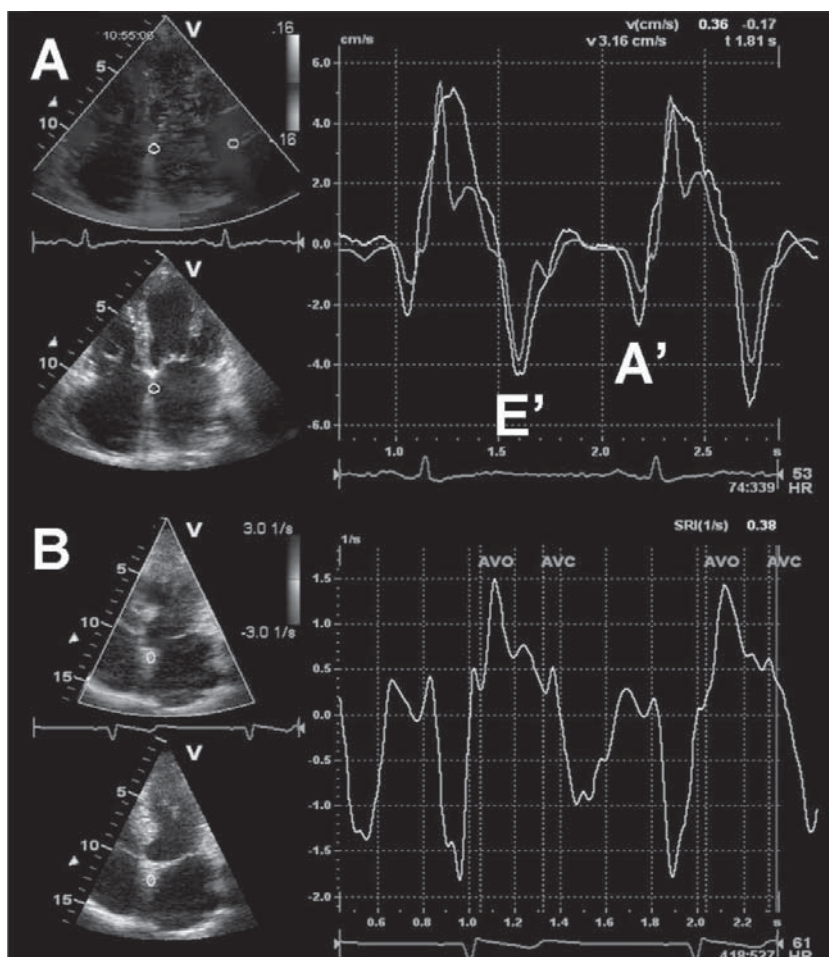
ASSESSMENT OF REGIONAL LA FUNCTION

Regional LA function is not routinely assessed, and therefore no standardized parameters for regional LA function are available. This can be partly explained by the fact that non-invasive evaluation of regional LA function may be hampered by the relative thin LA walls. However, assessment of regional LA function may provide more insight in atrial electromechanical remodeling and may be helpful in the management of AF with surgical or catheter ablation. New echocardiographic techniques, such as tissue Doppler imaging and strain (rate) imaging, allow non-invasive measurement of regional function of the myocardium. Tissue Doppler imaging quantifies regional tissue velocities of the myocardium. Strain and strain rate represent local tissue deformation and the rate (speed) of local deformation, respectively (37). Both techniques have been well validated for the assessment of regional left ventricular function. Recently, several studies (38-42) have applied these new techniques to the left atrium.

Tissue Doppler imaging allows quantification of regional myocardial velocities, and assessment of the timing of peak systolic and diastolic velocities of the myocardium (Figure 6, panel A). Thomas et al (38) used tissue Doppler imaging in 92 healthy volunteers to evaluate regional LA function. The authors noted that atrial contraction velocities were significantly increased in the annular segments, compared with the more superior segments.

Tissue Doppler imaging also provides information on the timing of regional velocities of the myocardium. Therefore, it may quantify regional electromechanical LA function, such as the total electromechanical activity of the atria (represented by the interval between the onset of the P-wave on the ECG to the end of the A' wave on the tissue Doppler images) (39). However, the clinical relevance and the exact correlation of these new tissue Doppler derived parameters of regional LA function with conventional parameters, such as mitral inflow A wave velocity and LA volumes, needs further investigation. Furthermore, a limitation of tissue Doppler imaging for evaluation of regional LA function is the angle dependency of the technique. Therefore, careful adjustment of the beam and gain settings should be made to avoid aliasing and to allow reliable measurement of tissue velocities of the LA.

Strain imaging and strain rate imaging are new tools for the assessment of regional myocardial deformation of the LA (40). An example of strain rate imaging of the LA is shown in Figure 6, panel B. In contrast to tissue Doppler imaging, strain imaging is not hampered by myocardial tethering. Furthermore, strain imaging allows for differentiation between active contraction and passive motion (37). However, the thin atrial walls may not generate clear strain curves and therefore require careful interpretation. Several studies have demonstrated the value of regional atrial strain in the analysis of patients with AF undergoing cardioversion (41,42). Di Salvo et al (41) studied 65 patients with AF and performed tissue Doppler imaging of standard apical images of the LA. It was noted that all tissue Doppler imaging derived parameters of the LA, including tissue velocities, strain and strain rate, were significantly reduced in patients with AF, compared with healthy controls. Of interest, multivariable analysis demonstrated that atrial

Figure 6. Panel A: Color-coded tissue Doppler imaging in the apical 4-chamber view for the assessment of regional LA function. The samples are placed in the basal atrial septum and the basal atrial lateral wall. From the myocardial velocity curves, peak systolic and diastolic velocities can be assessed. Early diastolic filling is indicated by E' and late diastolic filling is indicated by A'. Panel B: Strain rate imaging in the apical 4-chamber view in a patient with a history of paroxysmal atrial fibrillation. A sample is placed in the basal atrial septum. From the time-strain curves segmental atrial contraction and time-to-peak strain can be derived. The vertical green lines indicate aortic valve opening (AVO) and aortic valve closure (AVC).

inferior wall peak systolic strain rate and atrial septal peak systolic strain were the best predictors of maintenance of sinus rhythm after cardioversion (41). The assessment of regional LA function by tissue Doppler imaging or strain imaging may be of value in the clinical follow-up of patients with AF undergoing catheter ablation or cardioversion. It has been suggested that diminished regional atrial strain values may warrant prolonged use of anti-arrhythmic drugs and anti-coagulation (41,42). However, more studies are needed to appreciate the value of regional left atrial strain and its role to guide use of medication in patients with AF.

IMAGING OF LA FUNCTION IN THERAPY FOR AF

As previously discussed, the association between LA remodeling and AF has been well recognized. Restoration of normal sinus rhythm by catheter ablation or cardioversion may result in reverse remodeling of the LA, with subsequent improvement of LA function. However, electrical or pharmacological cardioversion may cause transient atrial mechanical dysfunction or 'stunning' (28,43). It has been demonstrated that conventional parameters of LA function, such as A wave velocity or A wave velocity time integral, are decreased immediately after cardioversion (43). The subsequent depressed LA appendage flow velocities increase the risk of thromboembolic events after cardioversion.

With the use of new techniques such as strain imaging, LA dysfunction following cardioversion can also be assessed (42). In 37 patients with chronic AF, it was noted that immediately after cardioversion regional LA function was depressed compared with healthy controls. However, 6 months after successful cardioversion a significant increase in LA strain was observed. The maximal increase in regional LA strain occurred within 1 month after cardioversion (42). This observation is in concordance with previous studies (43,44) and suggests that 'atrial stunning' following cardioversion is a function of the preceding AF, rather than the cardioversion itself.

Catheter ablation has been demonstrated to be successful in the restoration of sinus rhythm, and is performed in an increasing number of patients with symptomatic drug-refractory AF. It has been demonstrated that maintenance of sinus rhythm after catheter ablation is associated with a decrease in LA volumes (Figure 7) (45). Reant et al studied 48 patients with lone AF treated with catheter ablation (46). Serial echocardiograms up to 12 months after the procedure revealed a progressive decrease in LA dimensions. Interestingly, with the use of new tissue Doppler derived parameters it was noted that in parallel to the improvement in LA function, both LV systolic and diastolic function improved in the patients who maintained sinus rhythm (46). Furthermore, with the use of MRI it has been demonstrated that in addition to LA reverse remodeling, the area of the pulmonary venous ostia may decrease after successful catheter ablation procedures (47).

IMAGING IN CATHETER ABLATION PROCEDURES FOR AF

Multimodality imaging

Catheter ablation procedures are being performed in an increasing number of patients worldwide. The recent guidelines on management of patients with AF propose catheter ablation as a reasonable option when first-line anti-arrhythmic drugs have failed (14). Various ablation strategies have been proposed, including segmental ostial ablation and anatomically based circumferential ablation, and there is still debate concerning the exact lesion set. Regardless of the ablation strategy applied, knowledge on the complex LA and pulmonary vein anatomy is
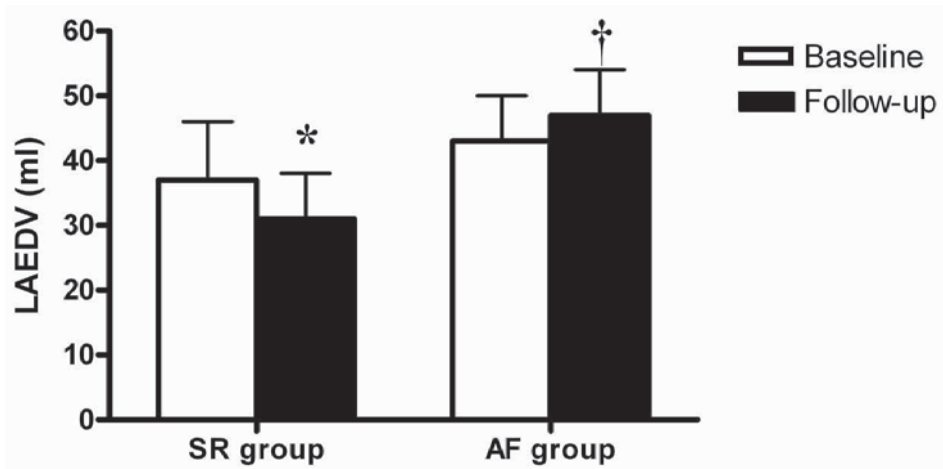
Figure 7. Reverse remodeling of the LA may occur after successful catheter ablation. A significant reduction in LA end-diastolic volume (LAEDV) was observed in the patients who maintained sinus rhythm after the catheter ablation procedure (SR group). In contrast, an increase in LA volumes was observed in the patients who had recurrence of atrial fibrillation (AF group). * = p<0.01 baseline vs. 3 months of follow-up; † = p < 0.05 SR group vs. AF group.

essential during the ablation procedure. The veno-atrial junctions and anatomical landmarks in the LA, such as the ridge between the left superior pulmonary vein and the LAA, are critical structures to identify during catheter ablation procedures.

Anatomical studies have demonstrated that LA and pulmonary vein anatomy is highly variable (15). Most frequently, two left-sided pulmonary veins and two right-sided pulmonary veins drain separately into the LA (Figure 4). Anatomical variations include a single insertion or 'common ostium' of the pulmonary veins, and an additional pulmonary vein (Figure 8). A 'common ostium' is most frequently found on the left-sided pulmonary veins, whereas an additional pulmonary vein is most frequently noted on the right side. In 201 patients undergoing MSCT scanning, Marom et al (48) noted a left-sided 'common ostium' in 14% of the patients, and an additional right-sided pulmonary vein in 28% of the patients. In addition, variations in LAA morphology and LA roof anatomy may be present in patients with AF (49). Because of the complex anatomy of the LA and the variability in pulmonary vein anatomy, a detailed 'roadmap' for the ablation procedure is mandatory. The various imaging modalities that are available for assessment of LA and pulmonary vein anatomy in catheter ablation procedures include MSCT, MRI, ICE and electroanatomical mapping systems.

MSCT and MRI (Figures 8 and 9) provide detailed information on the anatomy of the LA and pulmonary veins. With the use of volume-rendered three-dimensional reconstructions and cross-sectional images, the number of pulmonary veins and their branching pattern can be accurately assessed (Figure 10). Furthermore, the diameters of the pulmonary vein ostia can be measured on the different orthogonal planes. In addition, MSCT may identify the presence of thrombi in the LAA and provide detailed information on surrounding structures, such as the
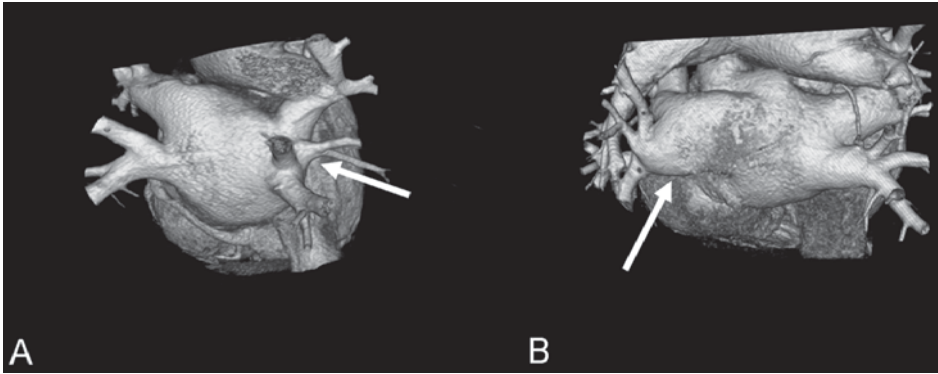
Figure 8. Variations in pulmonary vein (PV) anatomy shown on volume-rendered three-dimensional reconstructions of MSCT scans. Panel A demonstrates an additional PV on the right side. Panel B shows a 'common' ostium of the left-sided PVs.

esophagus and coronary arteries. However, the pre-procedural acquired MSCT and MRI images only provide off-line information.

In contrast to MSCT and MRI, ICE allows real-time assessment of the pulmonary veins and the veno-atrial junction during the ablation procedure. The Doppler capacities and the ability to monitor the catheter position in relation to the pulmonary veins are great advantages of this technique (29). In addition, ICE is helpful in assessment of the transmural extent of the ablation lesions (50) and ICE has been used to titrate ablation energy, thereby increasing the safety of the ablation procedure (30). Still, the major limitation of ICE is the mono-dimensional character of the technique. It has been demonstrated that three-dimensional imaging modalities
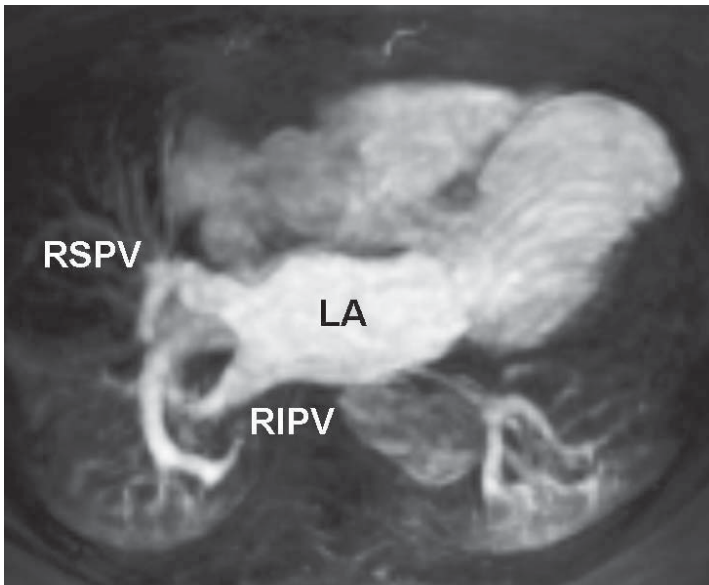
Figure 9. Maximum intensity projection of a gadolinium enhanced MRI angiogram of the pulmonary veins. LA = left atrium; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein
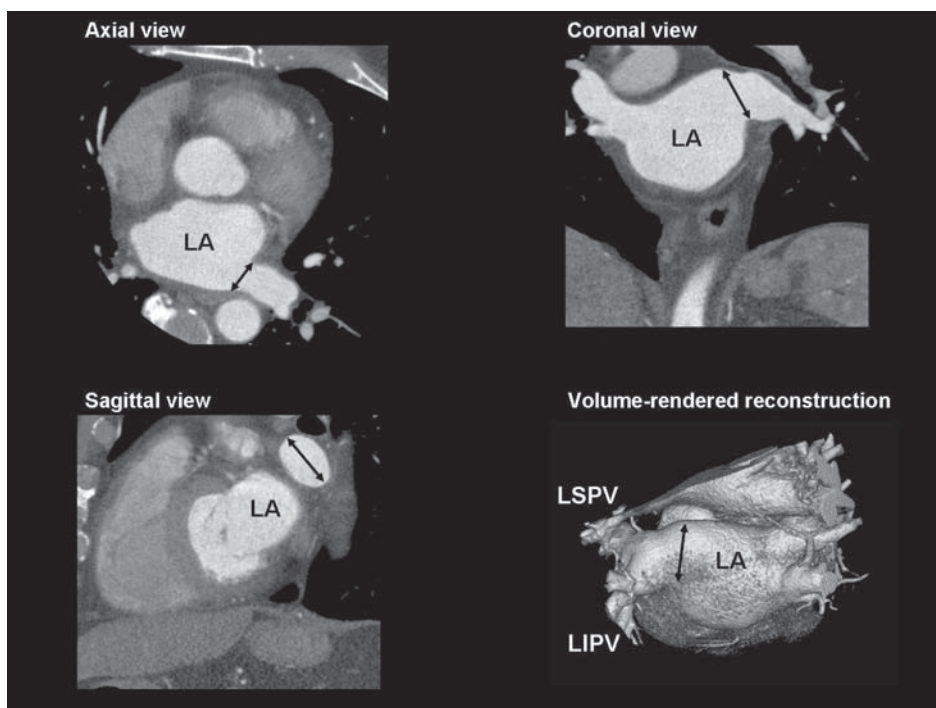
Figure 10. The different orthogonal planes (axial, coronal and sagittal) and three-dimensional volume rendered reconstructions of the MSCT scan can be used to assess LA and pulmonary vein anatomy. The black arrows indicate the large 'common ostium' of the left-sided pulmonary veins. LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein

provide the most accurate information on LA and pulmonary vein anatomy (16,17). In a direct comparison between MSCT and ICE (Figure 11), it was noted that MSCT has a higher sensitivity for the detection of additional pulmonary veins and that ICE underestimated the size of the pulmonary venous ostia (16).

During the ablation procedure, electroanatomical mapping systems such as Carto[TM] (Biosense-Webster, Diamond Bar, California, USA) are available to assess LA and pulmonary vein anatomy. These systems combine on-line electrophysiological data with anatomical information, acquired with mapping catheters positioned in the LA (51). When performing the actual ablation, the ablation points can be marked on the acquired electroanatomical map. The major limitation of these systems is the use of reconstructed anatomy. Ideally, the detailed anatomical information acquired with three-dimensional imaging techniques (such as MSCT and MRI) could be combined with the on-line electrophysiological information. Recently, image integration systems have been introduced that allow the on-line use of MSCT or MRI images during the actual ablation procedures.
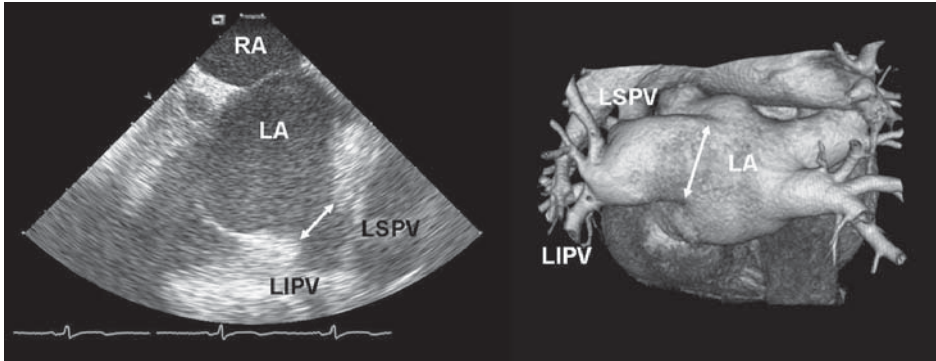
Figure 11. Comparison of MSCT and ICE to evaluate LA and pulmonary vein anatomy. In this patient, both techniques clearly visualize the 'common ostium' of the left-sided pulmonary veins (indicated with the white arrow). Whereas MSCT may provide more detailed three-dimensional information, ICE also provides on-line information on the relation between the ablation catheter and the pulmonary veins during the actual ablation. LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RA = right atrium

Image integration

With the use of new image integration systems such as CartoMerge[TM] (Biosense-Webster, Diamond Bar, California, USA), it has become feasible to merge pre-procedural acquired three-dimensional MSCT or MRI images with on-line acquired electroanatomical maps. Before the ablation procedure, the MSCT or MRI images are segmented into different structures (Figure 12). During the ablation procedure, the MSCT or MRI images are 'registered' with the use of dedicated software algorithms that minimize the distance between the electroanatomical mapping points and the three-dimensional MSCT or MRI images (Figure 13). Both pre-clinical (52) and clinical studies (53-55) have demonstrated the accuracy of image integration systems. Advantages of the image integration systems include the possibility to monitor the exact cath-eter position in relation to the endocardial border, the pulmonary veins and the surrounding structures (Figure 14). Hereby, potential complications such as pulmonary vein stenosis and atrio-oesophageal fistula may be avoided.

Recently, Kistler et al (54) compared 47 patients treated using conventional mapping alone with 47 patients treated using MSCT image integration. In the image integration group, fluo-roscopy times were significantly shorter (49 ± 27 minutes vs. 62 ± 26 minutes, $p<0.05$) and the number of patients with maintenance of sinus rhythm without anti-arrhythmic medication was significantly higher in the image integration group (83% vs. 60%, $p<0.05$) (54). However, these data have to be confirmed in larger, randomized trials.

One of the limitations of the new image integration technique is the time interval between the MSCT / MRI scan and the actual ablation procedure. Obviously, differences in fluid status, heart rate or rhythm are present between the two procedures, and may result in errors in the image fusion process. Furthermore, the accuracy of the image integration process may be affected by breathing during data acquisition and during the ablation procedure. In addition, variation of pulmonary vein location throughout the cardiac cycle may decrease the accuracy (56). Nonetheless, the various studies (52-55) have demonstrated the accuracy and the value
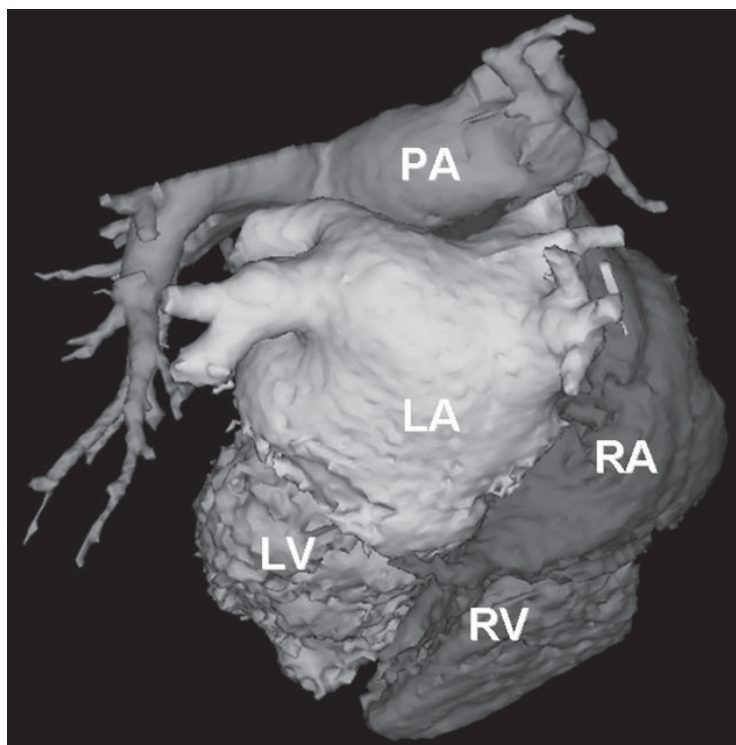
Figure 12. Segmentation of the MSCT scan into the different structures using the CartoMerge™ Image Integration Module. From the raw MSCT data, a three-dimensional volume is created. This volume is divided in the different chambers by placing anatomical landmarks and applying a dedicated software algorithm. The chamber of interest (LA in case of atrial fibrillation ablation) can then be used during the actual ablation procedure. LA = left atrium; LV = left ventricle; PA = pulmonary artery; RA = right atrium; RV = right ventricle

of image integration systems in guiding AF ablation procedures. By merging on-line acquired electrophysiological data with detailed anatomical information, these image integration systems are valuable tools in the invasive treatment of patients with AF.

SUMMARY

Assessment of LA size, anatomy and function is important in various clinical settings and can be performed with different imaging techniques. The assessment of LA size provides important prognostic information and is routinely performed with transthoracic echocardiography. Information on regional LA function can also be provided by transthoracic echocardiography and is important in the setting of treatment of atrial fibrillation. Catheter ablation procedures for AF require accurate imaging of LA and surrounding structures. Intracardiac echocardiography, MSCT and MRI provide detailed information on LA and pulmonary vein anatomy. New image integration systems allow the on-line use of pre-procedural acquired images and may facilitate the ablation procedures and potentially improve the outcome.
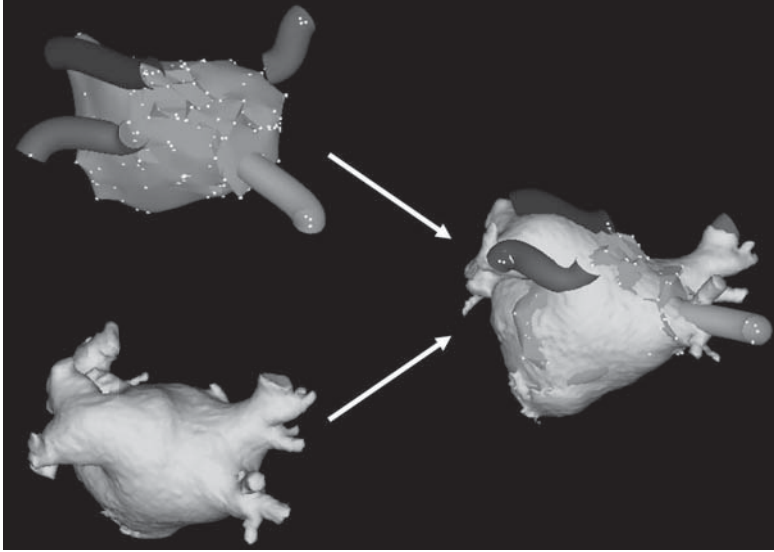
Figure 13. Image integration. The upper left panel demonstrates the conventional electroanatomical map with the reconstructed anatomy of the LA. The blue, purple, red and green 'tubes' represent the pulmonary veins. The lower left panel shows the segmented LA derived from MSCT (see also Figure 12). With the use of dedicated software, the CartoMerge™ Image Integration Module integrates the both modalities (right panel).
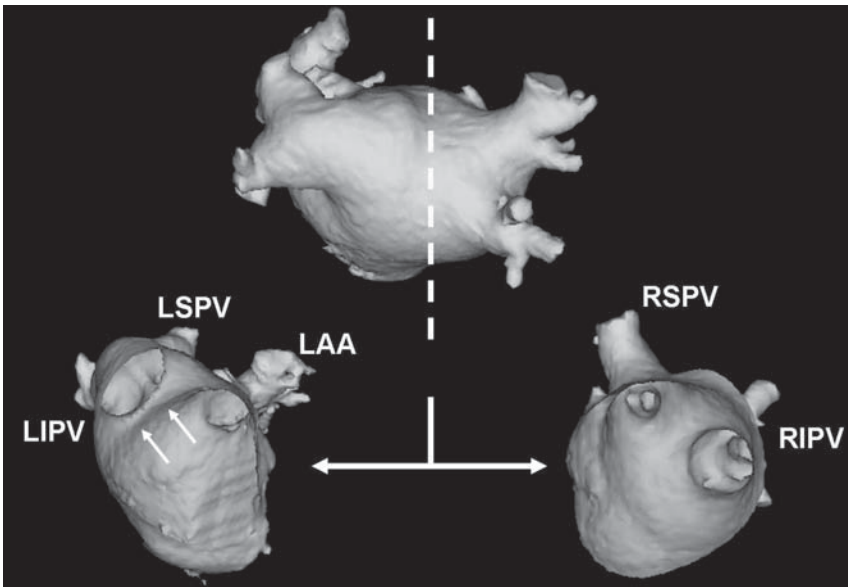
Figure 14. After the fusion process, the 'real' anatomy provided by the MSCT scan can be used to guide the actual catheter ablation. With the use of dedicated tools, such as a 'clipping plane' (represented by the dotted line), the ostium of the left-sided pulmonary veins (lower left panel) and the right sided pulmonary veins (lower right panel) can be visualized. The relation between the ablation catheter and the ostium of the pulmonary veins can be monitored constantly. In this patient, a 'common ostium' of the left-sided pulmonary veins is present. The white arrows indicate the ridge between the left-sided pulmonary veins and the left atrial appendage (LAA). LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein.

REFERENCES

1. Tsang TS, Barnes ME, Bailey KR et al. Left atrial volume: important risk marker of incident atrial fibrillation in 1655 older men and women. Mayo Clin Proc 2001;76:467-75.
2. Pritchett AM, Jacobsen SJ, Mahoney DW, Rodeheffer RJ, Bailey KR, Redfield MM. Left atrial volume as an index of left atrial size: a population-based study. J Am Coll Cardiol 2003;41:1036-43.
3. Tsang TS, Abhayaratna WP, Barnes ME et al. Prediction of cardiovascular outcomes with left atrial size: is volume superior to area or diameter? J Am Coll Cardiol 2006;47:1018-23.
4. Abhayaratna WP, Seward JB, Appleton CP et al. Left atrial size: physiologic determinants and clinical applications. J Am Coll Cardiol 2006;47:2357-63.
5. Pritchett AM, Mahoney DW, Jacobsen SJ, Rodeheffer RJ, Karon BL, Redfield MM. Diastolic dysfunction and left atrial volume: a population-based study. J Am Coll Cardiol 2005;45:87-92.
6. Douglas PS. The left atrium: a biomarker of chronic diastolic dysfunction and cardiovascular disease risk. J Am Coll Cardiol 2003;42:1206-7.
7. Vaziri SM, Larson MG, Benjamin EJ, Levy D. Echocardiographic predictors of nonrheumatic atrial fibrillation. The Framingham Heart Study. Circulation 1994;89:724-30.
8. Psaty BM, Manolio TA, Kuller LH et al. Incidence of and risk factors for atrial fibrillation in older adults. Circulation 1997;96:2455-61.
9. Sanfilippo AJ, Abascal VM, Sheehan M et al. Atrial enlargement as a consequence of atrial fibrillation. A prospective echocardiographic study. Circulation 1990;82:792-7.
10. Dittrich HC, Pearce LA, Asinger RW et al. Left atrial diameter in nonvalvular atrial fibrillation: An echocardiographic study. Stroke Prevention in Atrial Fibrillation Investigators. Am Heart J 1999;137:494-9.
11. Tsang TS, Barnes ME, Gersh BJ et al. Prediction of risk for first age-related cardiovascular events in an elderly population: the incremental value of echocardiography. J Am Coll Cardiol 2003;42:1199-205.
12. Osranek M, Bursi F, Bailey KR et al. Left atrial volume predicts cardiovascular events in patients originally diagnosed with lone atrial fibrillation: three-decade follow-up. Eur Heart J 2005;26:2556-61.
13. Benjamin EJ, D'Agostino RB, Belanger AJ, Wolf PA, Levy D. Left Atrial Size and the Risk of Stroke and Death : The Framingham Heart Study. Circulation 1995;92:835-41.
14. Fuster V, Ryden LE, Cannom DS et al. ACC/AHA/ESC 2006 guidelines for the management of patients with atrial fibrillation--executive summary. J Am Coll Cardiol 2006;48:854-906.
15. Ho SY, Cabrera JA, Tran VH, Farre J, Anderson RH, Sanchez-Quintana D. Architecture of the pulmonary veins: relevance to radiofrequency ablation. Heart 2001;86:265-70.
16. Jongbloed MR, Bax JJ, Lamb HJ et al. Multislice computed tomography versus intracardiac echocardiography to evaluate the pulmonary veins before radiofrequency catheter ablation of atrial fibrillation: a head-to-head comparison. J Am Coll Cardiol 2005;45:343-50.
17. Wood MA, Wittkamp M, Henry D et al. A comparison of pulmonary vein ostial anatomy by computerized tomography, echocardiography, and venography in patients with atrial fibrillation having radiofrequency catheter ablation. Am J Cardiol 2004;93:49-53.
18. Mansour M, Holmvang G, Sosnovik D et al. Assessment of pulmonary vein anatomic variability by magnetic resonance imaging: implications for catheter ablation techniques for atrial fibrillation. J Cardiovasc Electrophysiol 2004;15:387-93.
19. Hirata T, Wolfe SB, Popp RL, Helmen CH, Feigenbaum H. Estimation of left atrial size using ultrasound. Am Heart J 1969;78:43-52.
20. Lang RM, Bierig M, Devereux RB et al. Recommendations for Chamber Quantification. J Am Soc Echocardiogr 2005;18:1440-63.
21. Lester SJ, Ryan EW, Schiller NB, Foster E. Best method in clinical practice and in research studies to determine left atrial size. Am J Cardiol 1999;84:829-32.
22. Ujino K, Barnes ME, Cha SS et al. Two-dimensional echocardiographic methods for assessment of left atrial volume. Am J Cardiol 2006;98:1185-8.

23. 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.

24. Maddukuri PV, Vieira ML, DeCastro S et al. What is the best approach for the assessment of left atrial size? Comparison of various unidimensional and two-dimensional parameters with three-dimensional echocardiographically determined left atrial volume. J Am Soc Echocardiogr 2006;19:1026-32.

25. Rodevan O, Bjornerheim R, Ljosland M, Maehle J, Smith HJ, Ihlen H. Left atrial volumes assessed by three- and two-dimensional echocardiography compared to MRI estimates. Int J Card Imaging 1999;15:397-410.

26. Block M, Hourigan L, Bellows WH et al. Comparison of left atrial dimensions by transesophageal and transthoracic echocardiography. J Am Soc Echocardiogr 2002;15:143-9.

27. Klein AL, Murray RD, Grimm RA. Role of transesophageal echocardiography-guided cardioversion of patients with atrial fibrillation. J Am Coll Cardiol 2001;37:691-704.

28. Troughton RW, Asher CR, Klein AL. The role of echocardiography in atrial fibrillation and cardioversion. Heart 2003;89:1447-54.

29. Jongbloed MR, Schalij MJ, Zeppenfeld K, Oemrawsingh PV, van der Wall EE, Bax JJ. Clinical applications of intracardiac echocardiography in interventional procedures. Heart 2005;91:981-90.

30. Marrouche NF, Martin DO, Wazni O et al. Phased-array intracardiac echocardiography monitoring during pulmonary vein isolation in patients with atrial fibrillation: impact on outcome and complications. Circulation 2003;107:2710-6.

31. Verma A, Marrouche NF, Yamada H et al. Usefulness of intracardiac Doppler assessment of left atrial function immediately post-pulmonary vein antrum isolation to predict short-term recurrence of atrial fibrillation. Am J Cardiol 2004;94:951-4.

32. Rotter M, Sanders P, Jais P et al. Prospective validation of phased array intracardiac echocardiography for the assessment of atrial mechanical function during catheter ablation of atrial fibrillation. Heart 2006;92:407-9.

33. Yamanaka K, Fujita M, Doi K et al. Multislice computed tomography accurately quantifies left atrial size and function after the MAZE procedure. Circulation 2006;114:I5-I9.

34. Jongbloed MR, Dirksen MS, Bax JJ et al. Atrial fibrillation: multi-detector row CT of pulmonary vein anatomy prior to radiofrequency catheter ablation--initial experience. Radiology 2005;234:702-9.

35. Anderson JL, Horne BD, Pennell DJ. Atrial dimensions in health and left ventricular disease using cardiovascular magnetic resonance. J Cardiovasc Magn Reson 2005;7:671-5.

36. Kircher B, Abbott JA, Pau S et al. Left atrial volume determination by biplane two-dimensional echocardiography: validation by cine computed tomography. Am Heart J 1991;121:864-71.

37. Marwick TH. Measurement of strain and strain rate by echocardiography: ready for prime time? J Am Coll Cardiol 2006;47:1313-27.

38. 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.

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. Di Salvo G, Caso P, Lo PR 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.

42. 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.

43. Khan IA. Atrial stunning: basics and clinical considerations. Int J Cardiol 2003;92:113-28.

44. Stefanadis C, Dernellis J, Toutouzas P. A clinical appraisal of left atrial function. Eur Heart J 2001;22:22-36.

45. Tops LF, Bax JJ, Zeppenfeld K, Jongbloed MR, van der Wall EE, Schalij MJ. Effect of radiofrequency catheter ablation for atrial fibrillation on left atrial cavity size. Am J Cardiol 2006;97:1220-2.

46. Reant P, Lafitte S, Jais P et al. Reverse remodeling of the left cardiac chambers after catheter ablation after 1 year in a series of patients with isolated atrial fibrillation. Circulation 2005;112:2896-903.

47. Tsao HM, Wu MH, Huang BH et al. Morphologic remodeling of pulmonary veins and left atrium after catheter ablation of atrial fibrillation: insight from long-term follow-up of three-dimensional magnetic resonance imaging. J Cardiovasc Electrophysiol 2005;16:7-12.

48. Marom EM, Herndon JE, Kim YH, McAdams HP. Variations in pulmonary venous drainage to the left atrium: implications for radiofrequency ablation. Radiology 2004;230:824-9.

49. Wongcharoen W, Tsao HM, Wu MH et al. Morphologic characteristics of the left atrial appendage, roof, and septum: implications for the ablation of atrial fibrillation. J Cardiovasc Electrophysiol 2006;17:951-6.

50. Ren JF, Callans DJ, Schwartzman D, Michele JJ, Marchlinski FE. Changes in local wall thickness correlate with pathologic lesion size following radiofrequency catheter ablation: an intracardiac echocardiographic imaging study. Echocardiography 2001;18:503-7.

51. Gepstein L, Hayam G, Ben Haim SA. A novel method for nonfluoroscopic catheter-based electroanatomical mapping of the heart. In vitro and in vivo accuracy results. Circulation 1997;95:1611-22.

52. Dong J, Calkins H, Solomon SB et al. Integrated electroanatomic mapping with three-dimensional computed tomographic images for real-time guided ablations. Circulation 2006;113:186-94.

53. Tops LF, Bax JJ, Zeppenfeld K et al. Fusion of multislice computed tomography imaging with three-dimensional electroanatomic mapping to guide radiofrequency catheter ablation procedures. Heart Rhythm 2005;2:1076-81.

54. Kistler PM, Rajappan K, Jahngir M et al. The impact of CT image integration into an electroanatomic mapping system on clinical outcomes of catheter ablation of atrial fibrillation. J Cardiovasc Electrophysiol 2006;17:1093-101.

55. Heist EK, Chevalier J, Holmvang G et al. Factors affecting error in integration of electroanatomic mapping with CT and MR imaging during catheter ablation of atrial fibrillation. J Interv Card Electrophysiol 2006;17:21-7.

56. Noseworthy PA, Malchano ZJ, Ahmed J, Holmvang G, Ruskin JN, Reddy VY. The impact of respiration on left atrial and pulmonary venous anatomy: implications for image-guided intervention. Heart Rhythm 2005;2:1173-8.