Multimodal Imaging in the Management of Atrial Fibrillation

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1 Introduction

Atrial fibrillation (AF) is the most common form of cardiac arrhythmia so that a review of the role imaging in AF is a natural topic to include in this book. Further motivation comes from the fact that the treatment of AF probably includes more different forms of imaging, often merged or combined in a variety of ways, than perhaps any other clinical intervention. A typical clinical electrophysiology lab for the treatment of AF usually contains no less than 6 and often more than 8 individual monitors, each rendering some form of image based information about the patient undergoing therapy. There is naturally great motivation to merge different images and different imaging modalities in the setting of AF but also very challenging because of a host of factors related to the small size, extremely thin walls, the large natural variation in atrial shape, and the fact that fibrillation is occurring so that atrial shape is changing rapidly and irregularly. Thus, the use of multimodal imaging has recently become a very active and challenging area of image processing and analysis research and development, driven by an enormous clinical need to understand and treat a disease that affects some 5 million Americans alone, a number that is predicted to increase to almost 16 million by 2050.[55]

In this chapter we attempt to provide an overview of the large variety of imaging modalities and uses in the management and understanding of atrial fibrillation, with special emphasis on the most novel applications of magnetic resonance imaging (MRI) technology. To provide clinical and biomedical motivation, we outline the basics of the disease together with some contemporary hypotheses about its etiology and management. We then describe briefly the imaging modalities in common use in the management and research of AF, then focus on the use or MRI for all phases of the management of patients with AF and indicate some of the major engineering challenges that can motivate further progress.

1.1 Clinical profile of atrial fibrillation

Atrial fibrillation is a growing problem in modern societies with an enormous impact on both short term quality of life and long-term survival.[8] Approximately 0.5% of people aged 50–59 have atrial fibrillation and of those aged 80–89, 9% are afflicted with AF—and these prevalence are increasing.[4,55] While many with the condition go untreated, AF is associated with an almost two-fold increase in the risk of mortality. AF patients experience a dramatically increased rate of stroke, from 1.5% for those aged 50 to 59 years to 23.5% for those aged between 80 and 89,[35] a risk that, by contrast, decreases with age in the normal population. Treatment of AF represents a significant health-care burden with the annual costs estimated at around seven billion US dollars.[15]

Restoring and maintaining normal sinus rhythm remains one of the major goals in treating patients with AF. One treatment modality is a combination of cardioversion and antiarrhythmic drugs,[26] however, only 40–60% of the AF population is maintained in regular rhythm one year after such treatment. The treatment itself may also have serious adverse effects[6,16,27] and must usually continue for the lifetime of the patient. By contrast, maintaining sinus rhythm without the use of antiarrhythmic drugs seems to be associated with increased survival.[13] The inadequacies of drug-based treatments for AF have long been the major motivation for finding a truly curative approach to maintain sinus rhythm and suppress AF.

1.2 Mechanisms of atrial fibrillation

The mechanism underlying AF have been the topic of extensive research over many years and there is consensus that the disease, like most cardiac arrhythmias, has two components, the tissue substrate and some initiating electrical events or triggers. Perhaps the most complete description of the substrate of AF comes from Allessie *et al.*, who first postulated that the longer the atria spend in the state of fibrillation, the most difficult it becomes to reverse the condition, *i.e.,* “Atrial fibrillation begets atrial fibrillation”.[92] Their conclusions were based largely on animal studies in which rapid pacing of the heart induced AF through a continuous process of electrical and then structural remodeling, a transition that is initially reversible but then becomes essentially permanent. Rapid pacing of the heart does not, of course, occur spontaneously and the etiology of the disease in humans is thought to be closely linked to the gradual and inevitable elevation of fibrosis in the atria that comes with age[5,57] and that predisposes a heart to AF whether or not associated conditions such as heart failure are present.[11] In animals subjected to the rapid pacing protocols developed to induce AF, treatment with a drug that suppresses the formation of fibrosis reduced the likelihood of developing AF compared to control animals,[42] hence the clear link between fibrosis and the AF substrate. As we will see below, one application of imaging, especially MRI, is directed at identifying and quantifying the extent of fibrosis in the left atrium and thus identifying the progression of the disease substrate.

The role of triggers in AF is also motivation for novel imaging approaches. With electrical and electroanatomical mapping, *i.e.,* recording electrical activity from a number of known sites on a surface the heart, it is possible to identify the sites of triggers and thus also localize causes of induction of AF. Leaders in mapping triggers of AF include Haissaguerre *et al.*, who identified trigger sites both in the atria and especially within the pulmonary veins of the left atrium.[31,32,79,80] Once identified and localized, it is possible to electrically isolate these triggers, which was the unknown consequence of earlier surgical techniques for AF management, known as the Cox Maze procedure, first performed in 1988.[14] This operation isolates not only the pulmonary veins but also different regions of the atria by creating a “maze”, *i.e.,* a tortuous path for electrical conduction in the atria, reducing the ability of triggers to interact with a substrate that could sustain arrhythmias. Modern, catheter based *ablation* approaches seek to achieve similar goals by applying very focused energy to the endocardial surface of the atria to isolate the triggers known to exist in the pulmonary veins[32] and create the same maze of broken conduction in the left atrium.[31,33,49] The electroanatomical mapping approaches necessary to guide such interventions are, however, invasive and often time consuming so there remains a pressing need to develop noninvasive imaging approaches to localize trigger sites. Current research in AF management seeks to develop imaging based on MRI,[22,77,87] ultrasound,[93] and computed X-ray tomography[30] to visualize the ablation lesions and thus direct the intervention.

1.3 Imaging and AF

We outline in subsequent sections the use of a broad range of imaging modalities in AF management and then focus on a comprehensive approach to the management of AF using of MRI for all phases of evaluation and intervention. The most novel approaches to imaging in AF are in the areas of merging multiple modalities and in the rapid expansion of the use of MRI. The rationale for this growth is that, unlike other modalities, MRI is naturally suited to detect changes in soft tissue characteristics and hence capable of revealing the progress of substrate in AF and in visualizing the creation of lesions during ablation. These capabilities, combined with the ability to reveal atrial anatomy at high resolutions, makes MRI the natural adjunct to all phases of the management of AF patients.

2 Overview of current imaging modalities

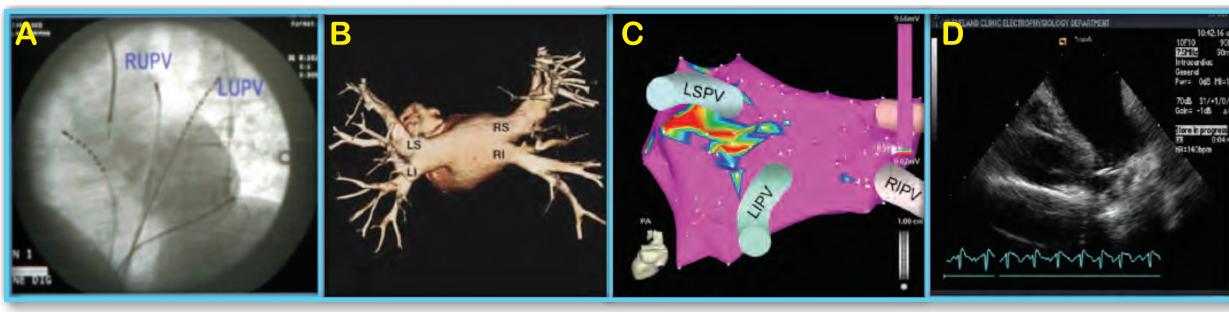

Figure 1: Overview of imaging modalities in common use for AF evaluation and ablation. The figure shows examples of fluoroscopy (Panel A), computed tomography (Panel B), electroanatomical mapping (Panel C), and intracardiac echo (Panel D) as they are used for guiding ablation of atrial arrhythmias.

The use of imaging is ubiquitous in clinical electrophysiology, especially in interventions that require remote access to the heart by means of catheters. One the one hand, imaging is required to guide the catheter and on the other, the catheter itself often captures and conveys functional and diagnostic information that must be integrated into the procedure. Figure 1 summarizes the most common modes of displaying information in a typical electrophysiology study and we describe briefly here these modalities. The focus of subsequent, more detailed discussion will be MRI, the modality that is now the topic of extensive research and development.

2.1 Fluoroscopy

Fluoroscopy is an x-ray based modality that has been a mainstay of cardiac catheterization procedures from their inception. Like all x-ray based imaging, fluoroscopy can reveal dense materials like bone and metallic objects (*e.g.,* electrodes, devices, and catheters) but without contrast agents is not capable of visualizing soft tissue or blood. In catheter ablation, fluoroscopy serves primarily to guide catheter navigation and to direct the the transseptal puncture of the atrial septum that is necessary to access the left atrium. With contrast agent injection, it is also possible to visualize vessels and cardiac chambers using fluoroscopy. Significant strengths of fluoroscopy include the ability to perform real time imaging at frame rates of tens per second, the simplicity provided by very evolved technology and ready availability. Acknowledged weaknesses include the poor soft tissue contrast and the cumulative exposure to ionizing radiation. More fundamentally, fluoroscopy is generally considered to be a two-dimensional modality so that revealing three-dimensional cardiac shape is difficult.

Modern fluoroscopy system seek to address these limitations by providing multiple, orthogonally oriented cameras (biplaner fluoroscopy) and rotational angiography systems for full, three-dimensional reconstructions of venous and cardiac shape during catheterization procedures,[40,45] all at the lowest possible field strengths. The anatomical models obtained by rotational angiography systems approach the resolution and accuracy of of CT and MRI images. Furthermore, because imaging occurs intra-procedurally, the resulting models can better aligned to the coordinate system in which the procedure occurs and less vulnerable to intravascular volume changes and shifts in body position and shape that may limit the accuracy of remotely acquired MRI and CT images.[59,82] Acquisition of geometric information in the same reference frame, and at the same time of procedures significantly aids the integration of imaging modalities by obviating the need for registration.[7]

2.2 Electroanatomical mapping and imaging

Electroanatomical mapping (EAM) is an essential component of cardiac ablation procedures that has been used widely in since the mid-1990's.[3,19,51,65,78,81] All such systems produce a patient specific geometric model of the endocardium together with electrograms at numerous sites on that surface. There are two competing EAM technologies, CARTO from Biosense-Webster[9] and EnSite from St Jude Medical,[3] which differ in the manner by which they generate the electrical signals on the endocardium. CARTO measures potentials directly by touching a manually steered catheter sequentially to the heart surface and can thus be used on both the endocardial and epicardial surfaces. Its major weakness is the time required to sample enough points to create true maps of electrical activity, which can present challenges when the underlying arrhythmias are unstable and poorly tolerate by the patient. The EnSite technology differs in that it is based on simultaneously recording from an inflatable catheter containing 80 electrodes that is placed inside the chamber of interest. The system solves the resulting bioelectric field inverse problem in terms of endocardial potentials from a single heart beat the reducing the burden on patients with unstable arrhythmias.

More recently, clinicians have adopted electroanatomical mapping for evaluation and guidance during ablation of AF[19,51,65] but here the goal is often simpler—to measure only the amplitude of electrical activity in the posterior wall of the left atrium and thus evaluate the success of ablation. EAM is just as essential in the context of MRI guided AF ablation and such systems have been developed for this application.[77]

2.3 Echocardiography/ultrasound

Various modalities of ultrasound based echocardiography are used in the management of AF. Transthoracic (TTE), transesophageal (TEE), and intracardiac (ICE) echocardiography are routinely used before, during, and after catheter ablation of AF, always with the goal of providing detailed and fine scale anatomical information. We will briefly describe the context in which each of these modalities are commonly employed.

Transthoracic echocardiography (TTE) TTE is routinely used for screening and evaluation purposes in the management of AF, typically to screen for underlying heart disease, including heart failure, valvular heart disease, and left ventricular hypertrophy.[58] Additionally, TTE can be used to assess LA size and anatomy.[41] Post-ablation TTE can be used to detect pericardial effusion and to evaluate LA function and size.[23] Although other imaging modalities outperform TTE in these tasks, TTE remains am effective, readily available, non-invasive, and relatively inexpensive modality.

Transesophageal echocardiography (TEE) TEE has shown high sensitivity and specificity for the detection of LA thrombus before ablation treatment.[66] It is also useful for assessment of the location and number of pulmonary veins when CT or MRI imaging are not feasible. Due to patient discomfort (the probe must be places in the esophagus at the left of the heart) and need for airway management, TEE has not traditionally been used intra-procedurally.[23]

Intracardiac echocardiography (ICE) ICE has become a standard imaging utility in most modern EP laboratories because of its high spatial and temporal resolution, achieved in part from the immediate proximity of the sensor and the heart. ICE is capable of visualizing the anatomy of the left atrium including the pulmonary veins and appendage, as well as other local anatomy including the aorta, mitral valve, and esophagus. In AF ablation procedures the ultrasound catheter is navigated intravenously to the right atrium, and is used to guide transseptal punctures, navigate ablation catheters, confirm electrode-tissue contact, and titrate energy delivery.[24,48,54,88] Additionally, ICE plays a critical role in the prevention and detection of complications by monitoring the formation of thrombus or coagulum, pericardial effusion and tamponade, and flow acceleration indicative of pulmonary vein stenosis.[34,71,72,74] Limitations of ICE include the requirement for additional intravenous access, and confinement to two dimensional imaging.

2.4 Anatomical MRI/MSCT

Multi-slice computed tomography (MSCT) and MRI based angiography are routinely performed pre-ablation to define left atrial and pulmonary vein anatomy and size. Models of the relevant cardiac anatomy, generated from these images, are created to help guide intra-procedural navigation and tissue targeting.[46,47,76] Trade-offs exist between the selection of MSCT or MRI for angiography. MSCT based angiography is faster and has higher spatial resolution, while MRI does not require exposure to ionizing radiation. Most patients with pacemakers or implantable cardiac defibrillators are also ineligible for MRI. High fidelity representations of the anatomy can be generated from both modalities, and consequently both are considered acceptable for this purpose. Both modalities are also used post-ablation to identify complications such as pulmonary vein stenosis, atrio-esophageal fistula, and reverse remodeling, *i.e.,* decrease in atrial volume.[23,43,63,69,75,86] MRI and MSCT have also been successfully used to identify surrounding structures that may be at risk of collateral injury during AF ablation, including coronary vessels and the esophagus.[44,84,85]

2.5 Merging of modalities

Clearly, no imaging modality is a panacea for all of the requirements inherent in the assessment and treatment of a disease with such diverse and complex imaging needs as AF. Often a merging of modalities is necessary or at least desirable to achieve the necessary coverage of anatomical and functional information to manage the disease. The challenges presented by merging imaging modalities include the need to align or *register* images acquired in different coordinate systems and different resolutions and then to present them to the operator in a way that is flexible and intuitive enough to be useful.

The centerpiece of contemporary integrated image merging systems tends to be the electroanatomical mapping system, which includes the necessary merging, registration, and visualization hardware and software. The goal of such systems is almost always to utilize a previously acquired angiography (by MRI or MSCT) to provide a geometric substrate for the subsequent electroanatomical mapping of the heart.[20,21,37,38,53,73,83] This registration step usually relies on operator identification of landmarks common to both the angiography and the electroanatomical map to rigidly align them in the coordinate system of the EAM system. Further refinements of the alignment are then updated as more points are sampled for the EAM. Much of the mismatch that remains can be attributed to the differences in the MSCT and MRI data acquired sometimes days before the procedure. Other sources of error in the match of MRI and MSCT models to intra-procedure anatomy include respiration, patient movement, and changes in cardiac rhythm.[17,60] Real time integration of ICE imaging with the EAM system has recently emerged as a means to allow intra-procedural generation and updating of anatomical models, further improving navigational accuracy.[18,62]

3 MRI based evaluation of atrial tissue

Cardiac MRI has become the gold standard for imaging and analysis of numerous cardiac conditions. Generally, MRI is limited by comparatively slow image acquisition and reconstruction times, low resolution, susceptibility to noise, and magnetic field incompatibility of some patients. However, the two primary benefits of MRI are soft tissue contrast, and absence of ionizing radiation. These two strengths come to bear significantly in the arena of AF management. First, AF is known to influence cardiac structural properties in a process known as remodeling. Second, the stated goal of AF ablation is to modify, isolate, or abolish arrhythmogenic tissues. In both cases the soft tissue contrast available in MR imaging provides insight for physicians into the entrenchment of AF, and success of scar formation, respectively. Finally, modern ablation procedures still rely heavily on fluoroscopy for procedural guidance. The introduction of AF ablation procedures into the MRI environment opens the door for the departure of ionizing radiation from the management of AF.

Late gadolinium enhanced (LGE) MRI is used to evaluate alterations in tissue structure associated with numerous cardiomyopathies.[61,91] To acquire LGE images a dose of chelated gadolinium contrast agent is administered intravenously as would be done for standard MR angiography. Following the injection, the gadolinium is allowed time to wash clear of normal myocardium and an inversion-recovery-prepared gradient echo pulse is acquired to detect regions of tissue where the contrast agent remains sequestered. Any region in which perfusion has decreased, or extracellular space increased will appear bright in LGE images due to enhanced concentrations of gadolinium relative to surrounding tissues.[56]

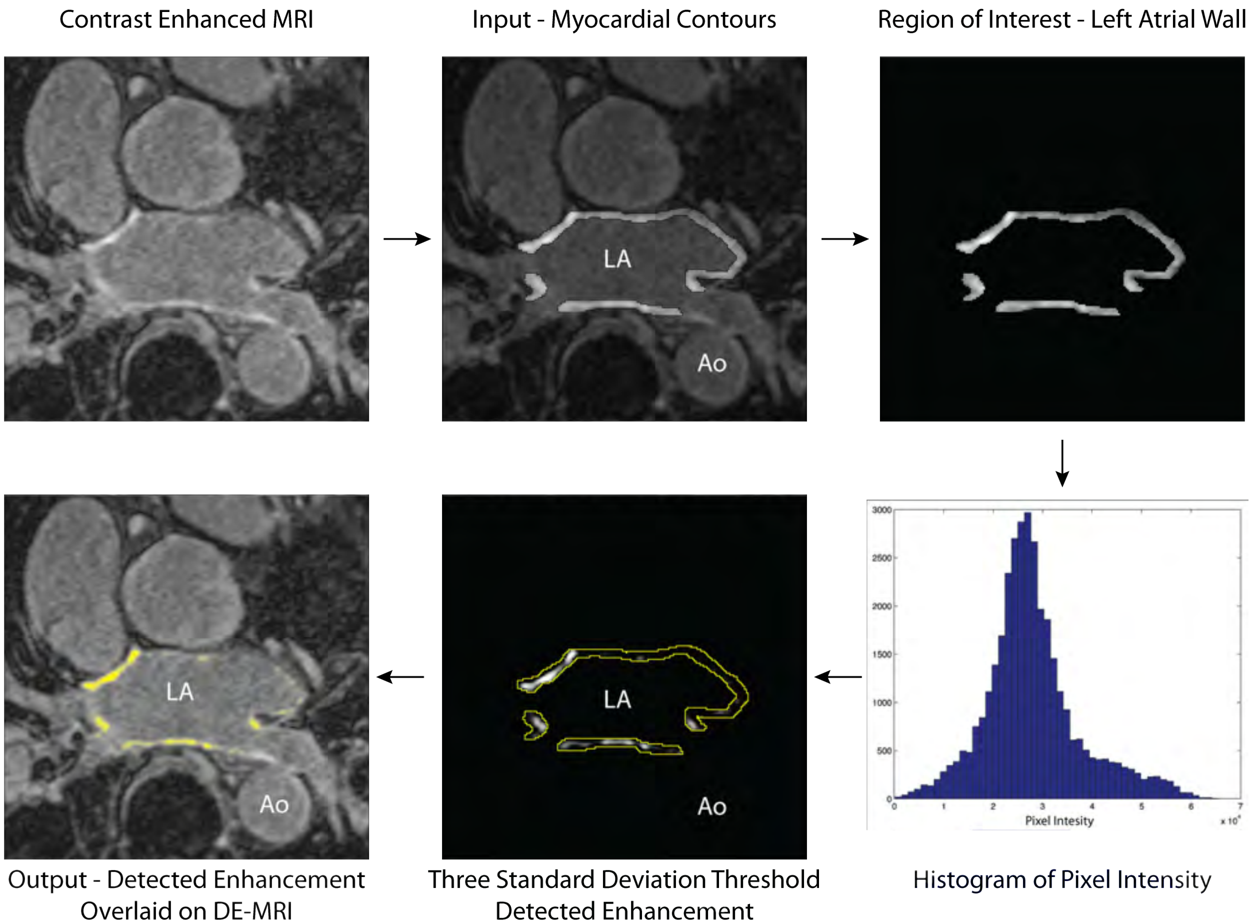

Figure 2: Algorithm for quantification of post-ablation scar burden in the LA. The wall of the LA in LGE-MRI scans (Top–L) is segmented on a slice by slice basis (Top-C). Once isolated (Top–R), a histogram of the LA wall pixel intensities is generated (Bottom–R), and the rising phase of the primary mode is used to predict normal tissue pixel intensities. Pixel intensities 3 standard deviations above the mean of normal tissue is marked as scar (Bottom–C). Overlays of pixels marked as scar onto original images shows good correlation with hyper-enhancement.

Evaluation of post-ablation scar formation The first reported use of LGE–MR imaging of atrial tissue to assess ablation lesions came from Peters *et al.*[67] In this prospective study contrast enhancement was found in the left atrium and pulmonary vein ostia of all patients who had previously undergone radio-frequency ablation of AF 1 to 3 months previously. These findings were supported by McGann *et al.*, who quantified the extent of enhancement observed in the left atria wall 3 months following ablation using the methods outlined in Figure 2 and compared extend of scar to procedural outcomes. In this study, patients who experienced a recurrence of AF were found to have less enhancement ($12.4 \pm 5.7\%$) as compared to those who did not recur ($19.3 \pm 6.7\%$, $p = 0.004$).[52] Subsequent studies have expanded on these initial findings to show that lesion remodeling stabilizes by 3 months post ablation, and that the extent and continuity of lesions encompassing the pulmonary veins play an important role in preventing recurrences.[2,68,70]

The ability to assess non-invasively the lesion sets created in AF ablation procedures can provide valuable feedback to electrophysiologists searching for the optimal ablation strategy. While freedom from AF after a single intervention will remain the goal for procedural success, LGE-MRI can help explain how and why a particular lesion set succeeds or fails at terminating AF and provide direction in subsequent ablation procedures.

Evaluation of AF substrate As previously noted, atrial fibrillation is associated with structural remodeling of the left atrium. Motivated by the success of LGE-MRI in identifying structural heart disease, and in particular fibrosis, Oakes *et al.*analyzed LGE-MRI scans form a cohort of 81 AF patients and 6 normal volunteers to explore the relationship between contrast enhancement and AF structural remodeling. This study revealed a positive correlation between low voltage tissue regions in electroanatomical maps (bipolar voltage amplitude $\leq$ 0.5 mV) and LA wall enhancement (r^2 = 0.61, P ¡ 0.05). Furthermore, patients with mild (¡15%, n = 43), moderate (15-35%, n = 30), and extensive (¿35%, n = 8) amounts of LA wall enhancement were found to have significantly different rates of AF recurrence at mean follow-up of 9.6 months (14%, 43%, and 75%, respectively). These findings suggest that the degree of LA wall enhancement, which is assumed to reflect extent of fibrosis in the atrial tissue, is a predictor of failure for ablation. Based in part on these results, a scoring system for determining the amount of enhancement has been proposed. Figure 3 shows what is known as the Utah scoring scheme with examples of LGE-MRI scans from each of the 4 stages. Under this scheme, patients with Utah stage 3 or stage 4 type enhancement are not considered to be ideal candidates for ablation therapy.

The utility of the Utah AF stage scheme is currently under extensive evaluation, both at our institution and through a multicenter clinical study involving major AF centers from around the world.

4 Real time MRI for ablation of atrial fibrillation

As outlined in Section 1, catheter based ablation of the left atrium represents the most common intervention to cure, or at least suppress symptoms of, AF. To carry out ablation requires considerable imaging support in order to identify anatomy, evaluate substrate, and determine success of the intervention. Conventional approaches to AF ablation make use of fluoroscopy, computed tomography, intracardiac ultrasound, and

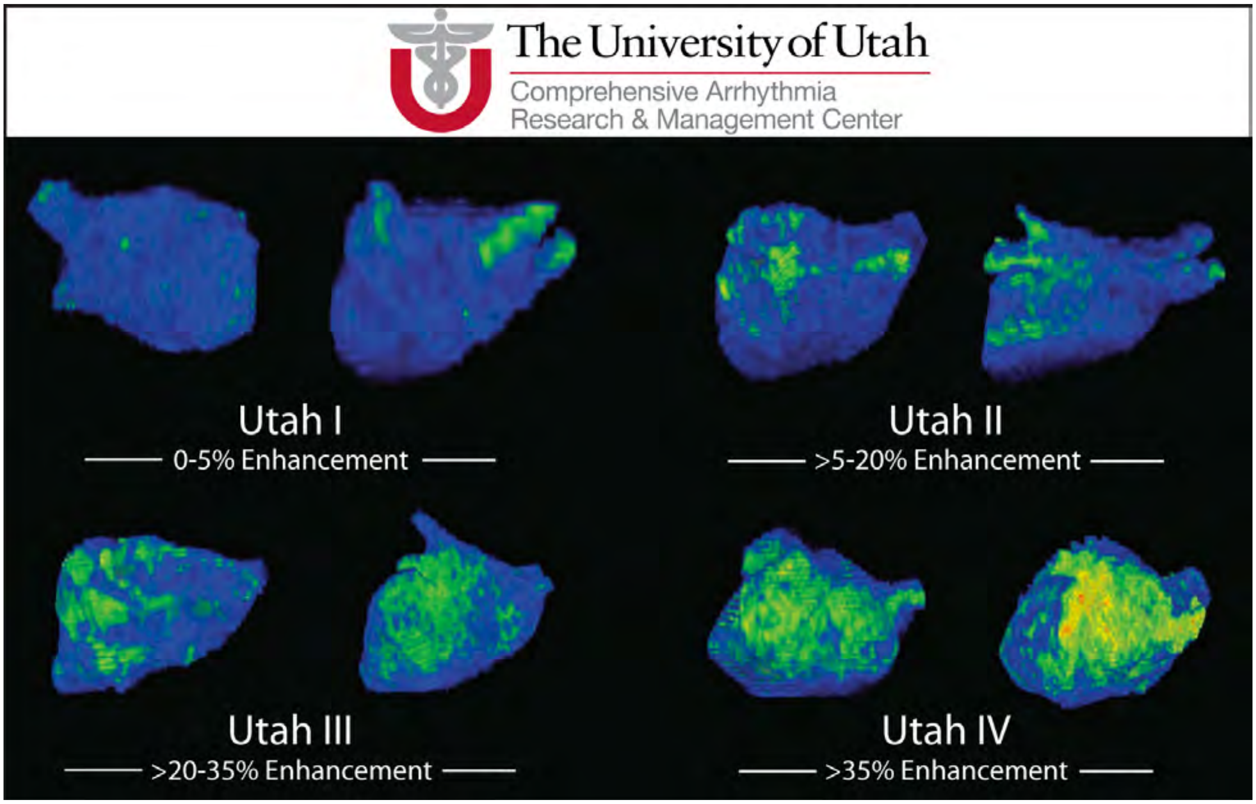

Figure 3: Utah scoring system for stratifying the amount of pre-ablation enhancement of the LA wall. Images in each of the four panels show examples of LGE-MRI images with enhanced regions color coded in green while normal tissues are in blue.

electroanatomical mapping. MRI is used not only as a pre-procedural method to generate anatomical images, but its broader use represents the leading edge of research into real time imaging modality to support the guidance of catheters and the evaluation of lesion formation in some three-dimensional form. The need to combine these two forms of anatomical and functional information continues to drive the development of novel merging and registration approaches.[19]

Catheter ablation of AF The past decades have seen significant progress in understanding the underlying mechanisms of AF that sustain its persistence[32, 92] and that knowledge has led to the treatment paradigm of AF ablation, the targeted destruction of tissue predominantly in the left atrium in order to isolate electrical triggers and reduce the ability of the atrium to sustain rapid activation. AF ablation, typically based on radio frequency (RF) energy delivery through a venous catheter, already has encouraging results and is the topic of innumerable research reports, but has yes to reach its full potential. Despite the fact that ablation, when successful, allows the patient to discontinue the use of antiarrhythmics anticoagulants, the success rate of ablation in maintaining regular sinus rhythm without the use of such medications still lies at only 60–80%.[10] Moreover, the penetration of ablation, while difficult to measure with accuracy, appears to lie well below the need, *i.e.,* there are fewer ablations carried out each year than there are new cases of AF. In an effort to increase the penetration of this potentially curative approach, there have been many modifications to the ablation procedure aimed at improving outcome and hence promoting the adoption of the ablation approach.[1,12,28,29,31,36,49,50,64] Despite such progress, there remain daunting technical challenges to carrying out successful ablation and many of these are related to imaging.

Currently AF ablation is performed using catheters that can be visualized under fluoroscopy and/or projected onto a three-dimensional virtual shell acquired through electroanatomical mapping during the procedure.[19] There are multiple challenges associated with these approaches. First, it is impossible for the operator to visualize the catheter tip/tissue interface; hence delivery of RF energy is based on guidance from the morphology of local electrogram or by using the virtual shell from electroanatomical mapping to assure that the catheter tip is in contact with the atrial wall. However, these approaches both have known errors that can exceed 1 cm,[25] leading to frequent delivery of inappropriate lesions that may only partially damage the atrial tissue, promoting tissue recovery and hence re-occurrence of the arrhythmia. Moreover, this lack of visualization of the catheter tip can result in localized heating of blood, thus leading to char formation, a major cause of embolic stroke during the ablation procedure.[90] Defining a technology or a system that would allow accurate visualization of the catheter tip/tissue interface would overcome this major problem for the operator. Another major challenge of the ablation procedure is the lack of an imaging modality that allows immediate assessment of tissue damage as the RF energy is applied. MRI is the most obvious and perhaps only imaging system that could overcome this problem.

While MRI has the inherent capability of visualizing soft tissue and thus providing both anatomical and functional guidance for RF ablation of AF, there are challenges to creating a viable MRI based approach. It is first necessary to develop an MRI compatible catheter and associated software that allows visualization of the catheter during navigation and energy delivery within the atrial chamber. This catheter and software must be part of a system that tightly integrates the diverse instrumentation required to complete a clinical atrial ablation procedure. The system must exploit the benefits of soft tissue contrast unique to MRI (*e.g.,* near real-time visualization of myocardial interfaces and ablation lesions) while providing a smooth workflow for the physician and technicians. Recent reports showing progress toward these ends by our and other groups[22,77,87] suggest that a full AF ablation procedure in humans, while still very challenging, is likely.

MRI compatible catheters The development of an MRI guided system for AF ablation is completely novel in terms of the devices and support systems that are required to create a working system. MRI compatible catheters have just begun to appear in the literature[3,22,39,77] but are still prototypes and have not been used in any human ablation studies. Similarly, the real time MRI guidance systems required to place the catheters in the appropriate locations are in their infancy with only sparse reports of just placing an MRI compatible catheter in the human heart under MRI guidance.[77] Most of the other elements of the contemporary AF ablation instruments—the lasso catheter, coronary sinus catheter, and the needle required to carry out transseptal punctures—are also only just under initial development and have yet to receive approval for use in humans.

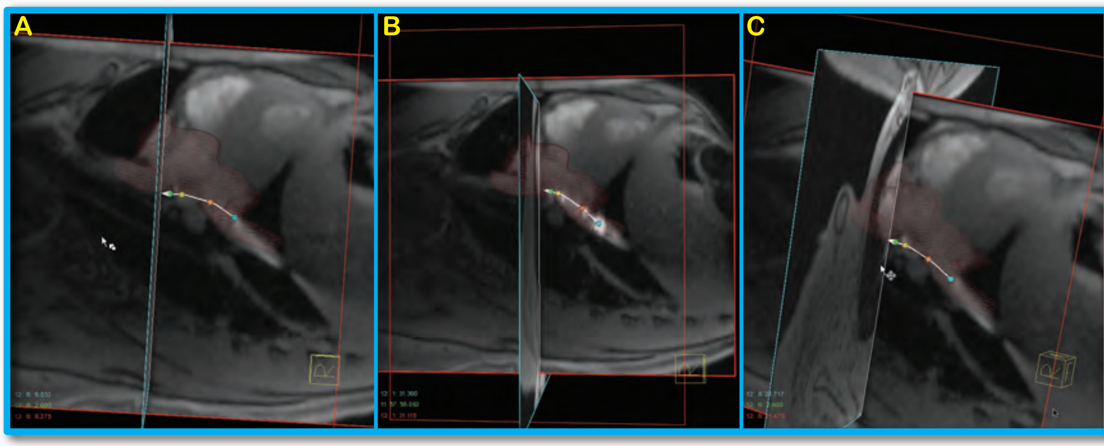

Figure 4: Visualization of catheter during real time MRI. Each panel shows a slightly different view of the MRI compatible catheter superimposed on the local MRI image together with a rendered mesh of the right atrium and superior and inferior vena cava from this animal.

We have participated in the development of catheters that are MRI compatible, steerable in a way similar to standard clinical catheters, and capable of both delivering RF energy and recording endocardial electrograms.[87] It is possible to track the location of the catheters and to display its position superimposed on the real time MRI images and with a geometric shell model of the atria and great vessels that we create from volumetric MRI scans recorded in the early phases of the procedure. Figure 4 shows an example of MRI images recorded during a real time ablation procedure in which the catheter is visible superimposed on the orthogonal MRI images. Also visible in the image is a polygonal surface or shell of the right atrium and inferior and superior vena cava, created by segmenting a previously acquired high resolution scan of the animal's atrial anatomy.

Visualization of imaging results

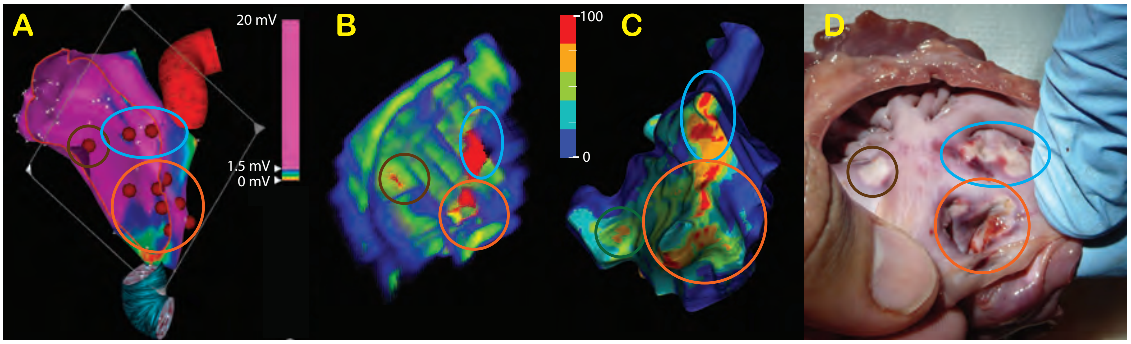

Figure 5: Multimodal visualization of ablation lesions from an experiment using MRI during and after lesion formation. The images show the results of electroanatomical mapping (Panel A), late gadolinium enhanced MRI (Panels B and C), and gross dissection of the right atrium from an animal experiment (Panel D).

Scientific visualization is an essential step in using imaging data and the unique and challenging needs of AF ablation continue to drive new approaches. For example, electroanatomical mapping requires the integration of spatial information describing the shape of the endocardial surface with time signals, electrograms recorded from that surface, and parameters extracted from them of. In addition, there is volumetric information from MRI and computed tomography, that can be visualized as s sequence of two-dimensional images but is much richer when rendered in some three-dimensional form. Naturally, there is a need to merge these two (and other) forms of anatomical and functional information and novel visualization technology continues to improve such merging in a setting of interactive manipulation and rendering.[19]

We have developed techniques that combine not only visualization of volume and surface based approaches but project the information from the volume to the surface. Figure 5 shows an example of such a visualization in which Panel A shows an electroanatomical maps from an animal experiment showing three clusters of lesions performed under fluoroscopy guidance—the red dots in Panel A show the lesion sites. The render in Panel B shows the late gadolinium enhanced (LGE) rendering of the same heart, performed in the MRI scanner directly after the ablation procedure. We then used segmentation of the volume images to define the endocardial surface and projected the information from the MRI scan onto that surface, shown in Panel C. Confirmation of the actual lesion locations is evident from dissection documented in Panel D.

The motivation of such projection approaches is to present information from multiple modalities—in this case electro anatomical mapping of electrogram amplitude and MRI tissue changes—into a common reference frame, in this case the endocardial surface. Such merging of information provides for quantitative analysis and comparisons and also a means of conveying information in a form that is familiar to the clinicians, in this case electrophysiologists who are highly conversant in the conventions of endocardial and epicardial mapping.

Real time detection of lesion formation The most significant advantage of MRI-guided ablation is its potential to obtain rapid feedback on tissue changes during the ablation procedure—to watch the lesions form. There is no viable modality at this time that can determine the effectiveness of ablation; even electrical mapping approaches only measure depressed electrical activity in the endocardium that may return within weeks of the ablation and cause a recurrence of AF. MRI, on the other hand, has the potential to visualize changes in tissue structure related to permanent cell damage following the application of energy and thus establish the presence and depth in the atrial wall of terminally destructive lesions. Visualization of lesion formation and extent would improve the effectiveness and the safety of RF-ablation procedures.

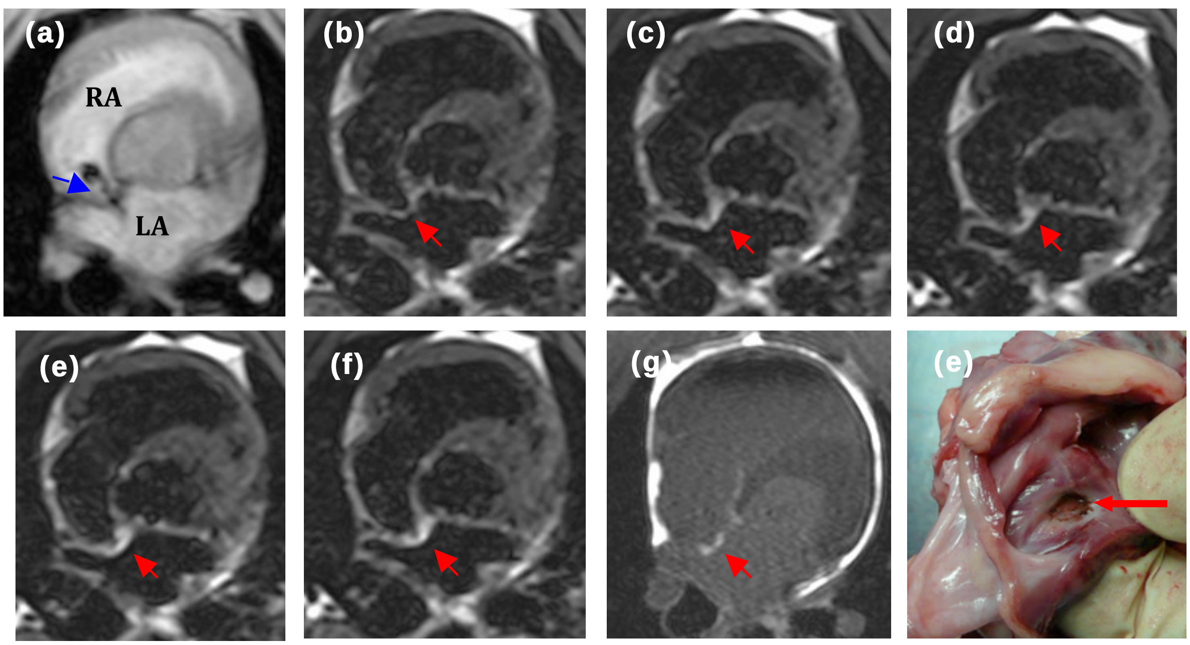

Figure 6: Detection of acute atrial lesion. (a): Image from 3D scan to locate the catheter tip. (b-f): T2-weighted dark blood images acquired pre-ablation (b), post-ablation: 20-second (c), 50-second (d), 2.5-minute (e), 8-minute (f). (g): post-mortem, high-resolution, delayed enhancement MRI. (h) photo of excised heart. Blue arrow indicates the position of the catheter tip at septal wall. Red arrow indicates the location where the lesion was created using a 30-second ablation with 30 Watts. RA right atrium, LA left atrium.

To visualize lesion formation with MRI requires acquisition of high quality images in rapid sequence in order to achieve adequate spatial and temporal resolution. As with all imaging modalities, there is a trade-off in MRI between the time needed to acquire the image and the quality of that image. Real time imaging of the heart is furthermore driven both by the need to capture information rapidly enough to avoid blurring due to cardiac and respiratory motion and the desire to optimize image quality to see small changes within structures that are only a few millimeters thick. Another challenge specific to ablation is the need to see changes quickly enough to allow the operator to control the time and the energy dose in order to create lesions that are deep enough, but not so deep as to degrade the structural integrity of the heart wall.

In animal studies within our group, we have achieved image refresh rates of up to 5.5 frames/sec based on customized MRI scan sequences and been able to visualize lesion formation within 10–15 s of onset of RF energy.[87,89] Figure Figure 6) shows just one example of such a case, in which catheter placement is documented in Panel (a), followed by a sequence of images (using a different MRI scan sequence) that reveal the formation of the lesion in Panels (b)–(f). Panel (g) shows a post mortem image in the same plane and Panel (g) contains a photographic record of the lesion seen immediately post-experiment. To our knowledge, this is the first report of visualizing lesion formation as it occurs in any tissues of the heart. We have also compared lesion sizes measured from MRI imaging with those determined through post mortem dissection and shown excellent agreement.[87]

5 Summary

Imaging has always been an essential component of the management of all forms of cardiac arrhythmias and its use will continue to expand in pace with improvements in the imaging acquisition technology, the image processing and analysis, and the integrating software that can efficiently support the clinical workflow. In the setting of atrial fibrillation, the use of MRI is making particular advances as its utility in all phases of the disease becomes evident. Preablation imaging provides a means to stage patients and determine their best treatment options; the emergence of the Utah AF scoring system suggests a very specific means by which image analysis and quantification can indicate disease status and risk. Similar techniques provide a means of noninvasively determining the outcome of AF ablation by mapping the formation of scar to both evaluate interventional success and to guide subsequent interventions, should they be necessary. The CARMA Center has carried out over 600 scans on over 250 patients to date and are now collaborating with similar laboratories around the world in multicenter trials of these MRI based approaches. The results of these studies could completely transform the way that AF is treated when it arises and even enable how preventative measures that are simply impossible without a means of tracking the tissue changes that preface the onset of electrical symptoms

The potential for imaging and especially MRI in the treatment of patients with AF is equally exciting and bright. We have now carried out over 30 animals studies to date in developing the prototype MRI guided navigation system and are focused on developing and testing such system for use in humans. We have created lesions both under fluoroscopy and real time MRI guidance in the atria and ventricles of anesthetized dogs and swine, then carried out detailed imaging both of the entire animal thorax and of the excised, preserved heart. In the process, we have made advances in MRI compatible catheter design, exploitation of novel sensing coils, incorporation of tracking coils into catheter housings, improvement in pulse sequence design for rapid acquisition, integrated, interactive display of images and devices, and image processing and analysis tools for post-procedure evaluation of results. Other groups have made similar progress and there is little doubt that the first human studies

A major initial goal of these studies was to ensure that it is indeed possible to visualize lesions soon after ablation, despite the thin atrial walls and small extent of RF lesions. Figure 6 shows an example of such a result in which we sampled from the same slice before, during, and repeatedly after application of the RF energy.[89]

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