Real-time Imaging in Left Atrial Mapping and Ablation

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Summary

The catheter based ablation of atrial fibrillation has been transformed greatly by the introduction of new technologies and techniques. This review describes the major advancements in real time navigation systems, their accuracy and impact on clinical outcome, and emerging magnetic resonance imaging technologies that will allow assessment of disease progression and allow for procedure planning.

Introduction

Over the past few years, the management of atrial fibrillation (AF) has evolved significantly. In particular, the technologies and techniques underlying invasive catheter-based strategies for managing atrial fibrillation, as well as the role of these strategies in the electrophysiologist's clinical armamentarium, have been rapidly transformed [1, 2]. This evolution has naturally been driven by improvements in the safety and success of these procedures.

Many advances have facilitated this progress, including the advent of irrigated-tip radiofrequency ablation catheters [3], improved maneuverability of catheters and catheter energy delivery mechanisms, and progress in our understanding of the pathophysiology underlying atrial fibrillation [4-6]. Perhaps the most revolutionary progress has been in the area of real-time left atrial imaging and radiofrequency catheter navigation. Our abilities to assess the left atrial anatomy, with high spatial resolution and without additional radiation exposure, before and during catheter-based procedures, and to accurately position our catheters relative to anatomic landmarks have vastly improved in recent years, bringing atrial fibrillation ablation into a new era [7, 8]. The purpose of this article is to briefly review the current imaging and navigation modalities used in AF ablation and explore the future alternatives soon to be available.

Left Atrial Anatomy

The anatomy of the LA is complex and variable [9, 10]. Even though multiple varieties of pulmonary vein (PV) ostial configurations have been reported (Table I), the most common presentation is the typical branching pattern with 4 distinct ostia for the superior left, inferior left, superior right, and inferior right pulmonary veins [10]**.** The true ostium, in the language of ablationists, describes the most distal aspect of each pulmonary vein immediately before its diameter abruptly increases. The communication between the pulmonary vein ostium and the proper left atrium is then formed by a conical structure called the antrum. Though the anatomic margins of the antrum can be vague, particularly with regard to their margins on the posterior wall, this tissue forms both an anatomic and electrophysiologic bridge between the PVs and atrial tissues, with electrophysiologic characteristics distinct from both.

A tubular structure then communicates both left and right-sided antra, limited inferiorly by the mitral valve annulus and apparatus, with an anterior, superior (roof), septal, lateral, and posterior walls determining the classical structure of the LA (Figure 1)**.** The LA endocardium is smooth except the LA appendage where left-sided pectinate muscles are confined. The LA appendage is anterior to the orifice of the left superior pulmonary vein.

Fluoroscopy Imaging of the Left Atrium

Although virtual catheter navigation systems aim to limit use of fluoroscopy and the incumbent radiation exposure, ablationists still rely on 2D fluoroscopy to introduce catheters into the left atrium, to confirm anatomic features of other modalities, and to confirm catheter positioning relative to anatomic landmarks [11, 12]. The complexity and variability of pulmonary vein antrum anatomy defies simplicity in fluoroscopic interpretation, but several guidelines can be useful.

To delineate the ostial margins with fluoroscopy, one favors a view perpendicular to the distal position of the pulmonary vein. For right-sided ostia, this is obtained with a slight right anterior oblique angle, and for left-sided ostia, with a left anterior oblique angle. For positioning circumferentially within the antra, one favors an '*en fas*' view, looking down the barrel of the respective pulmonary vein, which is obtained with a left anterior oblique angle for right-sided veins, and a right anterior oblique angle for left-sided veins.

Effective fluoroscopy-guided catheter manipulation in the LA requires extensive previous experience. The position, attitude and movement of the catheter tip determine its specific location, critical when ablating the antrum portion of the veins. Unfortunately, the overall accuracy of fluoroscopy guidance alone is sub-optimal for the current ablation strategies in the LA [13-16]. In order to avoid potential complications including cardiac perforation and pulmonary vein stenosis, further methods have been developed, which minimize the radiation exposure and offer a three-dimensional perspective on intra-atrial navigation.

Mapping and Navigation Systems

Over the past few years, navigation and mapping systems have become widely available during LA ablation procedures. The most commonly used systems include:

CARTO (Biosense Webster, Baldwin Park, CA)

This system is based on the premise that a metal coil placed in a magnetic field will generate an electric current. The magnitude of this current will depend on the field's strength and orientation of the coil. This system generates three low-level magnetic fields from a unit mounted underneath the patient table, and records features of the current generated in mapping catheter electrodes, thus localizing them to a the specific location in the magnetic field [17].

A three-dimensional map is then created by sampling endocardial points, and by mathematically projecting these points to a smoothed, fitted surface. The initial points in this geometry are obtained using fluoroscopic guidance, but a majority of the other points are sampled using virtual (magnetic) catheter navigation alone.

In LA mapping, the initial anatomical reference points are defined by the pulmonary veins os. Catheter tip impedances, which drop suddenly as the catheter is advanced across the ostium, can also aid in the initial mapping procedure (Figure 2). At our institution, special attention is paid to the posterior and septal walls, where a large number of points are acquired. Besides pulmonary vein isolation, we have encountered significant clinical benefits in outcomes after a complete electrical septal and posterior LA walls debulking.

A recently available algorithm (CARTOMERGE, Biosense Webster, Baldwin Par, CA) offers the capabilities of merging a previously obtained cardiac computerized tomography or magnetic resonance images with predetermined fluoroscopic anatomical points [18]. This allows intra-atrial navigation over a pre-structured left atrium, minimizing fluoroscopic exposure. Whether the overall accuracy of catheter manipulation is improved using merged image data remains controversial [13, 15].

NavX (Endocardial Solutions Inc, St Paul, MN)

A surface-based system is used to define cardiac anatomy and visualize catheter position. Three distinct low amplitude electrical currents (in the range of 5.6 kHz) are emitted across three orthogonal pairs of surface electrodes, and electrode positions are calculated by assessing the component-wise amplitudes of these signals at the electrode tip [17]. Currently, up to 8 catheters and 64 electrodes can be visualized in the 3-D space, and navigation is possible for all cardiac chambers. Relative to CARTO, positioning of the catheter is performed with higher temporal resolution (position is calculated 93 times per second) and is therefore not gated to the cardiac cycles. The system is compatible with cryo and standard radiofrequency ablation. As with the CartoXP system, the newer versions of NavX also allow for the fusion with CT and MRI images.

Overall mapping systems accuracy:

The overall accuracy of both mapping systems in LA ablation procedures prompted multiple comparison studies demonstrating often large error profiles [8, 13, 15].

Even though the current available methods have demonstrated reproducible measurements and applicability, they represent a static representation of a hemodyamically active structure, which fluctuates with inspiration, expiration and different filling pattern associated with arrhythmias. These findings do not rebut the potential advantages of a 3D imaging modality; however, in order to target specific endocardial locations with 2D imaging, the operator must accurately conceptualize the orientation of this imaging plane relative to the complex 3D anatomy of the left atrium.

A recently performed blinded correlation study at our institution demonstrated an approximately 1cm error correlation between ICE guided anatomical distribution and CARTOMERGE locations [13]. The error profile appear greater over the left sided pulmonary vein structures and was independent of the number of registration points or overall left atrium size. Electroanatomic mapping is an important modality if used in adjunction with 2D imaging methods, avoiding potentially large spatial registration errors inherent to current mapping technology.

Intracardiac Echocardiography:

Transducer miniaturization and advances in micro-electric and piezoelectric crystal technology have allowed intracardiac echocardiography (ICE) to be widely available during electrophysiological procedures [19]. Intracardiac visualization is performed by femoral venous approach [20, 21]. The ultrasound catheters caliber ranges from 6-10 Fr, with a relatively atraumatic tip. Most recently a 5.5-10 MHz, 10 Fr electronic phased-array catheters was developed (AcuNav, Siemens Medical Solutions USA, IC. Mountain View, CA), with pulse/continuous width and color Doppler capabilities and a flexible tip. This device optimizes visualization and flow of left atrial and ventricular structures by increasing resolution and deeper penetration form the right atrium.

The advantages of ICE imaging are multiple. It's applicability and relatively low cost makes it an ideal real-time imaging modality for LA ablation. The main disadvantages of ICE rely on the 2D visualization of cardiac structures. For this reason ICE is rarely used as a single navigation method during ablation.

The most important applications of ICE include:

- **Trans-septal Catheterization:**

Visualization of the inter-atrial septum is critical for a successful and safe transseptal puncture [22-24]. Intracardiac visualization of the right and left atrium successfully determines anterior structures like the ascending aorta and LA appendage and posterior structures like the left pulmonary veins. Ultrasound guided puncture allows for specific anterior or posterior location and a superior or inferior puncture. Direct visualization allows for continuous evaluation of the septum tenting by the needle and sheath and contrast guided puncture also confirms an LA position by fluoroscopy and by ICE (ICE trans-septal figure). In our experience, puncture directly oriented toward the left pulmonary veins offers the best results in regards to ablation and lasso catheters maneuverability. Puncture through a foramen ovale or a more anterior location tends to make mapping and ablation of the posterior structures difficult and limited.

- **Pulmonary Vein Anatomy:**

Direct visualization of the left and right pulmonary vein system is one of the main advantages of ICE. It allows specific definition of the os and antrum of the pulmonary veins to establish anatomic locations for landmark registration using CARTOMERGE. Real-time visualization of the lasso and ablation catheters can guide mapping and subsequent ablation, potentially minimizing the risks of energy delivery inside the pulmonary vein and subsequent pulmonary vein stenosis [25-27].

- **Radiofrequency Energy Titration:**

Direct visualization of energy delivery in the LA is another attractive features of ICE. Multiple studies have demonstrated that screening for type II microbubbles formation prevents further injury to the mediastinal structures or the presence of catheter-tip related thrombus formation, minimized by power titration.[20, 28-30]

- **Continuous intracardiac monitoring:**

Intracardiac echocardiography permits continuous monitoring of potential acute complications of LA ablations. It has been demonstrated to be both sensitive and specific for the detection of pericardial effusions and other mediastinal complications [20, 31, 32].

Magnetic Resonance Imaging of the Left Atrium

MRI provides a powerful tool for the investigation of injury to tissues near the posterior LA wall. It has excellent soft tissue contrast and spares a patient from unnecessarily being exposed to ionizing radiation. MRI holds great promise to become a viable future alternative for real time imaging. Currently, Delayed Enhancement Cardiovascular Magnetic Resonance Imaging (DE-MRI) is an established clinical method for visualizing tissue necrosis in a variety of cardiac disease processes. These include visualizing myocardial infarction and injury due to myocarditis [33-35]. Contrast enhancement in injured tissue observed by MRI occurs due to altered washout kinetics of gadolinium relative to the normal surrounding tissue. Due to challenges in acquiring a scan with sufficient spatial resolution to visualize the LA wall, DE-MRI had largely been relegated to use within the ventricles. Recently, however, new scan sequences have been reported with sufficient enhancement and spatial resolution for visualization and analysis of LA tissue [36, 37].

One novel application of DE-MRI includes three dimensional visualization and analysis of the LA following pulmonary vein antrum isolation for AF. Using these techniques, it is possible to visualize lesion formation caused by RF ablation (Figure 4).

As MRI compatible catheters become available more available and real-time MRI intracardiac navigation is developed, real time MRI treatment of AF will become a reality. Despite the recent advances, however, there are still several important technical difficulties to real-time, interventional MRI of cardiac arrhythmias. These include the need for better tracking of ablation catheters and improved real-time acquisition. Current work at our and other centers currently focuses on direct visualization of the endocardium, evaluation of RF lesion depth and size, and attempts to determine transmurality in real time. Few electrophysiology laboratories have this imaging modality available, however. Our institution is expected to have a fully functional MRI compatible laboratory by mid 2008.

Our initial experience has proven that MRI pre and post LA ablation offers crucial evidence of effective lesion formation and overall evaluation of cardiac function.

Conclusions

Despite major advances in the field, there is no ideal method for intracardiac real-time navigation. Each method offers potential benefits and limitations. In our experience, fusion between fluoroscopy guidance, and electro-anatomical mapping complemented with continuous ICE guidance offer the best safety profiles and clinical outcomes. The future of real-time imaging during mapping and ablation will most likely rely on MRI. This method offers the greatest advantages in spatial and temporal resolution, critical for an effective ablation strategy.

Future Perspectives

Left atrial mapping technologies are growing exponentially. The current available methods have demonstrated reproducible accuracy and applicability, but their weakest point is based on the suboptimal correlation with an in-vivo, real time representation of the complex left atrial anatomy. Intravascular volume and other hemodynamic beat to beat variations significantly influence the accuracy of mapping. Intracardiac echocardiography has emerged as a useful guide in maximizing temporal resolution, but their suboptimal special resolution limit its applicability.

With the introduction of smaller equipment and electrophysiolgical compatible catheters, magnetic resonance imaging represents the future of real-time imaging in atrial fibrillation.

Not only MRI will render a real hemodynamic representation of the cardiac anatomy, but optimize navigation by improving both temporal and special resolution. Detail assessment of LA tissue pre and post ablation will help determine or sub-classify different AF phenotypes, establishing a correlation between anatomy, type of presentation and clinical outcomes. A tailored approach to AF ablation given the specific arrhythmic substrate will be possible, minimizing the risk of the procedure and maximizing the overall curative rates for left atrial ablation.

Executive Summary

Management of Atrial Fibrillation

- The management of atrial fibrillation (AF) has evolved significantly. In particular, the technologies and techniques underlying invasive catheter-based strategies for managing AF, as well as the role of these strategies in the electrophysiologist's clinical armamentarium, have been rapidly transformed.

Left Atrial Anatomy

- Our abilities to assess the left atrial (LA) anatomy, with high spatial resolution and without additional radiation exposure, before and during catheter-based procedures, and to accurately position our catheters relative to anatomic landmarks have vastly improved in recent years, bringing AF ablation into a new era.
- The anatomy of the LA is complex and variable. Even though multiple varieties of pulmonary vein (PV) ostial configurations have been reported, the most common presentation is the typical branching pattern with 4 distinct ostia for the superior left, inferior left, superior right, and and inferior right pulmonary veins.

Mapping and Navigation Systems

- Although virtual catheter navigation systems aim to limit use of fluoroscopy and the incumbent radiation exposure, ablationists still rely on 2D fluoroscopy to introduce catheters into the LA, to confirm anatomic features of other modalities, and to confirm catheter positioning relative to anatomic landmarks
- Navigation and mapping systems have become widely available during LA ablation procedures. A three-dimensional map is created by sampling endocardial points, and by mathematically projecting these points to a smoothed, fitted surface. The initial points in this geometry are

obtained using fluoroscopic guidance, but a majority of the other points are sampled using virtual (magnetic) catheter navigation alone.

- Merging algorithms between electroanatomic maps and CT-rendered images allows intra-atrial navigation over a pre-structured LA, minimizing fluoroscopic exposure. Whether the overall accuracy of catheter manipulation is improved using merged image data remains controversial.
- Intracardiac echocardiography (ICE) optimizes visualization and flow of LA and ventricular structures by increasing resolution and deeper penetration form the right atrium, ideal for transseptal catheterization, pulmonary vein anatomical guidance, ablation energy titration and continuous monitoring. The main disadvantages of ICE rely on the 2D visualization of cardiac structures. For this reason ICE is rarely used as a single navigation method during ablation.

Magnetic Resonance Imaging of the Left Atrium

- With the advent of MRI compatible catheters, intracardiac navigation has been proven to be highly accurate; with excellent anatomically distributed radiofrequency lesion formation. Direct visualization of the endocardium will allows specific and accurate evaluation of the RF lesion depth and size, crucial to determine transmurality.

Tables

Table I *

Pulmonary Vein Anatomical Pattern	(%)
Typical Branching Pattern	57%
Short Common Left Trunk	20%
Right Middle Pulmonary Vein	12%
Long Common Left Trunk	7%
Right Middle and Right Upper Pulmonary Veins	3%
Two Right Middle Pulmonary Veins	2%

* Compiled from Kato, Lickfett, Meininger, et al. Pulmonary Vein Anatomy in Patients Undergoing Catheter Ablation of Atrial Fibrillation: Lessons Learned by Use of Magnetic resonance Imaging. *Circulation*. 107(15), 2004-2010 (2003).

Figures

Figure 1. CT LA Anatomy. Segmented Left Atrial Surface from Contrast Enhanced CT Angiogram (CTA). Whole Heart View (A), PA of left atrium (B), AP view of left atrium (C).

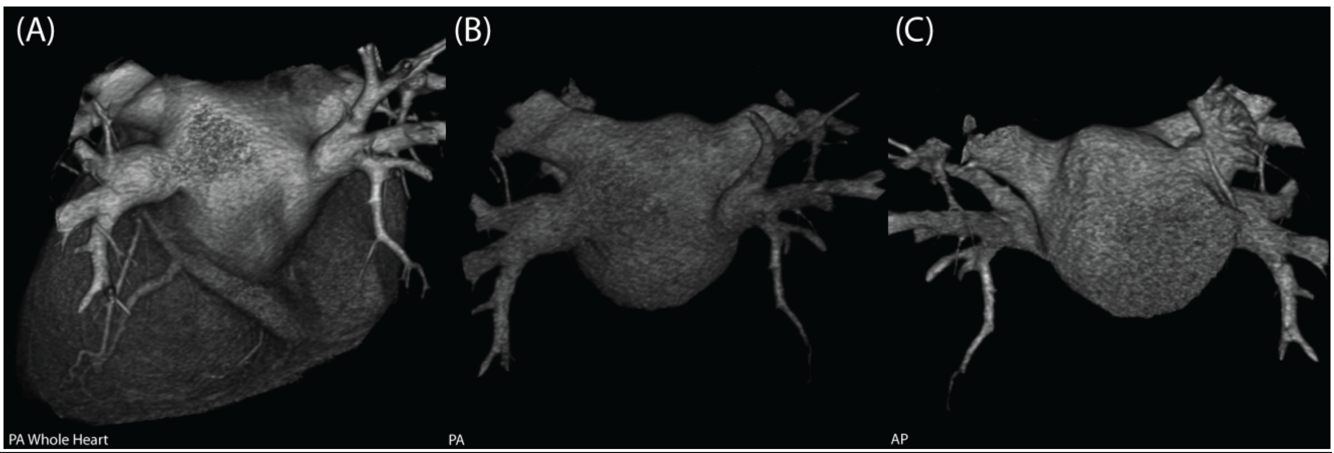


Figure 2. Carto electroanatomic mapping system with CARTOMERGE.

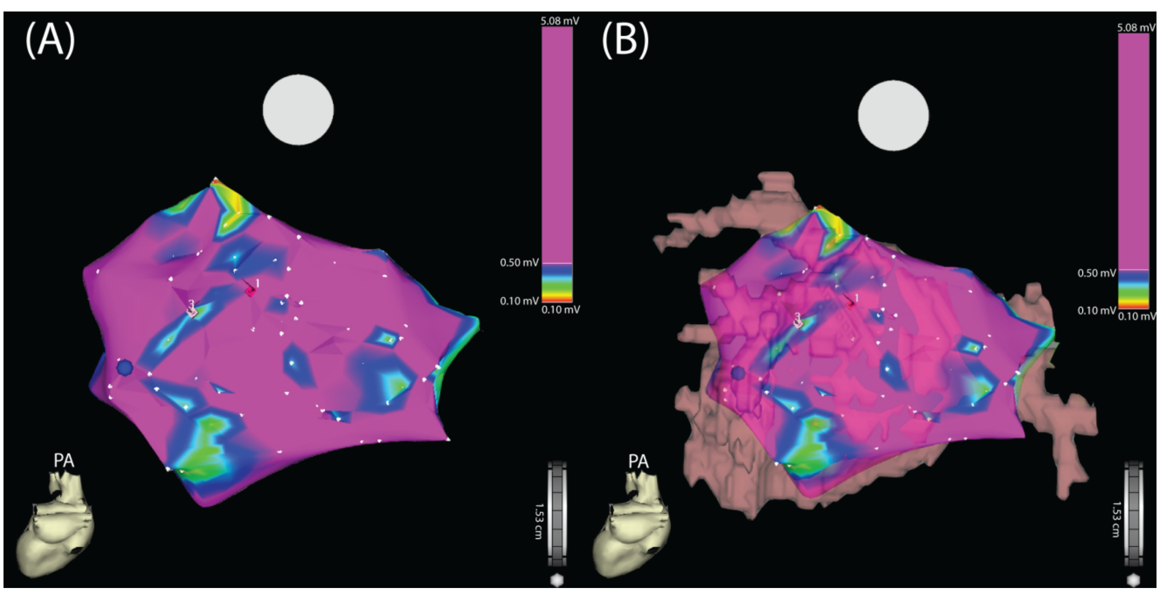


Figure 3. Catheter and trans-septal needle positioning for trans-septal puncture and subsequent tenting during the trans-septal puncture **(A)**. Bubble formation immediately following septal puncture **(B)**. Anatomy of left-atrium as viewed in intra-cardiac echocardiography (ICE) with left superior and inferior pulmonary veins visible.

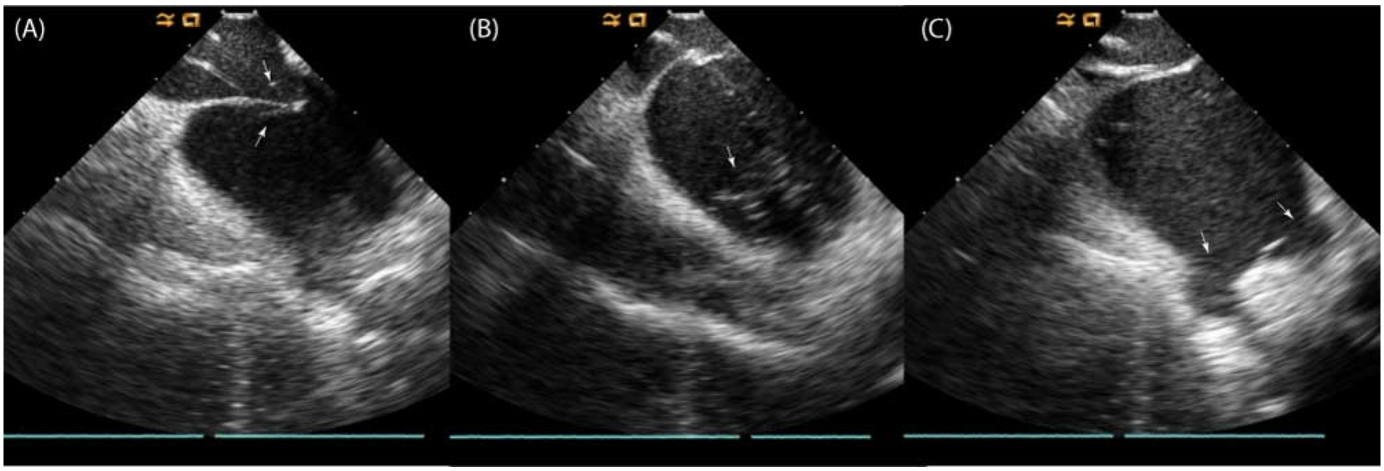
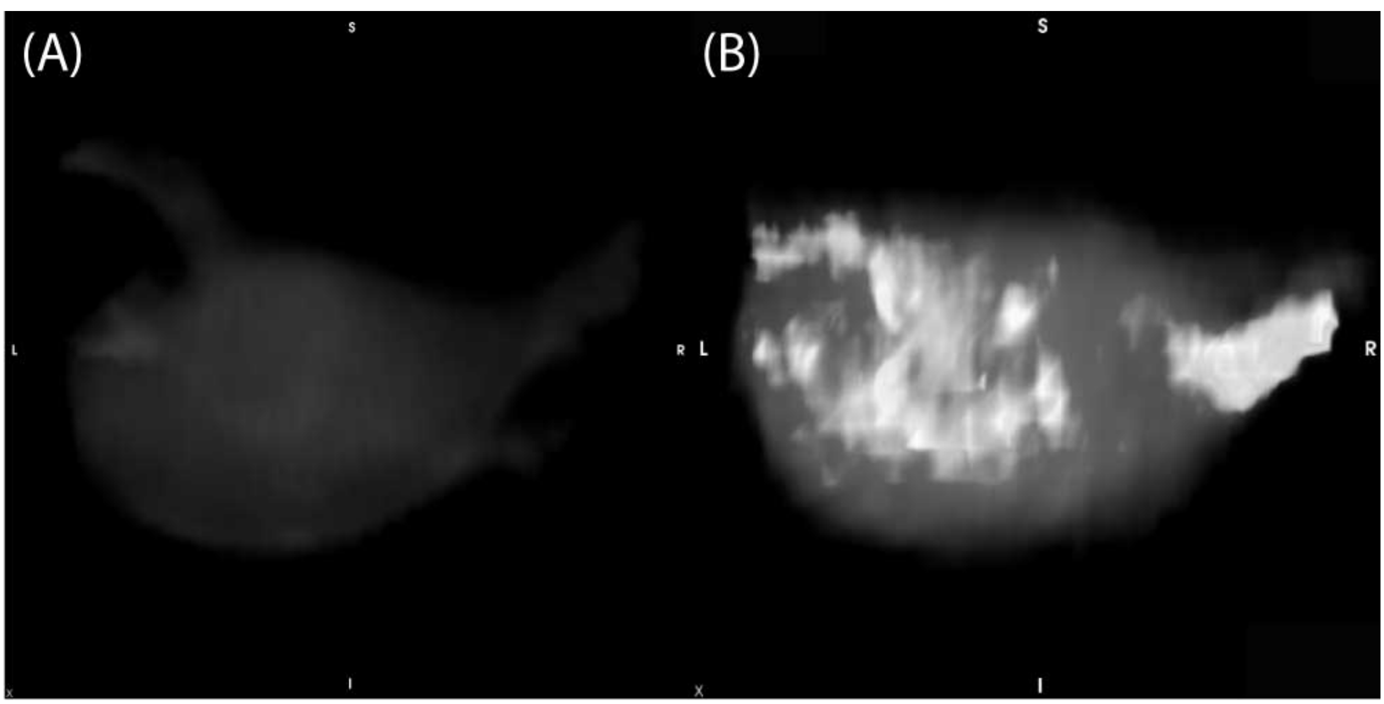


Figure 4. Detection of left atrial scar three months post procedure using delayed enhancement MRI (DE-MRI). **(A)** DE-MRI acquired 24 hours prior to ablative treatment for atrial fibrillation. **(B)** DE-MRI acquired 3 months post procedure. Clear enhancement in the posterior wall and pulmonary vein antrum is visible, sites of lesion formation targeted during the ablative treatment.



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