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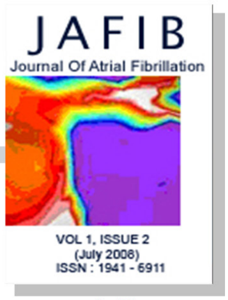

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Pre-Procedural Imaging to Direct Catheter Ablation of Atrial Fibrillation: Anatomy and Ablation Strategy

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Abstract

Successful catheter ablation of atrial fibrillation (AF) requires a detailed understanding of left atrial anatomy in order to maximize the safety and efficacy of the procedure. Common and rare variants of left atrial and pulmonary venous anatomy have been described which can affect the optimal ablation strategy for each individual patient. These variants include the presence of a right or left middle pulmonary vein, a left or right common pulmonary vein, a common inferior pulmonary vein, a right top pulmonary vein, and other rare forms of anomalous pulmonary venous drainage. There are also important patient-specific differences in pulmonary venous ridges and left atrial roof morphology. Pre-procedural CT or MR imaging can define these anatomic variants in exquisite detail and be used with image-integration strategies to direct the ablation procedure. In this review, we describe common and uncommon variants that can be identified by pre-procedural imaging, and suggest ablation strategies tailored to these anatomic variants.

Introduction

Catheter-based pulmonary vein isolation has become an accepted treatment for atrial fibrillation (AF),[1] based on the observation that electrical activity in the pulmonary veins may serve to trigger AF.[2] To perform this procedure successfully and safely requires knowledge of the anatomy of the left atrium (LA) and pulmonary veins (PVs). Early ablation procedures utilized fluoroscopy (at times aided by contrast injection), providing limited anatomical detail in regard to the anatomy of relevant structures. As catheter ablation for AF has evolved, it has become increasingly clear that a detailed understanding of a patients' LA and PV anatomy can facilitate the ablation procedure and reduce the potential for complications such as pulmonary vein stenosis. Magnetic Resonance Angiography (MRA) and Computed Tomography (CT) can produce highly precise images delineating the anatomy of the LA, PVs and surrounding structures. Recent advances in image integration have allowed the merging of LA/PV images from pre-procedural MRA or CT with real-time electroanatomic maps, allowing for direct visualization of catheter position within the MRA or CT images.[3] Anatomical variants of the LA and PVs have been identified by these imaging studies that have implications for the catheter ablation procedure. In this review, we summarize common and uncom-

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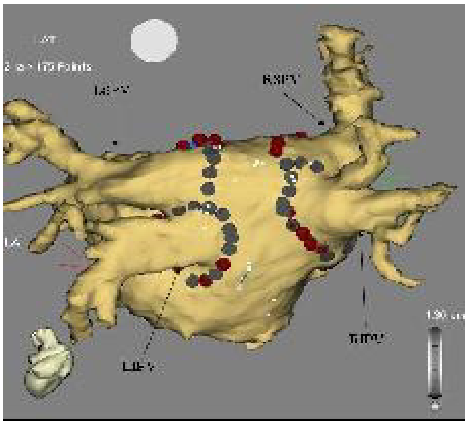
Figure 1: Typical Pulmonary Vein anatomy is shown in this posterior MRI view of the left atrium, including single discrete ostia for each of the four pulmonary veins



(LSPV: left superior pulmonary vein, LIPV: left inferior pulmonaryvein, RSPV: right superior pulmonary vein, RIPV:right inferior pulmonary vein). Ablation lesions inred are projected onto this view with fusion of electro anatomic mapping with MRI imaging, showing a typical antral ablation strategy around each pulmonary vein, with additional ablation at the ridges separating superior and inferior pulmonary veins.

mon LA and PV anatomy, and also describe ablation strategies that can be utilized when these anatomic variants are encountered.

Typical PV Anatomy

Typical PV Structure

The most common PV anatomy involves 4 pulmonary veins: 2 left and 2 right. (Figure 1) This pattern has been reported in various series in: 56% of 105 patients with AF imaged by MRA4, 62% of 55 patients (approximately 1/2 with AF) imaged by MRA,[5] and 81% of 58 patients with AF imaged by CT.[6] Typically the superior pulmonary veins (both left and right) are more anteriorly directed compared to the inferior pulmonary veins.

Size and Shape of Typical PVs

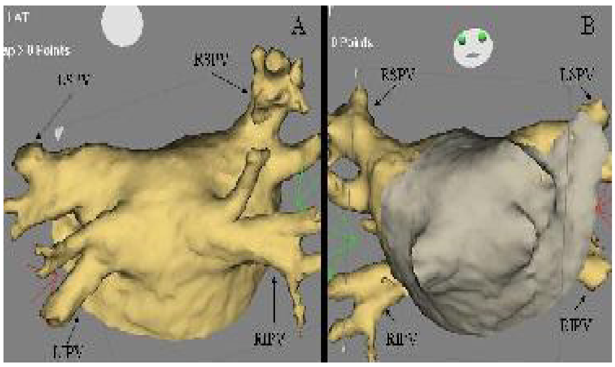
Most studies of PV size have reported ostial diameters ranging from approximately 7-25 mm in the setting of typical PV anatomy. [4-10] Some studies have reported that the superior veins have a larger ostial diameter than the inferior veins[4,6-8,] while other studies have reported similar ostial size for the superior versus inferior vein ostia.[5,9] When the PV anatomy is typical, the right vein ostia have been reported to be slightly larger than the left in most studies[4,7-9], and comparable in another study[5], although rigorous statistical comparison was not performed between left and right vein ostial diameters in all studies. Some of the discrepancies might be explained by the finding that there is substantial ovality to the pulmonary vein ostia[8,10], which could affect the measurement of ostial diameter depending on the axis utilized for measurement. It was also found that there is greater ovality to the left veins compared to the right, with ovality ratios of 1.4-1.5 on the left versus 1.2 on the right[8], possibly related to a "compressive" effect of the ridge separating the left pulmonary veins from the left atrial appendage (LAA), and also to compression of the left pulmonary veins (particularly the left inferior pulmonary vein) by the aorta.

There is also substantial variation in the distance between the right and left pulmonary veins. (Figure 2) The distance from the os of the RSPV to the LSPV averages 33 + 11mm, but with great variation between AF patients, ranging from 10 to 66 mm. The distance from the os of the RIPV to LIPV is similar (39 + 12 mm), and also shows great interpatient variability, ranging from 17 to 71 mm.[8]

Ablation Strategies

With typical PV anatomy, encirclements are typically made around the antra of each set of pulmonary veins (Figure 1), with the goal of achieving electrical isolation of the veins. If the ridges separating the superior and inferior pulmonary veins are sufficiently wide, further linear ablation may be performed along these ridges to electrically

Figure 2: A patient with a narrow distance between the right and left pulmonary veins is shown in posterior (2A) and anterior cutaway endoluminal (2B) MRI views.



Note the small distance between the antra of the left and right veins (particularly the inferior veins).

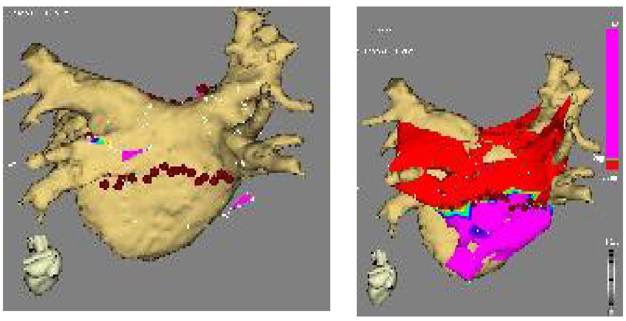
separate the superior and inferior veins on either the left and/or the right side. Alternatively, a "box lesion" can be performed around all 4 pulmonary veins, isolating them en-bloc from the remainder of the left atrium11 (Figure 3). This "box" lesion has potential advantages in that a larger region of the posteror left atrium is isolated compared to the traditional lesion set, and fewer ablation lesions are delivered along the posterior left atrium in regions which may be adjacent to the esophagus. The box lesion may be particularly desirable when there is a relatively small distance separating the right and left pulmonary veins, whereas it may be more difficult to achieve electrical isolation using the box lesion when this distance is very large.

Common Pulmonary Vein Variants

Right Middle Pulmonary Vein (RMPV)

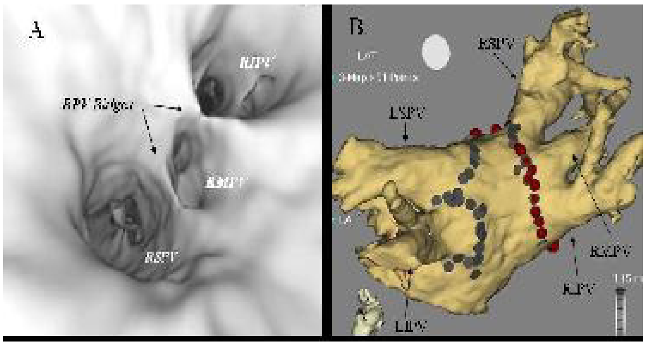
A single RMPV (3 total right sided veins) is the most commonly encountered PV variant in most reported series, with incidence ranging from 9.5%[10] to 27%.[4] When present, this vein is nearly always smaller than typical pulmonary veins, with a reported ostial diameter ranging from 7.5 + 2.1 mm4 to 9.9 + 1.9 mm.[6] The RMPV may project either anteriorly or posteriorly, depending on which segment of lung it is draining.[4] The ridges

Figure 3: A "box" ablation lesion set is shown in this posterior MRI view of the left atrium



(theview and anatomical structures are similar to figure 1). 3A shows ablation lesions in red in a singlecontinuous ring around all 4 pulmonary veins without posterior ablation lines in the superiorinferior axis. 3B shows electro anatomic voltage mapping after the completion of ablation. The entire "box" area within the ablation lesions is colored red, representing electro gram amplitude less than 0.42 mV, demonstrating electrical isolation of this region. Inferior to the ablation line, the voltage map is purple, representing a nonisolated region.

Figure 4: A right middle pulmonary vein is shown in these views.



4A shows an endoluminal view demonstrating the ridges between the right pulmonary veins. Note the narrowness of the ridges separating these veins, which could potentially impair catheter stability if ablation was performed along these ridges. 4B shows a left posterior view, demonstrating the ablation lesions required to isolate the left and right pulmonary veins. Note that ablation was performed between the LSPV and LIPV, but that all of the right pulmonary veins were isolated en-bloc in the presence of a RMPV.

separating the right pulmonary veins are typically quite narrow when a RMPV is encountered (<2mm in narrowest width in > 50% of patients). [12] (Figure 4) Because these ridges are generally narrow in the presence of a RMPV, we typically avoid catheter ablation along these ridges when this variant is encountered to reduce the risk of inadvertent ablation within the pulmonary veins, as catheter stability along these narrow ridges is typically poor. Of note, a left middle pulmonary vein has been reported only rarely (0-3% in one study[8] and not described at all in many other similar series).

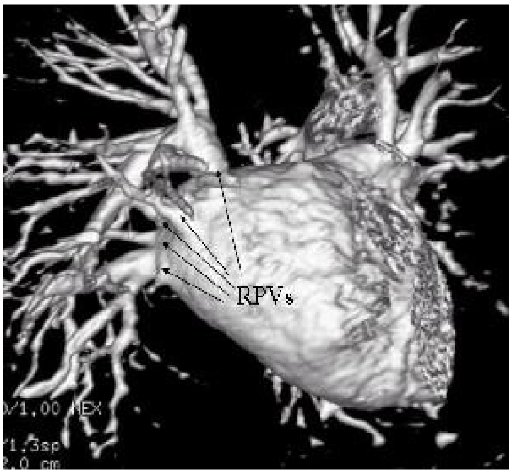
Multiple Right Middle Pulmonary Veins

Multiple (>2) right middle pulmonary veins are also encountered in the LA. (Figure 5) The incidence of this variant has been reported in various series at 2%[5], at 4-5%[8], and 4%[13]. These variants can be sub-classified based on whether there are 2 or 3+ right middle pulmonary veins and on the branching pattern13, but currently reported series are too small to accurately estimate the relative frequency of these sub-variants. Although no published reports are available on dimensions of the ridges separating multiple right pulmonary veins, it is our experience that the widths of these ridges (as well as the diameters of the vein ostia) tend to be quite small14. Based on concern for pulmonary vein stenosis if ablation is performed inadvertently in these small veins, we typically avoid ablation along the ridges separating multiple right middle pulmonary veins.

Left Common Pulmonary Vein (LCPV)

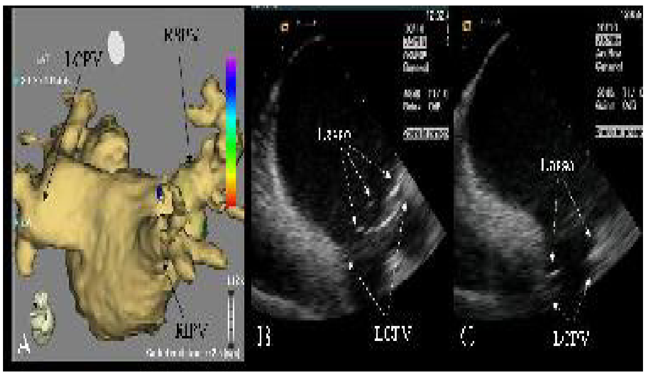
The second most common pulmonary vein variant reported in most studies is a LCPV, which has a single ostium from the LA, and then typically divides distally into superior and inferior branches. (Figure 6) The incidence of LCPV has been reported to be as rare as 3.4% of patients6 whereas another study reported this variant in 32% of patients with AF.[5] Other studies have reported a LCPV incidence of 9.5%[10], 14%[13], 17%4,9, and 6% in patients with AF and 20% in patients without AF8. Of note, in the study describing a 32% incidence of LCPV in AF patients, 7% were described as a LCPV with a "long trunk" and the remaining 25% with a "short trunk". [5] It is possible that some investigators might describe a particular anatomy as comprising separate left superior and inferior pulmonary veins, while others might classify this same anatomy as a LCPV with a "short trunk", and this may contribute to the reported discrepancies in the incidence of LCPV. Given that this single vein must drain the entire left lung, it is not surprising that it generally has an ostium that is substantially larger than the ostia of typical pulmonary veins. The average ostial diameter of the LCPV has been reported at 19.4 + 5.3 mm9, 26.0 + 4.0 mm4 and 32.5 + 0.5 mm.[6] Studies which measured the LCPV ostia in 2 dimensions have noted it to have significantly greater ovality than other pulmonary veins8,10, and so axis of measurement may explain the discrepancies in reported diameter of this vein.

Figure5: Multiple right pulmonary veins are shown in this anterior MRI view



Arrows denote at least 5 separate ostia of right pulmonary veins (RPVs) in this patient.

Figure 6:A left common pulmonary vein (LCPV) is shown.



6A shows a posterior-right oblique MRI view of the LCPV. Note the very large size of the ostium of this vein compared to the typical, separate right inferior and superior pulmonary veins (RIPV and RSPV). 6B shows an intracardiac echocardiogram (ICE) demonstrating a circular mapping ("lasso") catheter at the os of the LCPV. Note that the LCPV os is far larger than the lasso catheter. 6C is an ICE image showing the lasso catheter deep in the LCPV.

Typically we attempt to isolate a LCPV by encirclement around the entire antrum of the common vein. Of note, commercially available "lasso" catheters are often smaller than the os of a typical LCPV, and will often slide deep into this vein (Figure 6). Effective imaging of this vein, with pre-procedural CT/MR and/or intra-procedural ICE, can help to prevent inadvertent ablation within a LCPV. Ablation within the LCPV (along the ridge between superior and inferior branches) is generally avoided given the risk of pulmonary vein stenosis when ablating within a vein. It is our experience that it is generally more difficult to isolate a LCPV with this approach compared to isolation of separate LSPV and LIPV. In some cases, especially when a LCPV has a very "short trunk" before branching, limited ablation is performed carefully between superior and inferior branches in order to achieve LCPV isolation when isolation can't be achieved by ablation around the ostium of the LCPV.

Right Common Pulmonary Vein (RCPV)

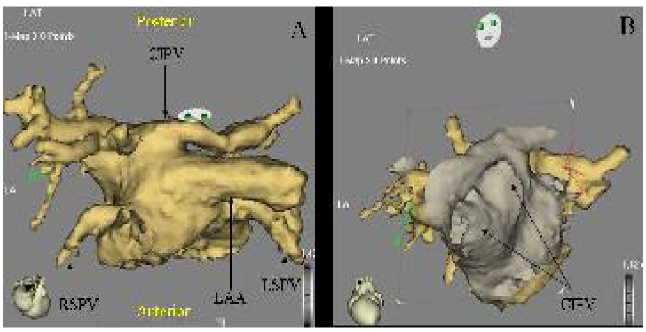
A RCPV (a single right pulmonary vein ostia, typically then separating into superior and inferior branches) is less commonly encountered than a LCPV. This variant has been reported in 0-2%[8] and 2%[13] of patients, while other studies with similar numbers of patients have not reported this variant.[4,6,9,10] As with a LCPV, there may be a certain degree of observer discretion in identifying a RCPV with a "short neck" versus typical anatomy including separate RSPV and RIPV. We typically plan an ablation strategy for a RCPV similar to a LCPV, with attempts to isolate the entire vein en bloc with antral encirclement. We reserve ablation at the ridge between the superior and inferior branches of a RCPV only for cases in which the ridge is wide, catheter stability on the ridge is good, and if ablation at this site is necessary to completely isolate the vein after full antral ablation has been performed.

Uncommon Pulmonary Vein Variants

Common Inferior Pulmonary Vein (CIPV)

A rare variant of drainage for the inferior lobes of both lungs is an CIPV, which typically empties via a common ostium into the central region of the infero-posterior LA. (Figure 7) It is not clear what the true incidence is of this rare variant, but it appears to be encountered in less than 1% of patients, relegating its description to single case reports.[15,16] Like a LCPV or RCPV, it is possible to isolate an CIPV en bloc by a single encirclement around the common ostia, reducing the risk of pulmonary vein stenosis which would exist with ablation deeper into each vein.

Figure 7: A common inferior pulmonary vein (CIPV) is shown in this superior MRI view.



A shows a superior view demonstrating the common trunk of the CIPV, as well as typical separate ostia of the right superior pulmonary vein (RSPV) and left superior pulmonary vein (LSPV). The large left atrial appendage (LAA) is also seen. 7B shows a cutaway end luminal view "looking into" the large common ostium of the CIPV.

Right "Top" Pulmonary Vein (RTPV)

Another uncommon pulmonary vein variant is the RTPV. This is characterized by a single, typically small pulmonary vein draining the upper regions of the right lung and emptying into the roof of the right atrium, superior to the typically larger RSPV. (Figure 8) Its incidence has been reported as 3 out of 91 subjects in one series[17], although other similar series have not reported it, and so its true incidence is somewhat uncertain. It is important to identify this variant in pre-procedural imaging, as its ostium is superior to the antrum of the RSPV, at a region that is typically ablated when performing circumferential ablation of the right pulmonary veins. It is possible that a RTPV could be identified by electroanatomic mapping or intracardiac echocardiography (if pre-procedural imaging was not performed), but there would be far greater risk of failing to identify this vein by these modalities, especially if its presence were not being actively sought. Given the generally small size of the RTPV, the risk of PV stenosis is presumed to be high if ablation is performed inadvertently within this vein. When this variant is encountered, modifying the ablation line to avoid ablating within this vein (possibly by extending the ablation line further onto the LA roof to incorporate the RTPV into the encirclement of the other RPVs) seems to be a prudent choice.

Variant Pulmonary Vein Drainage

Partial anomalous pulmonary venous return (PAPVR) has been extensively reported in the cardiac surgical literature18, and these variants may be defined in great detail by pre-procedural CT or MR imaging.[19] One example we encountered is a patient presenting for catheter ablation of paroxysmal AF with an anomalous RSPV draining directly into the SVC (Figure 9). This abnormality is often associated with the presence of sinus venosus ASDatrial septal defect. Other variants in the PAPVR category include the scimitar syndrome (drainage of right lower lobe pulmonary veins into the IVC at or below the level of the diaphragm), and left sided PAPVR (drainage of left superior pulmonary vein into a vertical vein that connects to the left innominate vein, therefore causing a left to right shunt). A separate entity in the spectrum of pulmonary venous return abnormalities is the cor triatriatum, where all four pulmonary veins drain into a posterior receiving chamber that is separated by an abnormal septum from an anterior left atrial chamber.[20]

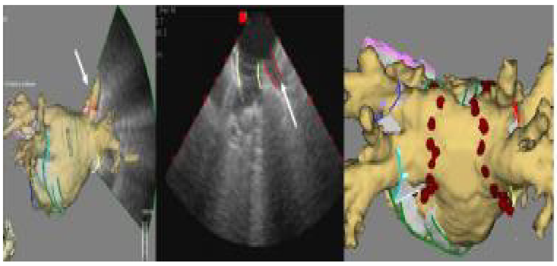
There is, however, a paucity of published information about ablation strategies in patients with PAPVR. Without pre-procedural imaging or detailed intra-procedural ICE imaging, it seems likely that many of these variants would be missed in a typical anatomical ablation strategy. When these variants are identified during pre-procedural imaging, however, alternative ablation strategies for these patients, such as electrical isolation of the SVC (thereby electrically disconnecting the anomalous RSPV from the SVC and right atrium) in the patient shown in Figure 9, can be tailored to an individual patients anatomy.

Other Left Atrial Structures

Pulmonary Vein Ridges

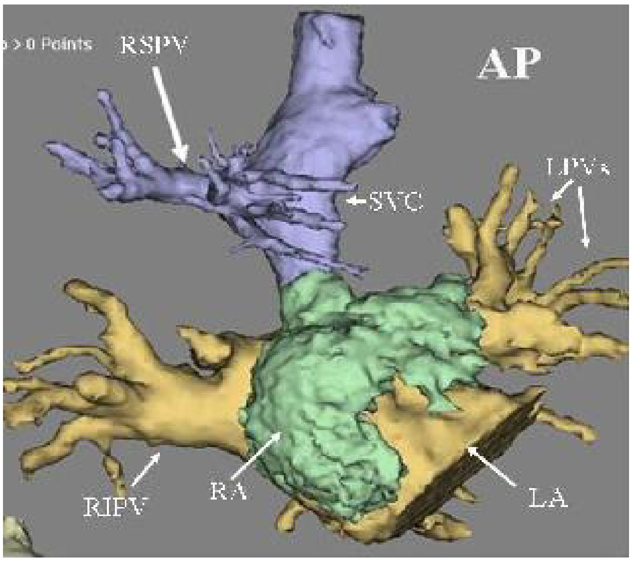
The dimensions of the ridges separating the pul-

Figure 8: A right "top" pulmonary vein (RTPV) is shown, marked by the arrow in all 3 figures.



8A shows a posterior-left oblique MRI view merged with intracardiac echocardiography (ICE). The colored lines represent ICE images delineating the LA anatomy and allowing for integration with the MRI image (CARTO Sound software). 8B shows the ICE image. The green lines represent the left atrial endocardium, the red lines define the RTPV, and the yellow lines represent the right superior pulmonary vein. 8C shows a posterior integrated view demonstrating the ablation lesions shown in red which have been positioned to avoid the ostium of the RTPV. Ablation of the superior region of the right pulmonary veins was directed leftward to avoid the RTPV.

Figure 9: A patient with an anomalous right superior pulmonary vein (RSPV) connection to the superior vena cava (SVC) is shown.



The SVC and RSPV are colored purple, the left atrium (LA) and other pulmonary veins (LPVs: left pulmonary veins, RIPV: right inferior pulmonary vein) are yellow, and the right atrium (RA) is green.

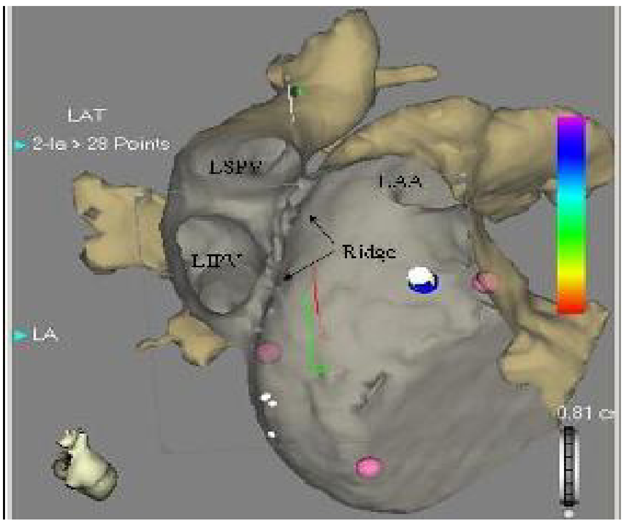
monary veins, and separating the left pulmonary veins from the left atrial appendage (LAA), are highly relevant to the ablation procedure (Figure 10). Ablation along these ridges can facilitate isolation of the veins, and wider ridges typically allow for greater catheter stability with less risk of inadvertent catheter slippage into the pulmonary veins. It is difficult to accurately assess these ridges even with highly detailed electro-anatomic mapping alone. The dimensions of these ridges can be assessed with high accuracy with pre-procedural MR or CT imaging, however, and can also be assessed with intracardiac echocardiography. Intracardiac echocardiography (possibly used in conjunction with pre-procedural imaging) can also provide important real-time information on catheter position in relation to these pulmonary vein ridges.

The pulmonary vein ridges relevant to the ablation procedure have average minimal widths in the range of 2-8 mm.[12] The average width of the ridges separating the RPVs (in the presence of a RMPV) are significantly less than average width of the ridges separating the LSPV from the LIPV. The width of the ridge separating the LPVs from the LAA tends to narrow as the ridge ascends from the LIPV to the LSPV. As a LCPV is relatively uncommon, the width of the ridge separating the LCPV from the LAA has not been described. These generalities cannot fully account for patient-specific differences in ridge dimensions, however, and so accurate imaging to delineate the ridges in each patient is useful to direct the ablation procedure.

Left Atrial Roof Morphology

A variety of morphologies of the LA roof have been described, including flat, convex and concave.[21] Although the ablation strategy at the LA roof is not substantially different for these variants, identification of an individual patient's LA roof morphology can facilitate catheter contact along the LA roof and minimize risk of perforation. Pouches arising from the LA roof have also been described, which may increase the difficulty of creating complete electrical isolation along a "roof line" connecting antral ablation lines from the left and right superior pulmonary veins. Of note, the right pulmonary artery often passes very close to the LA roof, and so potentially could be injured by ablation at this site.[21] Pulmonary artery injury has not yet been reported as a complication of catheter ablation of AF, however, and this may relate to the cooling effect of high blood flow in this structure.

Figure 10: The ridge separating the left atrial appendage (LAA) from the left superior and inferior pulmonary veins (LSPV and LIPV) is shown.



Note that this ridge characteristically is widest in the inferior region, and narrows superiorly adjacent to the LSPV. The narrow superior portion of this ridge can be associated with difficultly in achieving vein isolation due to catheter instability

Esophagus

The esophagus runs in close proximity to the left atrium, and injury to the esophagus during AF ablation has resulted in the rare but potentially fatal complication of atrio-esophageal fistula formation.[22,23] The relationship between the esophagus and the left atrium can be identified by pre-procedural cardiac CT scanning[24] and by MRI, providing a potential tool to identify LA sites that are in close proximity to the esophagus. It has been noted, however, that the esophagus can migrate from a site adjacent to the left PVs to a site adjacent to the right PVs during an ablation procedure.[25] For this reason, real-time assessment of esophageal location by methods such as esophageal temperature monitoring,[26] barium swallow[27] or intracardiac echocardiography[28] may be more useful in minimizing the risk of esophageal injury than pre-procedural assessment of esophageal location.

Left Atrial Appendage (LAA)

The LAA lies in close proximity to the left pulmonary veins. It is rare to target ablation within the LAA during typical ablation procedures for AF, although atrial tachycardias have been reported which were successfully ablated within or at the antrum of the LAA.[29] The ridge separating the LAA from the left pulmonary veins is a target for ablation during isolation of the left pulmonary veins, and catheter stability allowing effective lesion formation without inadvertent ablation within the LAA or left-sided veins can be difficult at this site (Figure 10). Pre-procedural cardiac imaging can be useful to define this ridge (including length, width, and orientation), and integration of electro-anatomic mapping with the resulting images can facilitate ablation along this ridge12. Pre-procedural imaging can also define the size and dimensions of the LAA in great detail, with substantial inter-patient differences documented in LAA size,[30] and this may prove useful in directing device occlusion of the LAA, which is currently an investigational strategy intended to reduce strokes resulting from AF.[31,32]

Limitations of Pre-Procedural Imaging

There are several limitations in the ability of pre-procedural imaging to accurately direct catheter ablation of AF. It is possible for volume shifts to occur in the atria between the time of imaging and the time of ablation that may lead to differences in pre-acquired images compared to real-time mapping. Three dimensional rotational LA angiography has been described which allows for LA imaging immediately prior to catheter mapping,[33] but this technology currently lacks the spatial resolution possible with CT or MR imaging. Concordance of cardiac cycle gating between pre-procedural CT or MR imaging and real-time mapping has not been universally performed, possibly leading to error in image registration. Additionally, cardiac deformation by catheter contact can create distortions during real-time catheter mapping which are not identified by pre-procedural imaging. Real-time imaging strategies, such as (currently available) intracardiac echocardiography or (currently investigational) interventional MR imaging during the ablation procedure can provide even more precise detail of catheter position in relation to complex LA anatomy.

Conclusions

The LA is a complex structure, with great inter-patient variability. A detailed understanding of an individual patient's LA anatomy may improve the ability to effectively isolate the pulmonary veins and to produce other desired ablation lines and lesions within the LA. This may also reduce the risk of complications such as cardiac perforation and damage to surrounding structures, including the esophagus and the pulmonary veins. Pre-procedural cardiac CT or MR imaging can produce highly detailed representations of each individual patient's anatomy within the LA and relative to surrounding structures. This allows an ablation strategy to be tailored for each patient to maximize both efficacy and safety.

Disclosures

Nothing to disclose.

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