Multimodality imaging for patient evaluation and guidance of catheter ablation for atrial fibrillation – Current status and future perspective


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A B S T R A C T
Left atrial catheter ablation is an established non-pharmacological therapy for the treatment of atrial fibrillation. The importance of a noninvasive multimodality imaging approach is emphasized by the current guidelines for the various phases of the ablation work-up e.g. patient identification, therapy guidance and procedural evaluation. Advances in the capabilities of imaging modalities and the increasing cost of healthcare warrant a review of the multimodality approach. This review discusses the application of cardiac imaging for pulmonary vein and left atrial ablation divided into stages: pre-procedural stage (assessment of left atrial dimensions, left atrial appendage thrombus and pulmonary vein anatomy), peri-procedural stage (integration of anatomical and electrical information) and post-procedural stage (evaluation of efficacy by assessment of tissue properties). Each section is dedicated to one of the subtopics of a stage, allowing a thorough comparison to be made between the strengths and weaknesses of the different imaging modalities and the identification of one that exhibits the potential for a single technique approach.

1. Background
During the last decade, left atrium (LA) catheter ablation has emerged as an established non-pharmacological treatment of atrial fibrillation (AF) [1–3]. Cardiac imaging plays a key role in patient selection and prediction of safety and efficacy for these LA ablation procedures (Fig. 1) [3–6].

The current guidelines advocate for an elaborate imaging approach and warrant a multimodality strategy [2,3,5,6]. In daily practice four different key, non-invasive modalities including transthoracic echocardiography (TTE), trans-oesophageal echocardiography (TEE), computed tomography (CT) and cardiac magnetic resonance (CMR) are combined for the assessment of underlying structural heart disease, exclusion of thrombus, identification of pulmonary vein (PV) anatomy and PV dimensions, and quantification of atrial function and dimensions [2,4].

Recent technological developments allow for non-invasive therapy stratification using pre-procedural atrial wall tissue characterization maps [7]. The extent of fibrosis, a surrogate for the progression of disease, has been successfully utilized to predict procedural outcome defined as post-ablative recurrence of AF [7,8]. Furthermore, evaluating the circumferentiality of the induced PV antrum ablation lesions might also be valuable for subsequent procedures [9].

On-site integration of electroanatomic maps (EAM) with CT or CMR derived images can assist LA ablation procedures [4,5,10,11]. Peri-procedural use of previously acquired images contributes towards improving therapeutic success [12,13] and reducing radiation exposure [14].

In this overview, the advantages and limitations of the different cardiac imaging modalities facilitating LA ablation for AF will be examined on their merits. Although there are other modalities currently being used (e.g. intracardiac echocardiography, rotational angiography) the scope of the review is limited to the four key modalities. The objectives are to explore the potential overlap and redundancy of these techniques and to show the added clinical value of a more uniform (single modality) imaging.

2. Pre-procedural imaging
2.1. LA structural remodeling – LA dimensions
LA dimensions are strongly related to adverse cardiovascular events and clinical outcome in the general patient population [15,16]. Furthermore, maintenance of sinus rhythm after ablation for AF is associated with a reduction of LA size [17], and in return the LA volume is correlated to procedural success [18,19]. Therefore, accurate knowledge of these
parameters is mandatory in order to correctly ascertain patient eligibility for ablation. Assessment of these parameters can be performed with various techniques including echocardiography, CMR and CT.

Despite its higher temporal resolution, TTE regularly underestimates the LA dimensions by 15–30 ml as a consequence of reduced image quality [20,21]. This modality also has a twice as high inter-observer variability (8.7 ± 24%) when compared to CMR (3 ± 10%) or CT (1 ± 11%) [20,21]. When measured with TEE, further underestimation of these parameters occurs by up to 10% [22,23]. This is caused due to incomplete visualization of the LA in the scan sector owing to its close proximity to the structure. Therefore, echocardiographic stratification may exert unjustified expectations on the ablation result.

CMR and CT show a good correlation for LA dimensions, with a correlation coefficient between 0.85 and 0.97 [20,21,24]. CT makes a small yet significant overestimation of LA maximal volume when compared to CMR (4.9 ± 10.4 ml) [20,24]. This difference is augmented in examinations performed during AF [21].

Despite a lower spatial resolution than CT and a lower temporal resolution compared to echocardiography, CMR seems to be the most ideal modality for the assessment of LA dimensions.
2.2. LA structural remodeling — LA geometry

Changes in dimensions cause alteration of the geometry. These geometrical changes have been indicated as an independent predictor of AF recurrence post-ablation and can also be used for patient selection [25,26]. Results indicate that LA roof shapes can be considered a marker of atrial remodeling with flat and coved roof shape related to higher incidence of non-PV foci AF and AF inducibility after the ablative procedure [25]. LA sphericity, a new method for LA geometrical analysis, has recently been identified as a strong predictor of AF recurrence [26].

2.3. LA structural remodeling — LA fibrosis

Detection and quantification of fibrosis in the atrial wall prior to ablation as a part of patient stratification is a controversial topic. Oakes et al. used a well-documented approach to acquire 3D late gadolinium enhancement (LGE). These images were analyzed with the aim of utilizing the amount of fibrotic tissue to predict procedural outcome [7]. In another study they describe tailored patient management based upon the pre-ablation LGE patterns (Fig. 2) [27]. Despite various attempts, other centers were so far unable to reproduce these results [28,29].

The recently published multicenter DECAAF trial [30], aimed to validate patient stratification based on the extent of atrial fibrosis, provided new insight on this topic. In total 329 patients, undergoing their first catheter ablation for paroxysmal or persistent AF, were enrolled amongst the 15 participating centers. The results demonstrated the feasibility of LA fibrosis quantification in 272 patients (83%). The remaining 57 patients (17%) had qualitatively poor 3D LGE MRI and were excluded.

2.4. Left atrial appendage thrombus

Stroke is a feared complication of AF, associated with a severe reduction in the quality of life. The presence of thrombus in the left atrial appendage (LAA) is considered the most important risk factor for stroke [31,32]. Therefore, excluding an intracardiac thrombus is a pre-requisite in all patients selected for a left sided ablation procedure. Due to its high...
sensitivity and specificity (100% and 99% respectively), today TEE is considered the gold standard [33]. However, TEE without sedation usually causes great discomfort and, although uncommon, the examination may result in potentially serious complications [34].

A recent meta-analysis of 19 retro- and prospective studies of patients undergoing both TEE and CT for the exclusion of thrombus prior to an ablative procedure revealed a high accuracy for these techniques in detecting LAA thrombus [35]. CT had a weighted mean sensitivity and specificity of 96% and 92% respectively. The positive predictive value and negative predictive value of CT were 41% and 99% respectively. The overall accuracy improved to 99% (PPV 92% and NPV 100%) when delayed phase imaging was used, making CT a non-invasive alternative for TEE under these terms.

Only 2 studies have compared CMR and TEE for the detection of thrombus [36,37]. With both studies being combined, we examined 147 patients and demonstrated a 100% concordance between the two modalities for the detection of LAA thrombus. Although not proven in a randomized fashion, this suggests that adding conventional magnetic resonance angiogram or early gadolinium enhancement pulse sequences to a standard CMR examination ensures adequate coverage of the LAA and may potentially substitute TEE in patients eligible for CMR, without a reduction in diagnostic yield (Fig. 3).

2.5. Pulmonary vein anatomy evaluation

Electrical isolation of the PV at the antrum level has long become the first step in the ablative treatment of AF. Both myocardial sleeves (i.e. cardiac muscular fibers extending into the pulmonary veins) as an underlying trigger of AF and the adjacent disperse atrial substrate, surrounding the PV ostium containing triggers and rotors, must be electrically isolated [1].

There is no uniform PV branching pattern and at least 1 accessory PV is present in 26% of the patients [11]. Therefore, detailed anatomical knowledge is desirable prior to the ablation procedure. TEE, CT and

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**Fig. 3.** TEE, CT and MRI images depicting thrombus in the LAA. TEE: arrows indicate thrombus and arrowhead indicates LAA. CT: arrow indicates thrombus in an axial view of the LAA. MRI: multiple sequences depicting thrombus (arrow) in a coronal view of the LAA. Adapted and reprinted with permission from Rathi et al [34].
CMR can provide this information; however, only CT and CMR provide true 3 dimensional (3D) datasets that can be imported and fused with the EAM. This allows for detailed visualization of the anatomy thereby increasing catheter maneuvers and procedural efficacy [12,13]. CT and CMR have a high level of agreement in assessing PV anatomy and dimensions [10,38].

3. Procedural imaging

3.1. Anatomic guidance

EAM systems are used to reconstruct 3D anatomy relative to a reference point and combine this data with local electrical information to guide catheter ablation. To further improve the usability, the EAM shell can be fused with fluoroscopic images or a 3D anatomic dataset from CMR or CT. Besides the obvious benefits of improved visualization and simplified catheter guidance inside the complex LA anatomy, this approach significantly reduces fluoroscopic exposure [14].

3.1.1. Fluoroscopy fusion

MediGuide™ technology (St. Jude Medical Inc., St. Paul, MN, USA) is an electromagnetic 4-dimensional catheter tracking technology. It allows visualization of catheters inside angiographic LA models and pre-recorded cine-loops. The system was aimed at limiting fluoroscopy duration thereby reducing radiation exposure [39]. Recent studies illustrated that both electrophysiological procedures and device implantation benefit from this technology due to reduced procedural fluoroscopy time [40–42]. The most elaborate experience is from Leipzig and covers 80 AF ablation procedures [39,43]. Procedures performed with MediGuide™ significantly reduced fluoroscopy time by 50% (31 min vs. 16 min for control vs. MediGuide™ respectively). The fluoroscopy reduction also led to a significant decline in the irradiation dose, from 14,453 ± 7403 to 7363 ± 5827 cGy·cm² (p < 0.001).

3.1.2. CT/CMR fusion

Studies comparing ablation procedures using conventional fluoroscopy versus the image integration approach report a lower arrhythmia recurrence rate for the image integration group, 19% vs. 48% for image integration vs. fluoroscopy respectively [12]. Similar findings were observed in another study, 22.6% for EAM with image integration versus 41.7% without image integration [13]. A more recent study reported no significant improvement in the clinical outcome, with an AF recurrence rate of 45% in the image integration group vs 48% in the without image integration group [14]. However, there was a significant decrease in fluoroscopy time, 22.1 + 11.4 min in the image integration group vs. 40.4 + 13.5 min in the without image integration group (p < 0.01).

Despite the limited number of patients studied, these data demonstrates the importance of EAM combined with 3D imaging. Fusion of datasets contributes to reduced fluoroscopic exposure and may increase the efficacy of the ablative procedure.

3.2. MRI guidance

Catheterization laboratories are successfully working towards performing ablation in an MR environment [44]. Catheter and tracking systems need to be adapted to function in a MRI environment. Personnel needs to be trained to adapt the safety measures required in an MRI environment. The transition to an MRI environment may prove to be a great advantage for electrophysiologists who can work outside the dangers of ionizing radiation. It also enables an enhanced visualization of anatomic structures and provides the potential to instantly adjust the ablation strategy based on tissue characteristics (edema and necrosis).

4. Post-procedural imaging

4.1. Assessment of PV stenosis

PV stenosis is a complication which may occur after ablation and can be treated with balloon dilation and stent placement [45].

The requirement for intervention depends upon the presence and severity of symptoms [1,45]. Evaluation of the PV anatomy at follow-up can be performed with echocardiography, CT or CMR. Analysis of the hemodynamic consequences of a stenosis using PV flow quantification is limited to echocardiography and CMR. Visualization of the PV is limited with echocardiography and the flow information underestimates the severity of obstruction [46]. However, a CMR flow map study can reliably and reproducibly perform this analysis (Fig. 4) [46–48]. Comparison of flow before and after ablation allows a more functional assessment to be conducted regarding severity of the stenosis and interventional indication [46].

4.2. Assessment of atrio-esophageal fistula

An extremely rare (0.03%) but potentially lethal complication (83% mortality) of catheter ablation is atrio-esophageal fistula (AEF) [49]. Various prevention strategies have been proposed to further limit these occurrences [50]. However, when an AEF is suspected, the evaluation of the esophagus can be conducted with both CMR and CT. Both modalities have proven valuable to confirm this diagnosis and determine the severity and extent of the injury [51].

4.3. Assessment of post-ablation scar

The ability to perform tissue characterization is restricted to CT and CMR. So far, CT has been used in a limited number of trials focused on scar in the ventricles and considering its low sensitivity, should be conceived as a developing technique [52,53]. CMR on the other hand is the gold standard for the detection of infarcted myocardium and assessment of viability [54].

Recent progress in 3D LGE imaging sequences enables identification and quantification of structural remodeling in cardiac tissue as thin as the atrial wall [7,55].

4.3.1. Acute atrial injury

Acute injury is characterized by the presence of both necrosis (fibrosis) and edema. Cardiac MRI allows for discrimination between edema and fibrosis. A combination of Short Tau Inversion Recovery (STIR), targeted at edema and LGE, defining necrosis needs to be performed. These images, once merged, show the distribution of edema and necrosis on an anatomic shell which can theoretically be used to predict arrhythmia recurrence and may guide redo ablation strategies (Fig. 2) [28].

4.3.2. Chronic atrial injury

The extent of post-ablation scar is shown to stabilize after a period of 3 months [56]. Studies utilizing this information suggest a correlation between procedural outcome and location and volume of scar tissue post-ablation [57,58]. Results indicated the absence of AF recurrence in the presence of circumferential scar around all PVs, whereas in patients with less than 2 PVs completely encircled, the chances of arrhythmia recurrence increased considerably [57]. Another study demonstrated that extensive scarring (≥1.98 ml) especially around the inferior part of the right inferior pulmonary vein is associated with a longer AF free survival [58].

Recent work examining the correlation between the site of ablation and localization of the scar provides information about conduction gaps that could help in guiding redo procedures [9,28,58]. Studies reporting an insufficient accuracy in determining these gaps after fusion of the EAM and LGE images [29,59] might be related to differences in patient...
selection, imaging protocol and post-processing tools. Technique inherent artifacts due to arrhythmias, motion or partial volume are also likely to play a role. These results show that the amount of ablation induced LA structural remodeling may be used as a marker for procedural outcome. This technique could play an important role during follow-up examination and for devising patient specific redo ablation strategies. Future research should therefore concentrate on the benefits of incorporating 3D LGE sequences during patient work-up. The inability of echocardiography and CT to perform atrial tissue characterization makes CMR the preferred modality for this purpose.

5. Future perspective

5.1. Body surface mapping

Electrocardiographic mapping (CardioInsight Inc., Cleveland, Ohio) is a non-invasive alternative for an invasive and time-consuming electrophysiological study. A validation study performed in patients with atrial tachycardia reported high accuracies in localizing the underlying arrhythmogenic focus. The diagnosis was accurate in 100% of unablated atria and in 83% (19 of 23 patients) of patients with previous ablation [60]. A feasibility study implemented this technique in AF patients [61]. The results showed successful detection of rotor activity. In addition, fusion between body surface maps and LGE CMR allowed analysis of the relationship between electrical and structural substrates. Furthermore, the resulting data was integrated with catheter navigation systems to guide ablation therapy. Despite the limited number of patients studied (n = 27), this technique shows great potential to improve the work-up of ablative procedures.

5.2. Rotor mapping

Although there has been controversy surrounding the existence and importance of rotors as electrical substrate for AF [62,63], invasive mapping of focal impulse and rotor modulation (FIRM) may be considered a valuable addition to existing ablation strategies [64]. Multiple groups have successfully utilized this information to augment ablation procedures [65,66]. Results from recent randomized control trials reported significant increase in single-procedure success rate for FIRM guided ablation in comparison to conventional ablation strategy, 82.4% and 44.9% respectively [66,67]. Though the ablation duration did not differ between the two groups [67], the drastically improved procedural outcome provides a compelling reason for FIRM guided ablation to be implemented.

6. Clinical consequences

Various non-invasive imaging modalities are currently employed in the treatment strategy of AF. All techniques have their advantages and limitations (Table 1), and due to a different gold standard for each step in the work-up, a multimodality approach is advocated in the daily practice.
An increasing demand for catheter ablation procedures has resulted in electrophysiology centers with high volume practices, necessitating an optimization of the existing work-up. Moreover, ongoing technological developments have increased the capability of the individual techniques and permit a single modality approach that can supply consistent and uniform imaging data, applicable during the work-up, guidance and evaluation of ablation procedures.

A general problem for echocardiography is reproducibility. Varying anatomic planes during follow-up exam may cause low inter-observer agreement. In addition TTE significantly underestimates atrial volumes and depends upon operator expertise and acoustic windows for image quality. TEE places a burden on the patient due to involvement of an invasive probe and usage of a sedative/anaesthetic prior to the examination.

CT has the highest spatial resolution amongst the imaging techniques and is the fastest modality to perform. However, its use is largely limited by radiation exposure, which prohibits its use in routine follow-up. Over the last decade, the efforts towards reducing this dosage have caused a steep decline, however still remains a significant load for the patient (Fig. 5) [68]. Tissue characterization serves an increasingly important role for ablation and although there is improvement, the prospects of CT are currently restricted.

Today, the most promising modality seems to be CMR, although it is the least frequently used modality due to time constraints and restrictions for some patient groups. Nevertheless, its ability to visualize the anatomy combined with information about tissue characteristics enables a detailed work-up to be performed. Using pre-procedurally acquired imaging data to guide ablation results in lower procedural radiation exposure and possible increase of therapeutic efficacy. A baseline for future follow-up examinations is established simultaneously.

Recent studies revealed the possibility for identifying potential interruptions of ablation lesions, the so-called electrical gaps which can be used to guide redo ablative procedures [9,28]. Gap identification, quantification of LA structural remodeling (volume, sphericity) and PV flow measurements allow for a thorough evaluation of procedural efficacy and related complications.

Minor contraindications like claustrophobia can be counteracted with anxiolytic. Free breathing and motion correction techniques are used to optimize image acquisition and reduce artifacts for challenging patients presenting with dyspnea and arrhythmia [69].

6. Conclusion

Multimodality imaging to guide catheter ablation therapy is time consuming and may not be suitable for high volume institutes. Modern day healthcare would benefit from a single technique, both cost-efficient and time-efficient, that covers the complete work-up of a patient for catheter ablation. CMR has shown to be comparable to the key imaging modalities, providing all the information during a single examination, in a safe and reproducible manner. As underlined by this review, further investigation is needed to establish whether a single modality can provide similar information with increased efficacy compared to the existing multimodality approach.

Conflict of interest

The authors report no relationships that could be construed as a conflict of interest.

References


