ATRIAL FIBRILLATION

REVIEW ARTICLE

Advances in Imaging to Assist Atrial Fibrillation Ablation

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ABSTRACT. Catheter ablation procedures to treat atrial fibrillation require sophisticated imaging for guidance. These imaging techniques have evolved from basic two-dimensional to complex three-dimensional methods that may involve fusion of data from different modalities such as computed tomography, magnetic resonance imaging, fluoroscopy, echocardiography and electroanatomical mapping. Summation of errors inherent with each individual tool can be a problem and new methods are under development. A quest for more user-friendly and highly accurate imaging tools continues.

KEYWORDS. Cardiac Imaging, Atrial Fibrillation, Catheter Ablation, Transesophageal Echocardiography, Intracardiac Imaging Techniques, Computed X Ray Tomography, Magnetic Resonance Imaging, Imaging, Three-Dimensional, Image Reconstruction, Left atrium, Pulmonary vein, Electrophysiology.

Introduction

Catheter ablation procedure for atrial fibrillation (AF) is becoming the mainstay of therapy for several forms of this arrhythmia and, consequently, more widely available. Technique of pulmonary vein (PV) focal ablation described initially has undergone multiple modifications and in its current form has become virtually impossible without the assistance of complex imaging. Multiple imaging methods have been utilized to guide AF ablation. Their development has led to the appearance of fairly complex and expensive technology that frequently involves a combination of several imaging modalities. As a result of this growth, several trends can be observed. One trend is the spread of AF catheter ablation procedures from academic to community hospitals. This ubiquity has brought about a parallel need for more standardized and simplified procedural approaches as healthcare institutions economize the expense and inefficiency of standalone imaging methods. In this review, we will focus on the development of modern imaging technologies to guide AF ablation and compare them in order to provide a comprehensive approach to the “choice of arms”.

Imaging modalities to assist atrial fibrillation ablation

Fluoroscopy

Historically, fluoroscopy has been the primary imaging modality to facilitate electrophysiological procedures. When combined with sophisticated mapping catheters, fluoroscopy alone can provide a imaging guide for AF ablation. The main advantages of this modality are availability, simplicity of use, low cost, and technical familiarity for all operators. However, the complexity of left atrial anatomy, frequent anomalies, and the presence of intricate arrhythmia mechanisms led most electrophysiologists to embrace some form of three-dimensional (3D) imaging for their ablation protocols. Additionally, due to its inherent radiation risk, there is a trend to limit fluoroscopy use. Recently, the feasibility of “fluoroless” AF ablation has been described.
Cardiac computed tomography and magnetic resonance imaging

Three-dimensional reconstruction of cardiac structures from cardiac computed tomography (CT) revolutionized understanding of left atrial anatomy and greatly facilitated the development of AF ablation (Figure 1). Detailed characterization of anatomic variants included a description of commonly observed two right and two left-sided PVs, their size and shape, and less often encountered variants, e.g., accessory right sided PVs, single right ostium PV and single left ostium PV. Sizing and location information provided by 3D imaging may become even more important with the advent of complex ablation tools such as cryoballoons. “One size does not fit all” and therefore pre-procedural determination of the tool size becomes more critical. The anatomical interrelationship of extra-cardiac structures (esophagus, phrenic nerve, etc.) to the left atrium (LA) and PVs is important in view of their vulnerability to ablative injury. Through CT, we have learned about different esophageal locations (common and uncommon), and their proximity to the LA.

Similarly, cardiac magnetic resonance imaging (MRI) can provide detailed information about variations of LA and PV anatomy. Interesting findings have come from detailed characterization of LA fibrosis by delayed enhanced imaging. Recently proposed Utah staging that attempts to categorize the extent of fibrosis seems to correlate with epidemiological variables and AF ablation outcomes (Figure 2). Delayed-enhancement MRI can show incomplete circumferential scar lesions after AF ablation and may be used to target those breaks during

Figure 1: (a) Cardiac computed tomography (CT); (b) segmental cuts; (c) cardiac CT three-dimensional rendered; (d) segmented left atrium and esophagus as seen in angulated posterior views. Green arrows point to measurements of pulmonary vein diameters. The esophagus is shown in brown.
Additionally, the same group has demonstrated that MRI can be used to guide catheter navigation while directly visualizing ablation lesions during RF (radiofrequency) energy delivery. However, at approximately 20% of Carto-tagged ablation sites there was no visible corresponding scar by delayed enhancement as shown by another prominent imaging group.

Respiratory changes in PV and LA location are important and may affect the ablation approach. Fortunately, relative motion of PV centers is fairly small (2.6 ± 1.4 mm) when compared with more distal PVs and the mitral annulus; this knowledge is important when selecting the appropriate tool for merging radiographic images into a 3D replica of the LA. Finally, overlay of a 3D shell of the LA on live fluoroscopy has been introduced as one of the first merge techniques to provide detailed anatomical views intraprocedurally. Close correspondence (1.3 ± 0.6 mm) of these reconstructed and registered LA images with actual anatomy confirmed by catheter mapping has been reported. Respiratory motion of the LA and PVs remains important for registration of a 3D shell on live fluoroscopy. Several current versions of imaging software incorporate some form of compensation for respiratory motion.

The disadvantages of CT and MRI include the need for expensive scanners and usually coordination between two different departments. As a consequence, CT/MRI is typically performed several days before the ablation procedure and may reflect a different volume/anatomical status. Additionally, surrounding organs depicted by CT such as the esophagus may be in a different position and their CT representation may not be accurate. Also, radiation exposure from a CT scan is not negligible despite recent advances in dose reduction techniques, particularly when combined with the subsequent fluoroscopy dose from AF ablation. Patient safety is yet another consideration with contrast associated with cardiac CT.

MRI obviates the risks of radiation exposure, especially benefiting younger patients and those who undergo multiple imaging procedures. However, MRI-guided electrophysiology (EP) procedures are currently cost prohibitive, require expertise, and the technology that may not be widely available, particularly in community hospitals. Several contraindications to MRI exist. Implantable cardiac devices prohibit its use, although this may gradually have less impact with the advent of MRI-safe technologies. MRI should also be avoided in patients with impaired kidney function (possibility of nephrogenic systemic fibrosis) and claustrophobia.

**Rotation angiography**

Rotational angiography with 3D reconstruction is a recently introduced imaging modality that allows acquisition of volume images of cardiac chambers (or blood vessels) by rotating the X-ray C-arm around the area of interest while injecting contrast (Figure 3). It was successfully applied to LA imaging and was named 3D atrigraphy (3DATG). More recently, other chambers of the heart have been imaged with similar techniques. Left atrial and detailed PV anatomy can be visualized in a vast majority of patients by using a variety of injection protocols. Additionally, the esophagus can be simultaneously visualized by administration of oral contrast. Resultant 3D images are comparable in quality to CT with significantly smaller radiation exposure and can be successfully used to guide AF ablation procedures as a single modality or in combination with electroanatomical mapping (EAM). A randomized comparison of 3DATG and CARTO-guided AF ablation procedures did not demonstrate excessive fluoroscopy dose or inferior ablation success with 3DATG. The recently introduced EP Navigator (Philips Healthcare, Best, The Netherlands) allows one to overlay the 3D image of the chamber of interest on live fluoroscopy and register it using anatomic landmarks or catheter placement. Registered LA volume then becomes an integral part of
Figure 3: (a) The 3DRA Rotational Angiogram with 3D reconstruction and corresponding computed tomography (CT) image in the same patient. (a) Reconstructed 3DRA image; (b) still-frame image from a rotational angiogram; (c) CT reconstruction. Note a close concordance between a more realistic 3DRA and a CT image; fine detail and branching of pulmonary veins (PVs) (LUPV: left upper PV; LLPV: left lower PV) are easily seen on 3DRA, and esophageal (e) position is very similar between both methods.25 (b) Three-dimensional reconstruction of the left atrium and pulmonary veins in the same patient. (a) Rotational angiography during adenosine-induced asystole. (b) Automatic segmentation of the left atrium and pulmonary veins. (c) Three-dimensional reconstruction of left atrium and pulmonary veins. (d) Computed tomographic imaging of left atrium and pulmonary veins. LAA: left atrial appendage; LSPV: left superior pulmonary vein; RIPV: right inferior pulmonary vein; RSPV: right superior pulmonary vein.27
the fluoroscopy screen, thereby providing a sole guide for the ablation procedure (Figure 4). Alternatively, 3DATG can be imported into the CARTO system or NavX (Figure 5) and provide real-time anatomical information to supplement EAM.28

Advantages of 3DATG include simplicity and familiarity with angiography for most operators, real-time anatomical information of CT-like quality with less cost and radiation exposure. These anatomical images can be used to guide the ablation procedure as a single tool or be easily integrated into the existing EAM. Imaging is performed in the laboratory and therefore reflects the volume status and position of surrounding structures (esophagus) more reliably than remote CT.25 The disadvantages are the need for contrast and some radiation exposure as well as a learning curve for the staff (unlike CARTO and NavX, no technical support during the procedure is currently offered by the imaging companies producing the equipment).

Transesophageal echocardiography/3D transesophageal echocardiography

Transesophageal echocardiography (TEE) is an important pre- and intraprocedural imaging tool for AF ablation. It is the method of choice to rule out the presence of LA appendage thrombus. It provides accurate anatomic information about the LA and PVs. Transesophageal echocardiography may be used to guide the transseptal puncture and ablation catheter navigation since it has been proven to be helpful in directly imaging the fossa ovalis, especially in subverted cardiac anatomies.32 Advantages of TEE include its wide availability, familiarity with the technique for most institutions, and absence of radiation exposure. However, use of 2D TEE alone to guide AF ablation may be impractical for a number of reasons. Three-dimensional TEE was recently introduced and has been mainly used to guide interventional valvular procedures (Figure 6).33 While it may be applicable to better evaluate 3D LA anatomy and possibly guide AF ablation procedure when merged with EAM, feasibility of this approach in humans remains to be evaluated.34

Intracardiac echocardiography/3D intracardiac echocardiography

Intracardiac echocardiography (ICE) is routinely used in many EP laboratories for intraprocedural imaging.35 Transseptal puncture can be made easier by ultrasound visualization of the fossa ovalis, especially during needle and sheath passage, an important consideration in difficult

Figure 4: Three-dimensional angiography of the left atrium (LA) with ablation point tagging. Endoview of the LA is shown. Also seen are CS coronary sinus catheter and transseptal sheath with Lasso catheter.
cases such as in patients with ASD (Atrial Septal Defect) repair where a synthetic patch may present an otherwise insurmountable obstacle. Intracardiac echocardiography provides excellent anatomical detail of the interatrial septum, PV antra, ridges, and other important parts of the LA, allowing one to fine tune the ablation catheter position in order to achieve antral PV isolation or target carinal areas (Figure 6). By providing the location of vital surrounding structures and their relationship to the LA, ICE may be used to avoid catastrophic complications such as atrioesophageal fistula. ICE has been also used to detect pericardial effusion, thrombus formation, and to titrate the RF energy delivery to avoid microbubble appearance or char formation. ICE technology is improving at a phenomenal pace. Innovations include better transducers with higher resolution and frequency agility (computer micromachined transducers: cMUTs), ultrasound probes incorporating a port for a radiofrequency wire allowing simultaneous visualization and ablation, percutaneous intrapercardial echocardiography, and 4D ICE with gated reconstruction of cardiac motion. Further advancements include ICE image integration with EAM, which will be discussed in a later section. The main advantages of ICE are no need for anesthesia and full control over imaging by an electrophysiologist. The challenges are a significant cost of a single use ICE probe and inability to obtain high-quality imaging in all patients.

Electroanatomical mapping

Electroanatomical methods have quickly gained momentum in the area of AF ablation. CARTO System, Biosense Webster, Diamond Bar, CA, USA and NavX (St Jude Medical, St. Paul, MN, USA) are two dominant modalities that provide similar electrogram and location data. Recently, a new non-fluoroscopic GPS-guided method—Mediguide (St. Jude Medical, St.Paul, MN, USA)—has been described. Electroanatomical mapping (EAM) provides activation data important in localization of macro-re-entrant and focal arrhythmias, local voltage information confirming successful ablation, and allowing characterization of its impact on overall LA function. Both encircling and linear lesions are easily assisted by EAM (Figure 7). The accuracy of electroanatomic 3D shells of the LA and the relationship to the esophagus was compared with CT data and was shown to be adequate for most locations. However, some discrepancies between the true and assumed anatomy (based on electromagnetic field measurements) exist and should be considered, particularly for robotic applications where the potential for cardiac perforation due to inaccurate location of the chamber wall may be higher because of the absence of tactile contact pressure information. The accuracy of EAM data confirming completeness of PV isolation (PVI) was compared with standard Lasso techniques and was found to be adequate. This may require a very detailed EAM and validation in larger studies before the well-established Lasso technique can be abandoned. EAM allows visualization of the ablation and Lasso catheter in real-time and thus the ablation procedure can be guided and lesion progress more easily tracked. Use of these methods clearly reduces fluoroscopy exposure to the staff and the patient; completely fluorless ablation of AF using EAM as part of the imaging strategy was recently described.

The main advantages of EAM include their fluorless nature, the ability to visualize and track multiple catheters near real-time and the ability to combine anatomical and electrical information in a single 3D map. Disadvantages include the lack of real-time anatomic feedback, possible distortion of anatomy during the procedure due to electrical impedance changes, or alterations in reference catheter or patch position. Point-by-point mapping required by some EAMs may distort the true anatomy because of catheter pressure or absence of catheter contact. Additionally, EAM requires specialized catheters or patches with associated extra costs and are dependent on specially trained staff/industry support in many institutions.
Merge technologies

CT/cardiac MRI/3DATG fluoroscopy merge

The idea of overlaying a 3D anatomical shell of the heart chamber on live fluoroscopy and “attaching” it to radiographic landmarks (registration) is attractive and has been realized relatively early on in AF ablation experience. Both CT, MRI and 3DATG data can be segmented and registered to a live X-ray screen. Early experience confirmed high accuracy of catheter navigation within properly registered images. Subsequent development of commercially available software (EP Navigator-Philips Healthcare, Best, The Netherlands,

Figure 6: (a,b) Three-dimensional transesophageal echocardiography (3DTEE) and (c) intracardiac echocardiography image of the real-time 3DTEE during transseptal puncture and respective explicatory diagram showing angle (a) between the fossa ovalis and transseptal needle. (c) Top image: circular mapping catheter positioned at the ostium of the left upper pulmonary vein (LUPV). LAA indicates left atrial appendage. Bottom image: Right upper and right lower pulmonary veins (RUPV and RLPV) are visible. The circular mapping catheter (Lasso catheter) is placed in the RUPV.
DynaCT Cardiac-DynaCT (Siemens, Forchheim, Germany) and its clinical application confirmed that registration error is typically 1–2 mm (Figure 8). One has to realize that overlay accuracy will not be absolutely perfect given physiologic heart and lung movements. Different registration methods based on superimposition of clearly identifiable anatomical landmarks (such as thoracic spine, right heart border) have been described. The easiest and most accurate method seems to be the superimposition of the reconstructed and the radiographic bronchial carina. A randomized comparison with EAM demonstrated similar radiation exposure when using CT overlay on live fluoroscopy as the only imaging guide and a shorter procedural time. This is explainable by availability of pre-acquired CT reconstructed anatomy and no need for additional time-consuming EAM. Similar data were obtained when comparing 3DATG versus CARTO as a single imaging guide.

Overlay methods allow the operator to perform catheter navigation within the 3D anatomical shell without the need for a specialized non-fluoroscopic mapping system. Endocardial views may be helpful to define PV antral positions or ridges. Difficult or atypical PV anatomy can be easier understood, thus allowing it to be reached with a catheter. Additionally, ablation point tagging helps keeping track of the ablation process, essentially positioning overlay systems as a standalone imaging modality for those EP procedures that do not require sophisticated electrogram mapping (Figure 4). These overlay tools are relatively inexpensive as they do not require specialized mapping catheters or patches. Disadvantages of purely X-ray-based methods include radiation exposure that may not be negligible with non-gated CT. 3DATG is associated with considerably less exposure and has been successfully used as a sole imaging tool to guide AF ablation. Another disadvantage of CT or MRI-based system is the lag between the actual imaging and the procedure day, as mentioned previously.

CT, MRI, or 3DATG with electroanatomical mapping

Fusion of 3D anatomical data with EAM was the next logical step in imaging development. It can theoretically...
correct anatomical imperfections of EAM methods while providing almost real-time non-fluoroscopic intraprocedural navigation guidance. Early publications praised feasibility and high accuracy of CT/MR and EAM fusion.\textsuperscript{51–55} Minimal discrepancy (about 2 mm) between the CT shell and mapping points was reported both in animals model in humans.\textsuperscript{51,54} The largest discrepancy was reported for the right ventricle image integration. This may be explained by the highly trabeculated nature of this chamber.\textsuperscript{51} Anatomical images taken at end-expiration were noted to integrate better with EAM, indicative of respiratory variability and the need to better synchronize different imaging modalities. The inability to maintain a long breath-hold may decrease accuracy of fused images for some patients. Good correlation between left atrium size determined by EAM and CT/MR was reported.\textsuperscript{52} However, the same authors have noted a greater integration error in patients with larger LA volumes, raising concerns about registration accuracy with fusion methods and leading some groups to declare that merge techniques do not improve procedural safety/efficacy.\textsuperscript{53} A later study comparing Carto-Merge versus Carto-XP has also reported a similarly modest long-term success rate of ablation guided by either method both in patients with paroxysmal (54% sinus rhythm maintenance at 12 months) and persistent AF (43% sinus rhythm maintenance).\textsuperscript{56} Reduced radiation exposure was noted with Carto-Merge. The Italian Carto-Merge registry reported improved long-term outcome after AF ablation guided by image integration versus Carto and Lasso catheter.\textsuperscript{57} However, the shortest procedural times were noted with the simple Lasso-guided approach. Other authors have attempted to improve image registration accuracy by adding ICE to the equation.\textsuperscript{58–60} ICE-guided image integration further reduced radiation exposure compared with MRI, but has again called into question registration methods.\textsuperscript{60} A higher precision of registration was reported when only posterior LA wall points were used for image fusion.\textsuperscript{58,60} Thus, attempts to improve registration accuracy have utilized additional imaging methods, with a potential for error multiplication when several modalities are fused into a combined image. Feasibility of combining intra-procedural 3DATG reconstruction of LA and PV with Carto was also reported.\textsuperscript{28} We have recently started fusing 3DATG with EnSite Velocity\textsuperscript{TM} Cardiac Mapping System (St. Jude Medical, Minneapolis, MN) obtaining a combined, truly electroanatomical map of the chamber of interest (Figure 5). The same potential advantages of 3DATG versus CT or MRI discussed above will probably apply when used in combination with EAM.

A different approach would entail the use of ICE to improve spatial detail and image integration (CartoSound, BiosenseWebster, Diamond Bar, CA) (Figure 9). While this method could potentially provide higher accuracy in mapping, it certainly may add another dimension in complexity to the fusion process.\textsuperscript{62,63} 

**Future directions in imaging for atrial fibrillation ablation**

Current ablation technologies continue to evolve rapidly. This progress is primarily driven by imperfect outcomes with existing methods, long procedural times, and higher than desired complication rates. Some of the new directions include endoscopic laser balloon ablation, MRI, and real-time-ultrasound lesion characterization.

Laser balloon ablation is a recently described technique. The compliant balloon catheter incorporates an optical fiber that generates 30° arcs of light projected onto regions of balloon and PV contact; this allows direct visualization of lesion formation. Laser energy (980 nm) is then delivered through the same optical fiber to ablate the target tissue in an overlapping manner to achieve circumferential ablation (Figure 10). In animal models, successful isolation was confirmed in 83–90% of targeted PVs after more than 1 month.\textsuperscript{64,65} In humans 65–83% of patients were free of AF more than 1 month after ablation, and about 60% at long-term follow-up.\textsuperscript{65–68} Possible complications with this new technique are similar to radiofrequency catheter ablation, and include right phrenic nerve injury, pericardial effusion, thrombus formation, and esophageal damage.

Another new technology that may increase the success rate with PVI is contact force assessment during catheter ablation. The EFFICAS I trial proved that higher contact force exerted by the ablation catheter results in fewer late

![Figure 9: Demonstration of CartoSound left atrium model interpolation, using SoundStar contours from all transducer locations combined (posterior-anterior view; appendage and pulmonary veins removed for clarity): Top: SoundStar contours; middle: interpolated model grown around SoundStar contours; bottom: interpolated model alone.\textsuperscript{62}](image-url)
gap occurrences after PVI. Following the same principle, the contact force time integral can be represented on a patient specific MRI shell after the procedure and potentially predict likely sites of PV reconnection secondary to inadequate lesion formation. MRI is an emerging useful technique for lesion characterization. Using real-time MRI in a swine model, gaps in lesion sets were identified that could be ablated acutely, leading to improved outcomes. In a similar setting, post-ablation-delayed and T2 enhancement MRI was able to predict arrhythmia recurrence in 15 patients with paroxysmal AF.

Ablation lesion formation and lesion characterization can be achieved in vivo by incorporating the ultrasound transducer into the ablation catheter. Early results are promising, allowing one to differentiate transmural necrosis from hemorrhage. There was a better correlation between ultrasound lesion characteristics and the degree of necrosis when compared to changes in local electrogram amplitude (Figure 11). Another new direction involves a novel computational imaging method to detect localized electrical rotors or repetitive focal impulses. This approach utilizes Hilbert transform analysis on signals obtained from a 64-pole
Application of this method in EP is under investigation.

Another tool that imparts less radiation to the patient.

A miniaturized sensor and projects its precise position in real-time.

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References


Conclusions

Complex EP procedures of today may frequently turn even more complex without sophisticated imaging. These guiding modalities have evolved from basic 2D concepts to advanced 3D techniques that often involve fusion of several datasets and overlay of real-time information. The complexity of some of these methods can be overwhelming for the operator and may require the participation of specialized support staff. Accuracy of navigation is often compromised by a summation of errors inherent with each individual technique. A quest for more user-friendly and highly accurate imaging tools continues and will hopefully result in the return of the “Golden Fleece”.

References


Figure 12: Rotor in Human Atrial Fibrillation http://www.hrsonline.org/Session/ScientificProgram/upload/CONFIRM_trial_LBCT.pdf. Shown in different colors is a rotor in a human left atrium during AF according to Dr. S. Narayan et al.


