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STATE OF THE ART REVIEW

Twenty-five years of research in cardiac imaging in electrophysiology procedures for atrial and ventricular arrhythmias

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Abstract

Catheter ablation is nowadays considered the treatment of choice for numerous cardiac arrhythmias in different clinical scenarios. Fluoroscopy has traditionally been the primary imaging modality for catheter ablation, providing real-time visualization of catheter navigation. However, its limitations, such as inadequate soft tissue visualization and exposure to ionizing radiation, have prompted the integration of alternative imaging modalities. Over the years, advancements in imaging techniques have played a pivotal role in enhancing the safety, efficacy, and efficiency of catheter ablation procedures. This manuscript aims to explore the utility of imaging, including electroanatomical mapping, cardiac computed tomography, echocardiography, cardiac magnetic resonance, and nuclear cardiology exams, in helping electrophysiology procedures. These techniques enable accurate anatomical guidance, identification of critical structures and substrates, and real-time monitoring of complications, ultimately enhancing procedural safety and success rates. Incorporating advanced imaging technologies into routine clinical practice has the potential to further improve clinical outcomes of catheter ablation procedures and pave the way for more personalized and precise ablation therapies in the future.

Keywords Imaging • Cardiac computed tomography • Cardiac magnetic resonance • Echocardiography • Electroanatomical mapping • Single-photon-emission computed tomography • Positron emission tomography

Introduction

Supraventricular tachycardia catheter ablation (CA) procedures, in general, are considered low risk interventions and have a high success rate. Electroanatomic mapping (EAM) systems and imaging are both considered not essential to improve safety or outcomes in this setting. However, some re-entrant atrial tachycardias and atrial fibrillation ablation procedures could significantly benefit from using these technologies.

Ventricular arrhythmia (VA) ablation procedures are complex, associated to a non-negligible rate of complications and require expertise and advanced electrophysiologist's skills. They have been commonly performed in high volume centres by highly experienced operators. The VA ablation therapy has evolved tremendously in the last 25 years, largely associated to a big progress in the understanding of the important role that the fibrotic tissue plays in the development of sustained ventricular tachycardia.[1]

Along with great improvement in catheter ablation technologies, cardiac imaging has undergone a great evolution. Different imaging modalities are nowadays considered essential tools to ensure procedure safety, assist in pre-procedure planification and help in catheter ablation guidance. Its usefulness has also been recognized and recommended to identify the VA substrate and improving outcomes in VA consensus document and guidelines.[2,3] Cardiac imaging implementation in the standard VA management and treatment workup has importantly contributed to the widespread of these complex ablation procedures and to offer VA ablation earlier in the evolution of the disease.

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The role of different imaging modalities in substrate identification, procedure planning and guidance for both, and atrial and ventricular arrhythmias, will be summarized in this issue.

Cardiac imaging for atrial arrhythmias procedures

Electroanatomical mapping

Traditionally, electrophysiological studies and ablation of atrial arrhythmias (AA) have been performed under fluoroscopic guidance, with the consequent[4] exposure to radiation. The EAM using electroanatomical navigation systems has made it possible to reduce the need for fluoroscopy in atrioventricular nodal re-entrant tachycardia, atrioventricular re-entrant tachycardia, atrial flutter, and atrial fibrillation (AF) ablation procedures[5–8] without compromising either efficacy or safety.[6–8]

The EAM permits recording bipolar, unipolar, or multipolar voltages; local activation times, or identifying certain characteristics of the electrograms (EGMs), such as the presence of Complex Fractionated Atrial EGMs, or rotors in AF. Additional information, such as conduction velocity, activation direction, and propagation can be evaluated. Far beyond anatomically based procedures in AF [pulmonary vein isolation (PVI)], functional atrial mapping has gained special relevance, allowing to identify potential—and amenable to ablation—arrhythmogenic substrate outside the PV. An international position paper has recently reviewed all available AF mapping technologies.[9] Cardiac magnetic resonance (CMR) imaging, cardiac computed tomography (CT), and intracardiac echocardiography (ICE) can be integrated into EAM systems during AF and other complex AA ablation procedures, as *Figure 1* shows. This may result in better procedural outcomes and efficiency, and less fluoroscopy utilization.[10–14] The CMR atrial tissue fibrosis has been independently associated with the likelihood of recurrent AF,[15] although a CMR fibrosis-guided AF ablation appears to be not superior to a pure PVI-based strategy.[15] Conversely, macro-re-entrant AA after AF ablation may benefit from this CMR-guided strategy.[16] Nonetheless, large discrepancies between CMR fibrosis and low voltage zones (LVZ) may still be found.[17] Atrial anatomy assessment is best obtained from CT images due to their great spatial resolution. The CT-EAM fusion may improve the efficacy of AF ablation procedures, although it still remains a matter of debate.[18] Still, CT can define the cardiac anatomy, included uncommon variants and the atrial wall thickness (WT);[19] and may improve procedural safety: detection of thrombi,[20] oesophageal position[21] coronary disease, etc.

Atrial fibrosis promotes heterogeneous slow conduction, increasing AF vulnerability and the likelihood of AF recurrence.[22] The PVI clinical outcomes in persistent AF may be improved when adding a voltage-guided substrate modification approach targeting LVZ.[23] Yet, the presence of LVZ can predict AF recurrences, while there is a bad correlation between the extent of LVZ and the indexed left atrial volume.[24] Moreover, the presence of any deceleration zone in sinus rhythm is also an independent predictor of AF recurrence, not always correlated to the presence of LVZ.[25,26]

Echocardiography

Ultrasound (US) imaging has been increasingly used for electrophysiology (EP) procedures. Pre-, peri-, and post-procedural imaging is critical to improve the procedural safety and success; as a matter of fact, each interventional stage can potentially benefit from real-time visualization of the underlying anatomy, thereby avoiding any anatomical assumptions that may be incorrect and potentially dangerous.

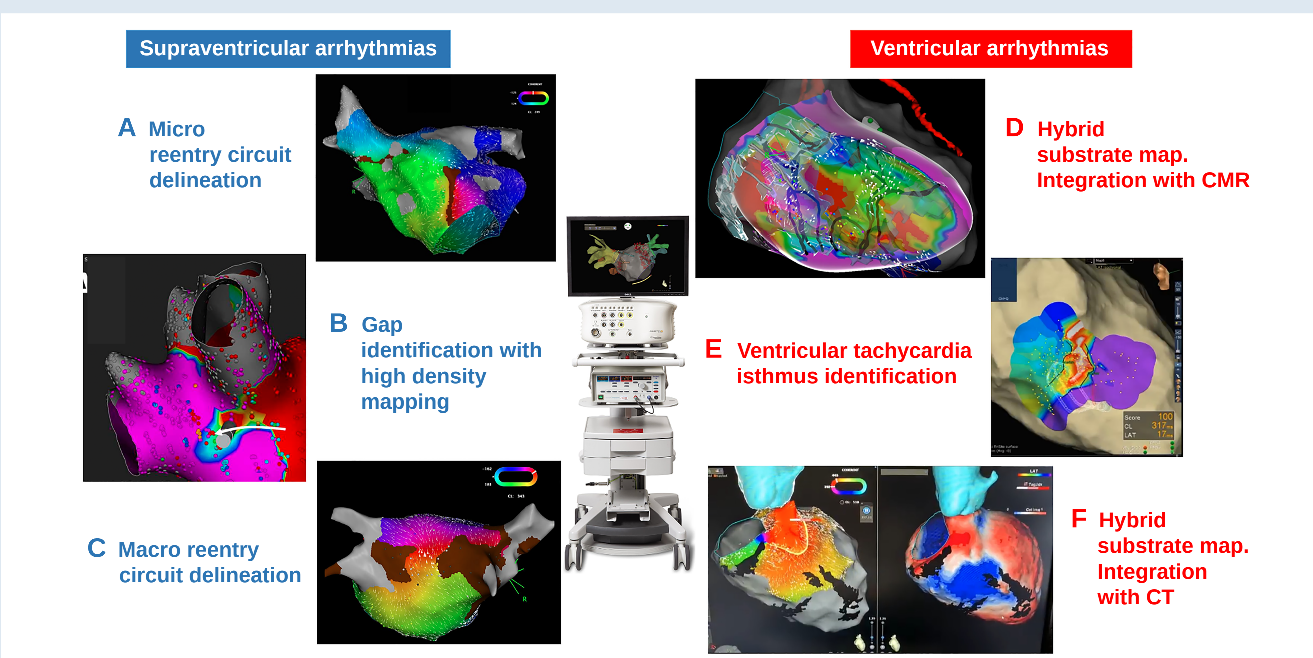

Figure 1 Usefulness of electroanatomical mapping (EAM) for catheter ablation of atrial and ventricular arrhythmias: *A*) delineation of a micro-re-entry circuit in the left atrial anterior wall; *B*) identification of a gap in the ablation line of the right pulmonary arteries; *C*) delineation of a macro-re-entry circuit of a roof-dependent left atrial flutter; *D*) integration of EAM with cardiac magnetic resonance in a patient with a scar-related ventricular tachycardia; *E*) protected VT isthmus identification; *F*) integration of EAM showing an activation map of a VT with anteroseptal exit with the pre-procedural CT containing myocardial wall thickness and lipomatous metaplasia information. CMR, cardiac magnetic resonance; CT, cardiac computed tomography.

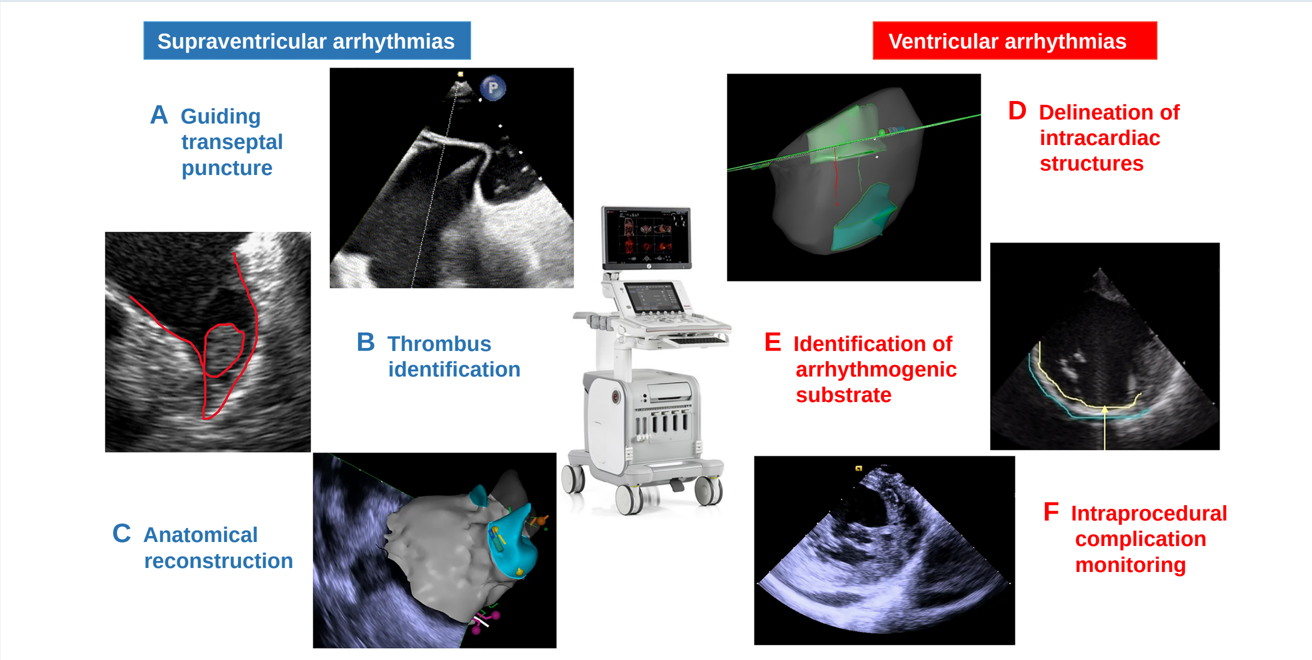

Figure 2 Usefulness of ultrasounds for catheter ablation of atrial and ventricular arrhythmias: *A*) transseptal puncture guided by transoesophageal echocardiography; *B*) intracardiac thrombus visualization in the left atrial appendage; *C*) left atrial reconstruction using Carto Sound Module; *D*) papillary muscle reconstruction using Carto Sound Module; *E*) shot axis view in a patient with an inferior myocardial infarction); *F*) short axis view in a patient with pericardial effusion during a VT ablation.

Conventionally performed via a palpation-based approach, vascular access is the procedural step associated with the highest number of complications, with an incidence ranging between 1% and 13%.[27–30] The US guidance has been demonstrated to significantly decrease (up to 65%) the risk of major vascular complications compared to an anatomical landmark-based approach. Similarly, this approach may successfully reduce the risk of minor complications (e.g. groin haematoma and inadvertent arterial puncture), thereby promoting a beneficial effect on comorbidities, hospitalization duration, and healthcare expenditure.[31] The US-guided access may be especially beneficial for EP procedures requiring a large bore access into the femoral vein [e.g. single-shot devices and percutaneous left atrial appendage (LAA) occlusion][32–34]; additionally, vascular US has been also adopted to guide vascular closure device deployment.[35,36]

Transseptal access is another critical step of left-sided EP procedures and can be associated with serious complications (e.g. cardiac tamponade, aortic puncture, and systemic embolism). Transoesophageal echocardiography (TEE) is commonly used to guide septal puncture (*Figure 2*). The main limitation of TEE is that it relies on a second operator to allow active and cooperative septal visualization optimization while the main operator is focused on manoeuvring the apparatus for transseptal access. The ICE is a valid alternative to TEE for transseptal access, as well as for a wide variety of other uses, as it allows direct, real-time visualization of many cardiac structures that are critical for EP procedures. The ICE currently plays a central role for flourless ablation procedures.[37] One of the most important features of ICE is continuous monitoring and early detection of peri-procedural complications, including steam pops, thrombus formation, and pericardial effusion/tamponade (*Figure 2*). Another advantage of this technology is the lack of need for general anaesthesia or an additional operator for TEE manoeuvring. The ICE catheter can also be advanced into the left atrium and is also currently used for LAA occlusion guidance; this approach has been demonstrated to reduce procedural duration and patient turnover.[38,39] Additionally, novel 3D-ICE probes feature direct anatomical visualization in multiplane/multislice and 3D modes.[40,41]

Computed tomography

Computed tomography has undergone significant technical evolution since its inception in the 1970s. This imaging modality has become an increasingly important tool for the non-invasive evaluation of cardiovascular anatomy and function. The evolution of cardiac CT has resulted in improvements in spatial and temporal resolution, image quality, motion artefact reduction, radiation dose reduction, and advanced post-processing techniques. These advancements have made cardiac CT an increasingly valuable tool for helping CA procedures.

Due to its great spatial resolution, cardiac CT provides detailed anatomical information of the atrium, including the size, shape, location of vessels, and their relationship with extracardiac structures (*Figure 3*). In the setting of PVI, the integration of CT images into the EAM[42,43] allows visualization of the fossa ovalis[44] anatomy and identification of unexpected anatomical PV variants,[45] facilitating procedural planning. This information can be particularly useful during cryoballoon ablation, as PV ostium shape and orientation can predict PV occlusion during the procedure, identifying unfavourable anatomies in which a point-by-point strategy might be more appropriate.[46]

Cardiac CT also allows to obtain information of the left atrial WT, a major determinant of lesion transmurality.[19,47] Left atrial WT-guided titration of radiofrequency delivery for paroxysmal and persistent AF ablation has been proved to allow for highly efficient and effective procedures.[47] Moreover, CT information can be used to increase procedure safety, allowing 3D visualization of the left atrium's relationship with the oesophagus,[48,49] the left superior pulmonary veins' relationship with the bronchi,[50] and the distance between the right upper PV and the right pericardiophrenic artery, an indirect marker of the phrenic nerve course.[51]

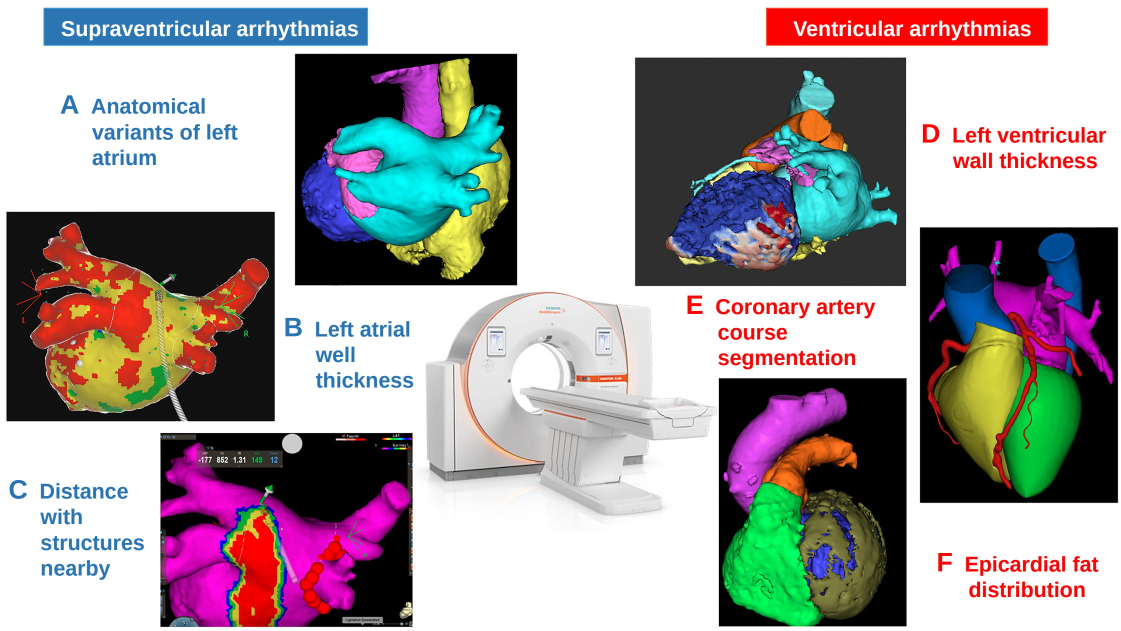

Figure 3 Usefulness of cardiac computed tomography (CT) for catheter ablation of atrial and ventricular arrhythmias: *A*) pre-procedural CT showing a common ostium of the inferior PVs; *B*) post-processed CT showing a color-coded map of the left atrial WT; *C*) isodistance map of the esophagus projected in the CT reconstruction of the left atrium; *D*) three-dimensional reconstruction of the left ventricle WT map (and channels) in a patient with an inferior infarction; *E*) coronary arteries course; *F*) left ventricular epicardial fat distribution. PVs, pulmonary veins; WT, wall thickness.

All this information allows us to move towards a personalized ablation strategy based on the patient's specific anatomy, preventing injury to sensible extracardiac structures during ablation. Cardiac CT also plays a major role in post-procedural handling, as it is the gold standard for verification of different complication diagnoses, such as the atrio-oesophageal fistula[52] or PV stenosis. Although initially designed for atrial fibrillation ablation, CT-image integration into the EAM may also improve the efficacy of CA in other complex atrial arrhythmic substrates. The use of CT scans may help to identify the origin of atrial ectopic focus.[53] Moreover, cardiac CT provides detailed information to properly select the course of the linear ablation lesions in patients with left[54] or right[55] atrial macro-re-entrant circuits. Conversely, left atrial WT maps have shown to be helpful in visualizing previous linear ablations and gaps, facilitating activation map interpretation in left atrial flutters.

Cardiac magnetic resonance

Pre-ablation cavotricuspid isthmus (CTI) visualization has gained significant attention in recent years with the development of the CMR-EP system.[56] This innovative technique allows for high-resolution visualization of the anatomy, substrate, and ablation lesions without the need for fluoroscopy, making it particularly useful in procedures requiring detailed anatomical visualization like CTI ablation.[56] This can lead to a reduction in radiation exposure for both the patient and the operator.

The use of real-time CMR, if translated to AF procedures, could be immensely beneficial. The prevalence and health burden of AF are much higher than atrial flutter, and there is a need to further improve procedural management of AF.

The use of CMR in the management of AF has a lot of benefits. For instance, it has been previously demonstrated that CMR can be used to assess underlying disease tissue or atrial fibrosis, as *Figure 4* shows.[57] These increasing levels of atrial fibrosis were independently linked to hard clinical outcomes like major cerebrovascular and cardiovascular events.[58] Also, the extent of disease in the left atrium has been shown to be a significant predictor of recurrence after CA. This was proved in the multicenter DECAAF I study, where patients were divided into four different groups of atrial fibrosis with high discrepancies in outcomes depending on the quantity of fibrosis.[15]

A sub-analysis of this study by Akoum *et al.*[59] showed that covering more fibrosis by ablation lesions can lead to fewer recurrences after the procedure. The DECAAF II trial was designed to prospectively test this hypothesis. So, patients were randomly assigned to receive either PVI-only or PVI plus fibrosis-guided ablation. However, the study results showed no significant differences between the two arms.[60]

Nonetheless, the application of CMR remains valuable, especially pre- and post-procedures. As mentioned earlier, the evaluation of baseline left atrial fibrosis provides valuable prognostic information for patients after the procedure. Additionally, the evaluation of the distance between the atrium and the oesophagus is a critical determinant of oesophageal injury due to CA.[61,62] Therefore, getting an image before the ablation can guide us on efficacy and safety outcomes. On the other hand, post-procedural CMR can also help guide redo ablations. Studies have shown that using CMR to guide redo ablations can lead to shorter procedural time and lower chances of recurrence.[63]

Positron emission tomography-scan and single-photon-emission computed tomography-scan

Nuclear cardiology exams (NCEs), namely single-photon-emission computed tomography (SPECT) and positron emission tomography (PET), constitute relevant imaging tools for cardiovascular diseases. To date, the main clinical applications of NCEs involve myocardial ischaemia, ranging from coronary artery disease (CAD) to coronary

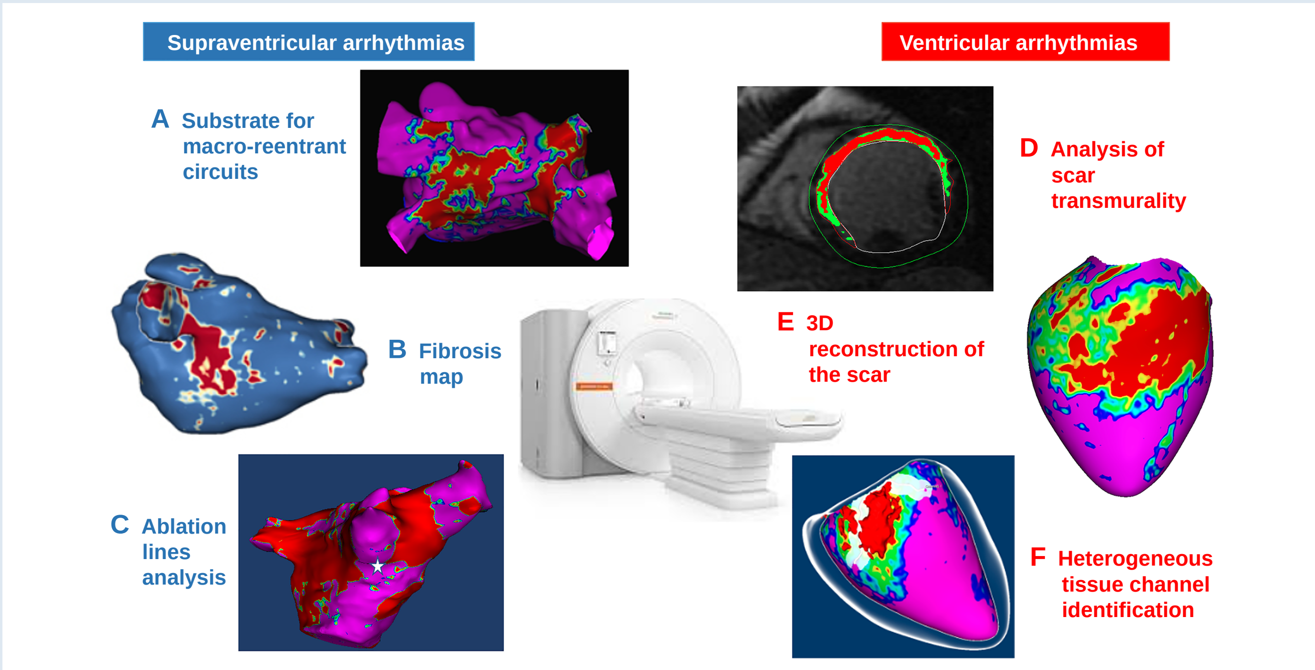

Figure 4 Usefulness of cardiac magnetic resonance (CMR) for catheter ablation of atrial and ventricular arrhythmias: *A*) pre-procedural CMR showing the fibrosis distribution in the left atrium in a patient with atypical left atrial flutter; *B*) post-processed CMR showing fibrosis distribution in a patient with atrial fibrillation; *C*) pre-procedural CMR showing the iatrogenic fibrosis due to a previous ablation in a patient who underwent a redo ablation procedure for atrial fibrillation; *D*) short axis view in a patient with an anterior myocardial infarction; *E*) pixel signal intensity map 3D reconstruction in a patient with an inferior infarction; *F*) heterogeneous tissue channel delineation.

microvascular dysfunction.[64] In detail, while stress/rest SPECT can identify ischaemic and necrotic areas, specific tracers in PET scan allow investigation of myocardial metabolism (18F-FDG-PET), and quantitative measurement of myocardial perfusion (H215O-PET or 13N-PET).[64]

To date, the clinical role of NCEs in cardiac arrhythmias is still limited. In fact, CMR and CT scan constitute the gold standard for substrate characterization and morpho-functional assessment of most myocardial diseases.[3] In selected cases, however, NCEs can provide significant information to guide diagnosis, prognostic assessment, and treatment strategies for patients with arrhythmias.

Among supraventricular arrhythmias, NCEs have been mainly applied to AF. For instance, 99mTc-MIBI SPECT perfusion imaging has been proposed to identify CAD as a substrate for unexplained AF.[65] In the setting of AF, however, the diagnostic value of SPECT has recently shown a low predictive value for CAD.[66] In fact, fast and irregular heartbeat may frequently account for poor image quality and subsequent inaccuracy in assessing ischaemia-induced regional wall motion abnormalities.[67] Instead, quantitative data from perfusion PET have shown that, even in the absence of epicardial CAD, myocardial blood flow and coronary flow reserve are abnormal in patients with persistent AF.[68] These data suggest that coronary microvascular dysfunction may be the consequence rather than the cause of AF,[68] and deserve further investigation by future studies.

NCEs have been employed also to characterize supraventricular arrhythmogenic substrates before CA. In one study,[69] SPECT was used in combination with other imaging techniques to identify atrial cardiomyopathy in young patients undergoing CA of atrial tachycardia. More recently, hybrid 99mTc-Pyrophosphate SPECT/CT has been proposed to detect latent inflammatory processes in patients with AF and biopsy-proven myocarditis.[70] Overall, these data indicate that an improved detection of atrial scars and inflammation may help identifying non-responders to CA, even in the absence of significant left atrial dilation.[3] Finally, a role for I-123-Metaiodobenzylguanidine SPECT imaging has been suggested to investigate dysautonomic manifestations in patients with AF undergoing CA.[71] Again, the clinical value of NCEs in defining suitable ablation targets and in predicting procedural outcomes is still to be proved.

Cardiac imaging for ventricular arrhythmias procedures

Electroanatomical mapping

The advent of 3D-EAM systems in the late 1990s clearly marked a major historical turning point for cardiac EP, particularly with respect to CA of VA in patients with structural heart disease.[72]

The 3D-EAM systems combine three important[72] features: (i) real-time visualization of catheters without the use of X-rays, (ii) 3D display of the virtual anatomy of heart chambers in relation to local EGM data, and (iii) fusion with non-invasive images of the heart (ICE, CT scan, CMR…). The 3D-EAM systems, which are very effective to reduce patient and staff exposure to fluoroscopy,[73] are currently widely used in daily practice for all types of CA procedures[74] in particular in over 90% of all ventricular tachycardia (VT) ablation procedures.[75,76]

With respect to VT ablation, one of the key innovative features of 3D-EAM systems was, for the first time, the complete virtual visualization of VT circuits through complete endocardial activation maps of the ventricles,[77,78] thus, allowing an accurate characterization of critical VT isthmuses, including not only their dimensions but also the elements that form their lateral boundaries (see Supplementary material online, *Video*).

The presence of slow conduction zones related to myocardial scars of various aetiologies (post-infarction, post-myocarditis…) is the pathophysiological substrate for macro-re-entry, which is the predominant mechanism of VT in patients with structural heart disease. Such scars harbour local abnormal ventricular activities (so-called *LAVAs*) in terms of voltage, duration, and morphology (i.e. split/fractioned EGM, late potentials…). Cross-correlation studies with CMR,[79,80] histology,[81] and VT mapping[79] have shown the accuracy of bipolar/unipolar voltage mapping in unmasking scars, with unipolar voltage mapping being more appropriate to detect intramural scars[82] and possibly diffuse fibrosis that cannot be easily imaged by CMR.[83]

Because many VTs are poorly tolerated, which impedes VT mapping,[84] substrate-based VT ablation that circumvents this issue, by targeting LAVAs, has early become very popular.[75] LAVAs related to VT circuits[85] can be directly[86] or indirectly[87] identified during 3D-EAM. Areas harbouring slow conduction can also be unveiled by pace-mapping[88] or by pacing with double ventricular extrastimuli.[87]

In patients with structural heart disease, a recent meta-analysis of the literature[89] showed that substrate-based ablation (aimed at modifying the substrate) was associated with better outcomes than 'standard' ablation (aimed at ablating stable VT) for the combined endpoint of VA recurrence and all-cause mortality.

Merging 3D-EAM maps with other cardiac imaging modalities is very useful when planning VT ablation procedures. Thus, ICE is a key exam to visualize papillary muscles that can hardly be outlined by 3D-EAM systems. The CT scan and CMR[90] are also important tools for the identification of ventricular arrhythmogenic substrate in patients with structural heart disease, with VT channels meandering through scars highlighted by a dedicated software applied to CMR.[91]

Echocardiography

The role of ultrasound assessment in VAs procedures is wide and includes the following tools: transthoracic echocardiography, TEE, and ICE.

Transthoracic echocardiography is useful in pre-procedural planning to evaluate the patient risk of VAs and to rule out left ventricle thrombus (contrast echocardiography may be considered in this case).[92] Global function of the left ventricle should be assessed with left ventricular ejection fraction (LVEF). The LVEF is a parameter integrated in the current risk stratification for pre-procedural mechanical support, besides its role as a known marker of VAs risk.[93] However, the absolute number of sudden cardiac death (SCD) victims is higher in the group of patients with LVEF >50%.[94] For this reason, a mildly reduced or normal LVEF should not be used to rule out VAs. If a patient is planned for a VT ablation, regional function evaluation by transthoracic echocardiography is useful to guide towards the scar area, in case of a suspected scar-dependent VT.[2] On the other hand, if a patient is evaluated for a premature ventricular contraction (PVC) ablation, transthoracic echocardiography can predict the recovery of LVEF in case of suspected PVC-induced cardiomyopathy. In a seminal study by Penela *et al.*,[95] an LV end-diastolic diameter >63 mm identified patients who will not normalize LVEF after PVC ablation.

Transthoracic echocardiography or TEE or ICE should be always available in the EP lab during VA ablation to rule out pericardial puncture/bleeding.[2] Indeed, PVC ablation is associated with a 2% complication rate, with pericardial effusion being the most frequent (40% of total complications).[96] Furthermore, during epicardial procedures with unintended puncture of the right ventricle can occur in up to 17% of cases.[2]

The TEE or ICE can be used to guide transseptal puncture. Being the LV with an inferior and anterior structure compared to the septum, the preferred position for the transseptal access should be the antero-inferior portion of interatrial septum.

Finally, ICE is recommended to localize the ostia of the coronary arteries prior to ablation in the sinuses of Valsalva.[2] It is also beneficial to identify and target the papillary muscles with ablation and to assess for catheter stability.[97] In particular, ICE allows a direct visualization of the papillary muscle during mapping and helps to correctly identify the anatomical site of the arrhythmogenic focus; during CA, it confirms contact between the ablation catheter and the target, avoiding collateral damage to surrounding anatomical structures (mitral valve chordae and leaflets).[98] It may be useful, during the procedure, as an adjuvant technique to identify wall segments with wall thinning, wall motion abnormalities, and segments with increased echogenicity, and also to identify intracardiac thrombi.[2]

Computed tomography

Several studies have demonstrated the potential of cardiac CT for pre-procedural planning in VT ablation. Wall thickness assessment using cardiac CT has recently emerged as an alternative cardiac imaging method to characterize arrhythmogenic substrate before VT ablation procedures,[99] showing a good correlation with low voltage areas and LAVAs.[100] Ghannam *et al.*[101] described that WT correctly identify the ablation targets in a population of post-infarction patients who underwent VT ablation. However, compared to CMR, cardiac CT presents a lower contrast-to-noise ratio, a characteristic that reduces the cardiac CT capability for scar characterization. As consequences, CT may not accurately identify non-transmural areas of myocardial scar, especially in cases where the scar is in the sub-endocardium in ischaemic patients.[90] In patients with non-ischaemic cardiomyopathy, who typically do not show myocardial thinning in scarred areas, the usefulness of CT may be also inferior compared to CMR.

The other side of the coin is the high spatial resolution of CT. While CMR spatial resolution usually ranges from 1.4 to 2 mm, CT spatial resolution is typically close to 0.5 mm. This results in better identification of the coronary arteries, phrenic nerve, and epicardial fat distribution[102,103] (*Figure 3*). Yamashita *et al.*[104] previously showed how the integration of cardiac CT during epicardial VT ablation can increase the safety of the procedure avoiding radiofrequency delivery in the very proximity of these structures. Furthermore, cardiac CT can easily identify lipomatous metaplasia, which facilitates the propensity of re-entry VT circuits in healed myocardial infarction.[105] Moreover, CT identifies intracardiac thrombus, which can be present in up to 11% of patients referred for scar-related VT-CA, as recently reported.[106] Finally, cardiac CT can be useful in the setting of PVC ablation. First, it can help to identify the site of origin in patients with outflow-tract PVCs by analysing the presence of anatomical modifications due to chronic overload.[107] Moreover, CT imaging integration into the EAM can be useful for aiding ablation procedures of PVC originating from complex intracardiac structures, such as the papillary muscles[108] for the aortic cusps.

The use of cardiac CT has shown to be a valuable tool in assisting CA of VA and can be easily integrated into the procedure workflow. However, it is important to carefully consider the potential limitations of the technique, such as limited soft tissue contrast and the risk of radiation exposure, particularly in patients requiring multiple scans.

Cardiac magnetic resonance

Fibrotic tissue has been recognized to be the main substrate for VA, is present in various degrees even in the case of a focal origin, and supports re-entry circuits. Contrast-enhanced CMR has proved its capacity to identify with high precision this scarred tissue, which confers an increased arrhythmia susceptibility.[1] Scar identification and quantification have demonstrated to help identify those patients at higher risk for VA in both ischaemic and non-ischaemic cardiomyopathies in various clinical scenarios, in a significant number of studies.[109–111]

The identification of myocardial scar and its distribution pattern through the myocardial WT has been shown to be of help to focus mapping and ablation on the area of interest and also to decide the endocardial approach vs. epicardial approach for free wall VTs or the right access vs. left access for septal scar-related VTs.[112]

The CMR also permits to differentiate between dense non-excitable scar and border zone fibrotic tissue surrounding the scar or creating channels through the scar or between the scar and an anatomical obstacle like a valve annulus. These channels can be identified using dedicated software for CMR post-processing.[91] The capacity of CMR to identify these channels is superior to that of the CT, the latter failing to detect the presence of arrhythmogenic substrate in one-third of patients with subendocardial myocardial infarction. However, the performance of CT improves in the presence of transmural scars.[90] A significant number of patients undergoing VT ablation have implantable cardioverter-defibrillator (ICD) that can cause image artefacts in CMR. In those patients, wideband CMR sequences have shown to decrease these artefacts while maintaining similar accuracy for substrate characterization.[113]

The presence of channels and the border zone channel mass has been shown to be the strongest determinant of VA occurrence after a myocardial infarction after adjustment for other variables related with the LV function and scar.[114] These channels also distinguish patients at higher risk of VTs during follow-up in other clinical situations like cardiac resynchronization therapy and even in non-ischaemic cardiomyopathy.[109,111,115]

The 3D reconstruction of the information obtained with the CMR displaying the heart anatomy, the scar, and the 3D structure of the conducting channels can be imported into the navigation system and integrated with the EAM. The CMR scar and channels have been shown to have a good correlation with the low voltage areas and channels identified with EAM.[80,116] The CMR allows to recognize the substrate architecture and distribution along the WT, otherwise, neither visible nor mappable with standard mapping and ablation catheters that only obtain direct information from the endocardial or epicardial surface.[79,80,116] The use of the information provided by the CMR once integrated into the navigation system has demonstrated to help performing more efficient procedures and obtain better outcomes. As compared with the standard VT ablation guided solely by the EAM, CMR-guided VT ablation is feasible and safe, significantly reduces the procedural, fluoroscopy, and radiofrequency times, and is associated to a higher non-inducibility rate and lower VT recurrence.[117,118]

Positron emission tomography-scan and single-photon-emission computed tomography-scan

In patients with VA, the applications of NCEs are wider and encompass ischaemic and non-ischaemic diseases. In patients with mid-to-high pretest probability of CAD and stress-induced ectopies from the LV, SPECT can predict epicardial vessel stenosis, even in the absence of LV systolic dysfunction.[119] Nonetheless, NCEs are not currently recommended by the ESC in the diagnostic workup of CAD-related VA.[3] Instead, FDG-PET has a recognized role in diagnosing both cardiac and extracardiac sarcoidosis.[3] In addition, FDG-PET scan has been proved clinically helpful in lymphocytic myocarditis with VA, in particular when CMR is contraindicated or unsuitable due to ICD-related artefacts.[120] Finally, recent studies suggested that FDG-PET is capable of identifying even the 'hot-phases' of primary cardiomyopathies of the dilated and arrhythmogenic spectrum.[121]

Beyond their diagnostic value, NCEs have shown a prognostic role in CAD,[65,122] as well as in other clinical scenarios. For instance, 99mTc-MIBI myocardial perfusion SPECT has been found useful to quantify LV scarring, and predicts outcomes in response to cardiac resynchronization therapy.[122] Consistently, the beneficial effects of biventricular pacing on septal metabolism can be proved by PET.[123]

In patients with inflammatory cardiomyopathy, the anteroseptal localization of FDG-PET abnormalities, more commonly found in cardiac sarcoidosis rather than classic lymphocytic myocarditis, is capable of predicting worse arrhythmic outcomes.[120] In inflammatory cardiomyopathy, the documentation of active myocarditis by multimodal workup including FDG-PET has shown to predict major VA recurrences even after CA.[124]

In light of their diagnostic role, NCEs have been investigated also to guide treatment strategies, such as CA of VA. For instance, SPECT-CT fusion imaging has been found time-sparing and useful to characterize LV substrate and scars.[125] In addition, areas with perfusion/innervation mismatch on SPECT scans could identify sites of LAVA on EAM to guide CA procedures.[126] Due to the lack of strong evidence, however, NCEs are not mentioned by the last ESC guidelines among the imaging tools recommended before CA procedures in patients with VA.[2,3] Exception is made for PET-CT scan in patients with inflammatory heart diseases like myocarditis or cardiac sarcoidosis,[3] who will likely benefit also from PET-CMR fusion imaging in the near future.[127] Finally, in the absence of artefacts from right ventricular pacing,[128] FDG-PET may find application in following-up ICD carriers with myocarditis, to allow disease restaging and guide the withdrawal of immunosuppressive therapies.[120]

Future directions

The future of cardiac imaging in arrhythmia and EP will be shaped by advances in technology and a greater understanding of the underlying arrhythmia mechanisms. Progress in these directions will be intertwined, leading to improved patient outcomes and increased efficiency of healthcare delivery.

A clearly charted direction would be the use of 3D imaging technologies, which are expected to become widespread, improving our ability to acquire unappreciated structural and disease-induced remodelling detail. Native T1 mapping and extracellular volume acquisition are making inroads, allowing to better characterize diffuse fibrosis.[129] Furthermore, fusion imaging, the integration of multiple imaging modalities, will enrich our ability to assess disease-modified heart structure/function. Indeed, hybrid PET/CMR scanners have already become commercially available[130]; the trend of fusion imaging will continue to grow.

Development of real-time imaging technologies will allow feedback during EP procedures. For instance, ICE, a high-resolution visualization of cardiac structures, enables integration of real-time images with EAM. Novel developments, such as electromechanical wave imaging, a high-frame rate ultrasound technique,[131] have made initial advances in non-invasively mapping the electromechanical activation of arrhythmias. Furthermore, while commercial systems for electrocardiographic imaging already exist, they do not yet have the spatial resolution necessary to clearly delineate targets for ablation; improved approaches are likely to be developed in near future.

The most rapid advances in technology will likely be made by artificial intelligence (AI). In addition to its widening use in electrocardiogram (ECG) analysis,[132] AI has also been used in segmentation, scar/fibrosis assessment, and clinical parameter extraction.[133] We are witnessing the first application of deep learning on raw CMRs and the use of multi-modality deep learning to predict risk of arrhythmia and time to SCD.[134] Future AI advances will enable identification of additional imaging patterns and biomarkers that are associated with specific types of arrhythmias.

Finally, digital twin technology is poised to play important role in personalized treatment planning and in prognostication of patients' disease trajectory. Heart digital twins (mechanistically-based personalized computational models of patients' hearts) have already made novel contributions to uncovering arrhythmogenic mechanisms[135] and to the guidance of atrial[136] and VAs.[137] The benefit of the digital twin technology is that treatment can be tailored based on the patient's response to therapy. The AI is also being combined with digital twins,[138] helping broaden clinical data inclusion in the models. In the future, we will witness the creation of continuously-adjustable heart digital twins based on patients' tracked data.

Supplementary material

Supplementary material is available at *Europace* online.

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