3D Whole-Heart Imaging in Cardiovascular MRI: Exploring the Range of Clinical Applications

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Clinical need

Initially introduced for coronary artery visualization, three-dimensional (3D) whole-heart navigator-based acquisitions have been used routinely for over two decades, especially to delineate complex congenital anatomy and morphology [1].

The technique is superior to other imaging modalities used in congenital heart disease (CHD), as it is free from ionizing radiation and does not require breath-holding. It also allows the acquisition of full-volume data including the entire heart and thoracic vasculature at a specific point of the cardiac cycle (usually end-diastole) with high signal-to-noise ratio and isotropic voxel resolution that enables reconstruction in any plane during post processing [2].

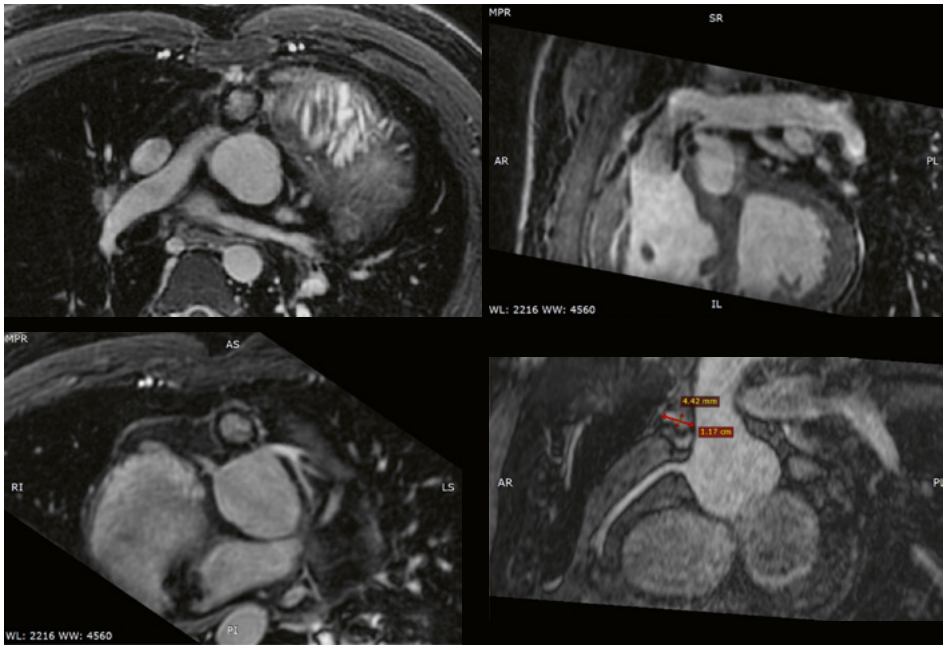
Apart from its value in anatomy and morphology, free-breathing high-isotropic-resolution 3D whole-heart late gadolinium enhancement (LGE) imaging has been established as a valid method of tissue characterization in a wide range of ischemic and non-ischemic cardiomyopathies [3, 4].

Recent major developments in electrophysiology (EP) ablation procedures for arrhythmia treatment have raised the need for novel 3D whole-heart high-resolution LGE (HR-LGE) techniques to image thin-wall cardiac chambers such as the atria and right ventricle. Technological progress in this area has made it possible to both identify the arhythmogenic substrate and illustrate its underlying architecture.

This information has been used to aid or even guide EP procedures, increasing both safety and success rates [5].

We will focus on using 3D whole-heart imaging in adult congenital heart disease (ACHD) and arrhythmias, and on how it helps the invasive cardiologists on the Structural Heart Disease team and on the EP team in their daily practice.

3D Whole Heart is work in progress. The application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.



1 3D free-breathing ECG-gated navigator-based whole-heart imaging in a young patient post arterial switch for transposition of the great arteries and multiple operations for supra- and valvar stenosis of the pulmonary valve (PV). Patient had a Melody valve in the position of critical PV stenosis, and a valve-in-valve procedure was planned. Despite the presence of a prosthetic Melody valve and ASD closure device, high-quality 3D whole-heart imaging offers critical information about the origin of the coronary arteries and its relation to RVOT and pulmonary annulus. Left main coronary artery (LMCA) high origin is noted in proximity of the Melody valve. RCA is at a safe distance from the area of planned intervention.

Adult congenital heart disease

Introduction

Cardiac magnetic resonance (CMR) imaging is already an integral part of the diagnostic evaluation, risk stratification, and serial follow-up of ACHD patients [6]. This is important, as adults living with CHD currently outnumber the children [7].

CMR image quality is not affected by body habitus, there is no need for geometric assumptions, and it is radiation-free. Diagnostic imaging in ACHD aims to illustrate anatomic and functional pathology, quantify the severity, and guide clinical decision-making.

ACHD patients are a heterogeneous population, covering a wide spectrum of anatomic patterns, even within specific lesions. Furthermore, most adult patients have undergone a previous corrective or palliative surgery and other interventions, making each patient a unique case, and residual hemodynamic/anatomic abnormalities very common. In addition, as the ACHD population ages, acquired heart disease will require diagnostic evaluation.

Non-invasive visualization of accurate patient-specific cardiovascular anatomy is essential – not only for illustrating morphological complexity in ACHD cases, but also due to the difficulty of pre-surgical decision-making.

3D whole-heart applications

The non-contrast free-breathing 3D whole-heart approach with respiratory navigator gating and ECG triggering was initially introduced for dedicated coronary imaging [1] in the pediatric[1] population. Nowadays, its use has expanded to the ACHD population. It is used to describe complex anatomy and enables reliable measurements of the aortic root and aorta at the desired timepoint of the cardiac circle, obviating the need for multiple 2D cine imaging across the area of interest [8].

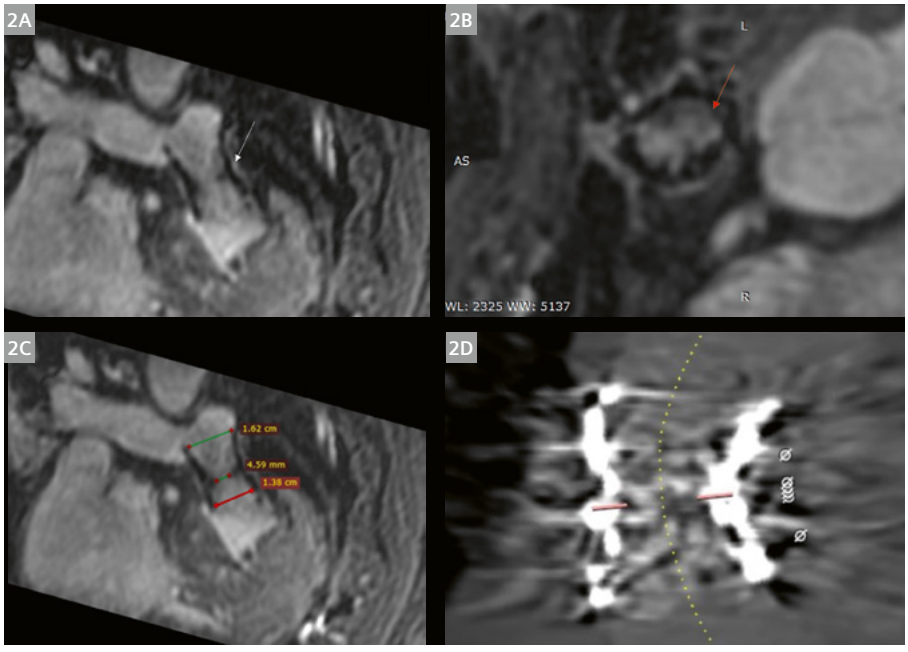
Many technological developments, mostly related to motion correction with the use of navigators during free breathing [9] and image-contrast improvement [10], have led to better image quality. As a result, the present technique has become integral part for intracardiac and extracardiac anatomy evaluation in complex ACHD cases, especially when there is a question of giving a gadolinium agent and in serial follow-up cases.

This is particularly important, as different cardiovascular anomalies can coexist in the same patient, posing the need for expert knowledge of the heart and vascular connections. Moreover, recent studies endeavor to show that routinely introducing a set of 3D volume data during the CMR scan for anatomy delineation and post-processing reconstruction on any plane can shorten the scan time, simplify the scanning protocol, and may obviate the need for direct expert supervision [11].

Isotropic 3D whole heart datasets are particularly useful for interventional planning in complex CHD.

Percutaneous interventions have completely changed the management of ACHD, especially the need for open heart surgery. In patients with predominant pulmonary valve regurgitation (either native or bioprosthetic, or a conduit), 3D whole-heart offers a complete evaluation of the

[1] *Siemens Healthineers Disclaimer: MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures. Note: This disclaimer does not represent the opinion of the authors.*



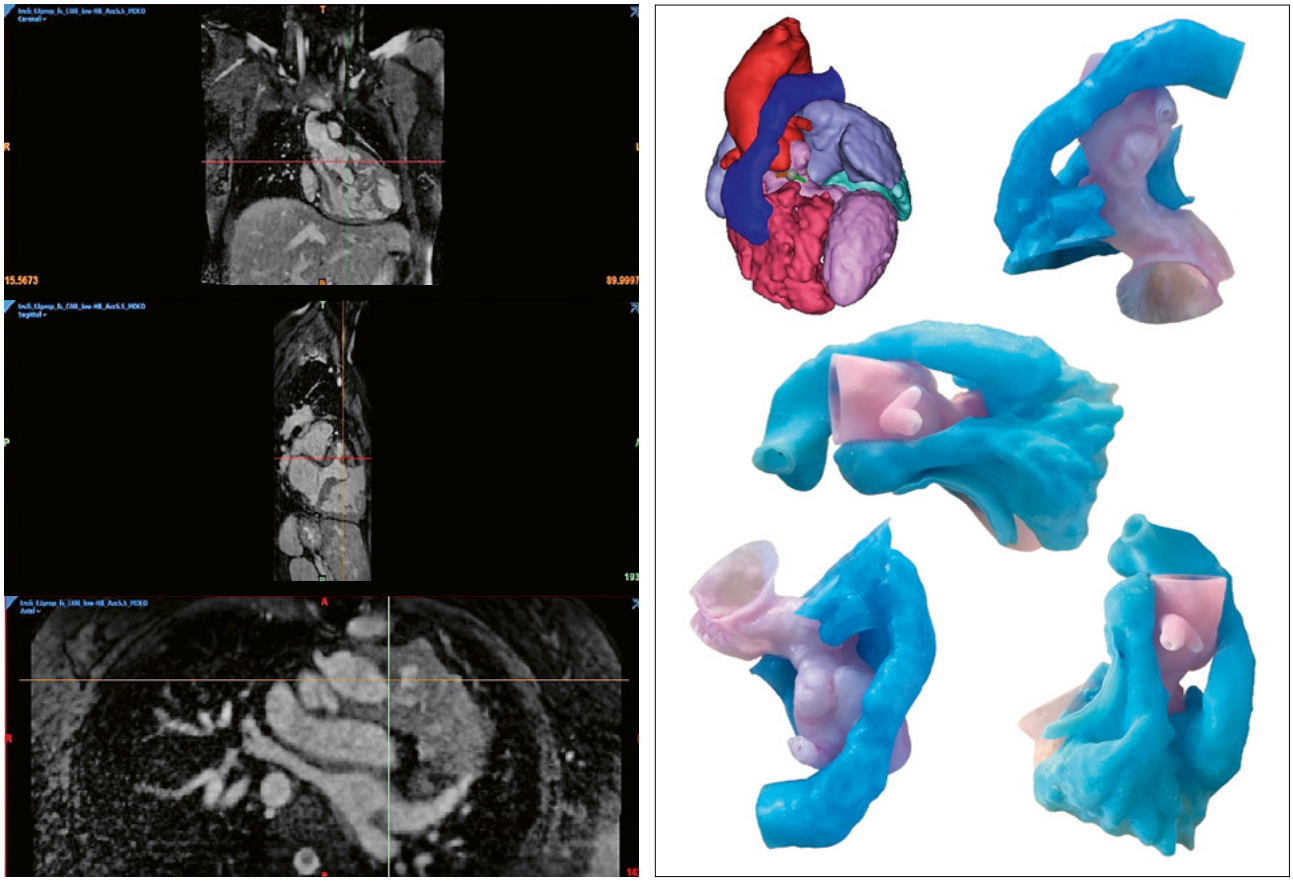
2 Same patient as in Figure 1. Reconstruction of RVOT/PV using data from 3D whole-heart imaging shows the in-stent stenosis at the mid-part of the Melody valve. Finding confirmed by CT measurement **(2D)**.

right ventricular outflow tract (RVOT), and the pulmonary artery dimensions and geometry. This is crucial for sizing and pre-planning the sitting position of the new valve/conduit even in valve-in-valve procedures [12]. Additionally, coronary anatomy is interrogated, along with higher risk anatomical features for transcutaneous pulmonary valve replacement (PVR), such as a coronary artery in close proximity to the RVOT and the risk of compression or co-existent pathology from supravalvar pulmonary stenosis, ascending aortic enlargement, or aortic coarctation [13]. Sample preprocedural images of a valve-in-valve transcutaneous PVR pre-procedure are shown in Figures 1 and 2.

Furthermore, the use of 3D volume data sets with the added advantage of gating are well suited for producing 3D-printed models to aid surgical planning in more complex cases, such as double outlet right ventricle (DORV), where the relative position of different anatomic regions is important for the surgeon when choosing the appropriate technique [14]. With 3D-printed models, it is also possible to simulate the surgical procedures in complex cases and check the results. Furthermore, the use of virtual reality platforms is expected to revolutionize the future of preprocedural planning for complex CHD [15].

All these innovations have been translated into daily clinical practice by fusing 3D whole-heart datasets with conventional fluoroscopy angiograms in the catheterization laboratory. This is to aid procedural guidance and to reduce time under radiation and the dose of iodinated contrast, both of which benefit the patient [2, 15]. It seems that the complex ACHD anatomy is the optimal paradigm in which 3D modelling and printing can permeate daily practice as augmented or virtual reality, leaving nothing to the imagination or risking misinterpretation by the clinician. Sample images of a 3D-printed model in a complex ACHD case are shown in Figure 3.

Finally, 3D LGE whole-heart imaging may have a role to play in risk stratification for sudden cardiac death, mainly caused by ventricular arrhythmias, in sub-categories of the ACHD population [16, 17]. It has been shown that right ventricular LGE burden independently predicts inducible ventricular tachycardia (VT) in repaired tetralogy of Fallot patients. However, for other types of CHD such as transposition of the great arteries (TGA) with atrial switch surgery, inducible VT appears to be of no prognostic value [18].



3 Young patient post-Rastelli procedure for double outlet right ventricle. 3D whole-heart imaging translated to 3D-printed model of the heart. *Courtesy of 3D Life SA, 3D4KARDIA European Funded Program, Onassis CSC, CERTH, 3D Life SA.*

Sample images of 3D LGE of the right ventricle in a patient with tetralogy of Fallot are shown in Figure 4.

Challenges

Current T2-prepared balanced steady-state free precession 3D whole-heart imaging suffers from off-resonance artifacts in small vessels, flow-related artifacts due to turbulence, and metal artifacts from stents and devices that may obscure areas of interest. Furthermore, scanning time is prolonged, especially in high-quality isotropic 3D data sets, and is often unpredictable due to the use of diaphragmatic navigators and their susceptibility to irregular respiratory patterns.

2D image navigators (iNAV) have been proposed to address the cardiac and respiratory motion problem [19]. This technique outperforms conventional diaphragmatic navigator gating and enables 100% respiratory scan efficiency, as well as shorter and predictable scan times. Dixon-based fat-water separation approaches enable superior fat suppression especially for 3D LGE applications [20] (Fig 4). Furthermore, Magnetization Transfer Contrast Bright-and-black blOOd phase SensiTive (MTC-BOOST) techniques [21] provide high luminal signal for small vessels, and optimal contrast between myocardium and blood pool, which overcomes flow artifacts.

Electrophysiology

Introduction

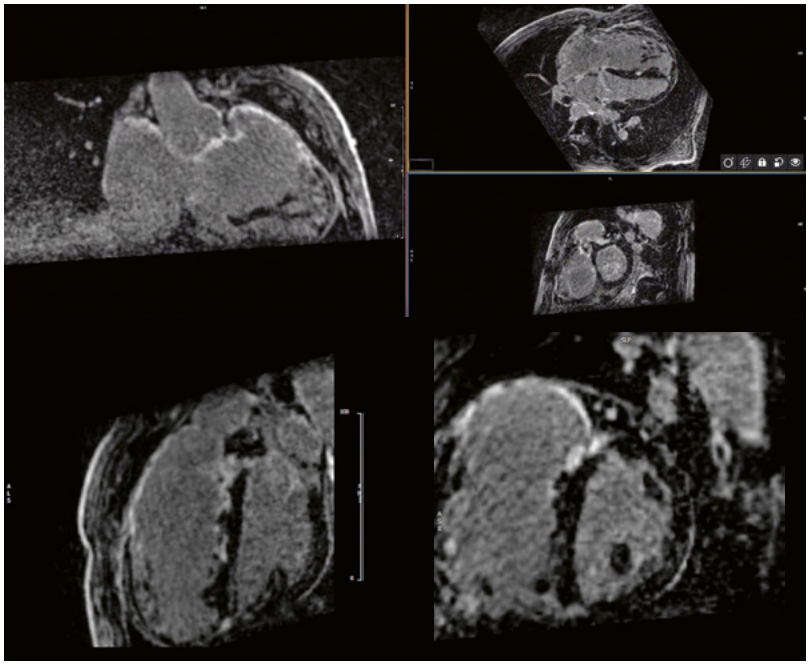
Advances in understanding arrhythmia and in technology for mapping and ablation have led to rapid growth in ablation techniques [22]. Ablation in atrial fibrillation (AF) and VT is an intervention with a growing need for imaging support. CMR is the gold-standard technique for tissue characterization and has made it possible to both accurately locate the abnormal tissue (scar/fibrosis) and assess its architecture and characterize the underlying arrhythmogenic substrate. Thus, CMR has been introduced to the EP lab routinely as a pre-procedural way of non-invasively mapping the underlying arrhythmogenic substrate, guiding ablations, and assessing post-procedural success.

Ventricular tachycardia

VT is the most common cause of sudden cardiac death in structural heart disease [23]. Invasive electro anatomical mapping (EAM) can, with the use of newer catheters, illustrate the presence of both scar (voltage maps) and slow conduction areas (activation maps). The most common arrhythmic substrate in patients with monomorphic VT refers to the presence of a scar-related re-entry pathway caused by slow conduction areas of intermediate tissue (so-called border zone, BZ) inside the electrically silent core scar that connects regions of healthy tissue. These areas are called conducting channels and can be accurately identified from the EAM obtained during VT ablation [24].

A high degree of concordance between EAM and images obtained by MRI has been reported [25].

Conducting channels in EAM are shown in two dimensions as an inherent disadvantage of EP mapping and this could be a reason for reduced ablation success. Therefore, there is a clinical need to improve the characterization of the VT substrate and the efficacy of VT ablation [26].



4 Middle-aged patient, post-surgical correction for tetralogy of Fallot. 3D GRE Dixon fat-water LGE imaging with image navigator.

In this context, CMR may play an important role in substrate characterization. This is especially true with the application of high-isotropic-resolution 3D whole-heart LGE imaging in the range of 1 to 1.3 mm^3 that allows illustration of the BZ, healthy tissue, and core scar, and provides a 3D model of VT corridors across all layers of myocardium.

3D whole-heart applications

3D whole-heart LGE imaging can define the location of the scar tissue across the different layers of myocardium (endocardium, mid-wall, and epicardial region) with great accuracy. This information is very useful for deciding on the ablation approach (endocardial, epicardial, or both) [27].

In addition, CMR has revolutionized clinical practice by making it possible to accurately discriminate between arrhythmogenic and non-arrhythmogenic scar. The scar location, signal intensity (SI), transmurality, shape, and heterogeneity can provide a 3D model of the heart with projection of the structural equivalent of conducting channels (CC), i.e., VT corridors [26].

Using dedicated post-processing software, color-coded pixel signal intensity (PSI) maps are produced and merged with EAM during VT ablation [26].

Recent studies have shown that CMR-aided VT substrate ablation with color-coded PSI maps obtained from pre-procedural 3D LGE whole-heart imaging reduces the need for radiofrequency (RF) delivery and improves VT recurrence-free survival [27, 28].

Sample images of a patient with a previous posterolateral wall infarction and monomorphic VT pre-ablation procedure show that the VT corridors from 3D LGE whole-heart imaging using a novel iNAV Dixon 3D fat-water separation sequence agree with the conducting channels in EAM.

Atrial fibrillation

Introduction

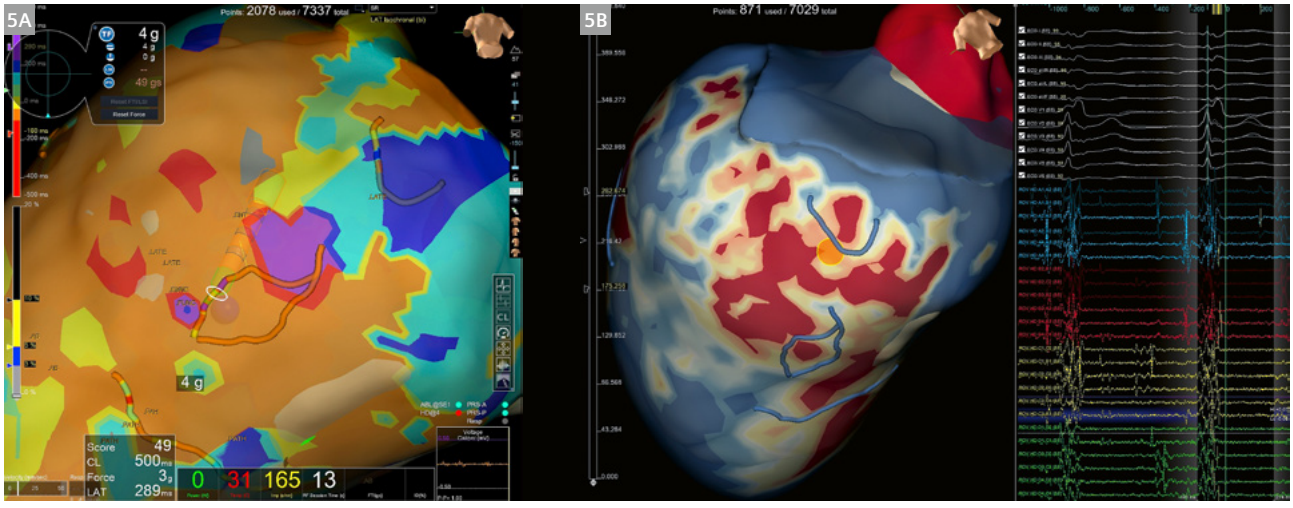
LGE CMR imaging of left atrial (LA) fibrosis in patients with AF has been associated with impaired LA mechanics [29] and lower voltage on electroanatomic voltage maps [30]. Clinically, this translates to increased adverse cardiovascular events, persistence of AF, and treatment failure [31].

Pulmonary vein (PV) isolation has become the cornerstone technique for catheter ablation in patients with drug-refractory AF. LGE CMR imaging of the LA could offer a valuable tool to evaluate location, depth, and possible gaps in created lesions.

As low-voltage atrial areas detected by EAM correlate quite well with structural alterations on LGE CMR, using and integrating LGE imaging in current clinical practice may provide a less operator-dependent tool for quantifying LA scarring and guiding ablation. This could improve procedural success rates. Sample images of post-ablation PV lesions and respective voltage maps are seen in Figure 5.

3D whole-heart imaging applications

Over time, 3D LGE imaging has become the reference for both pre- and post-ablation atrial scar imaging. Commercial 3D free-breathing LGE acquisitions are based on respiratory navigation and an ECG-gated gradient echo pulse sequence with fat suppression and inversion recovery preparation. Data are acquired during the diastolic phase of the cardiac cycle prior to atrial kick. Scan time depends on the respiratory pattern and heart rate of the patient, and can reach up to 12 minutes. Typical voxel size is 1.25 × 1.25 × 2.5 mm (reconstructed to 0.625 × 0.625 × 1.25 mm).

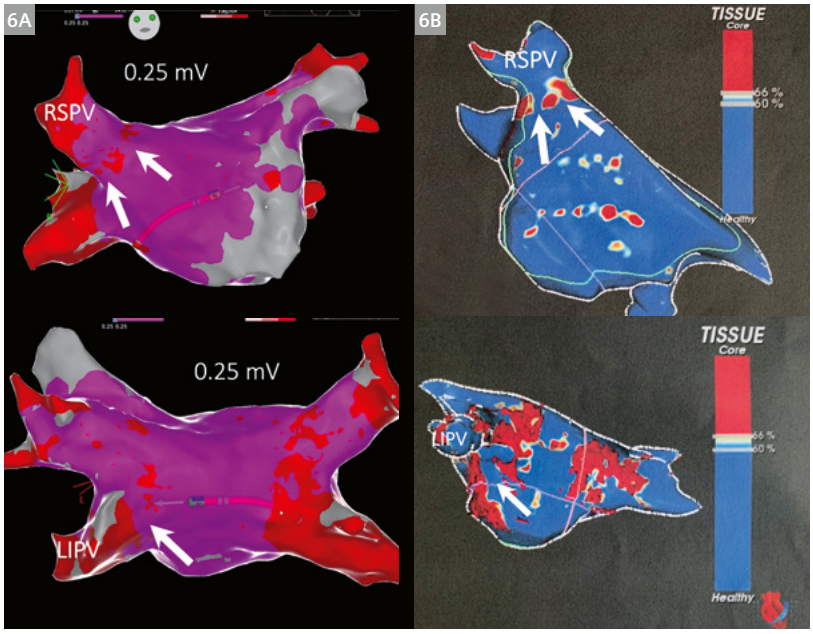


5 Middle-aged patient with posterolateral wall myocardial infarction and monomorphic VT. **5A:** Electroanatomical map showing arrhythmogenic substrate as conducting channels. **5B:** PSI map derived from 3D LGE whole-heart dataset showing the structural VT corridors in complete agreement with the EAM.

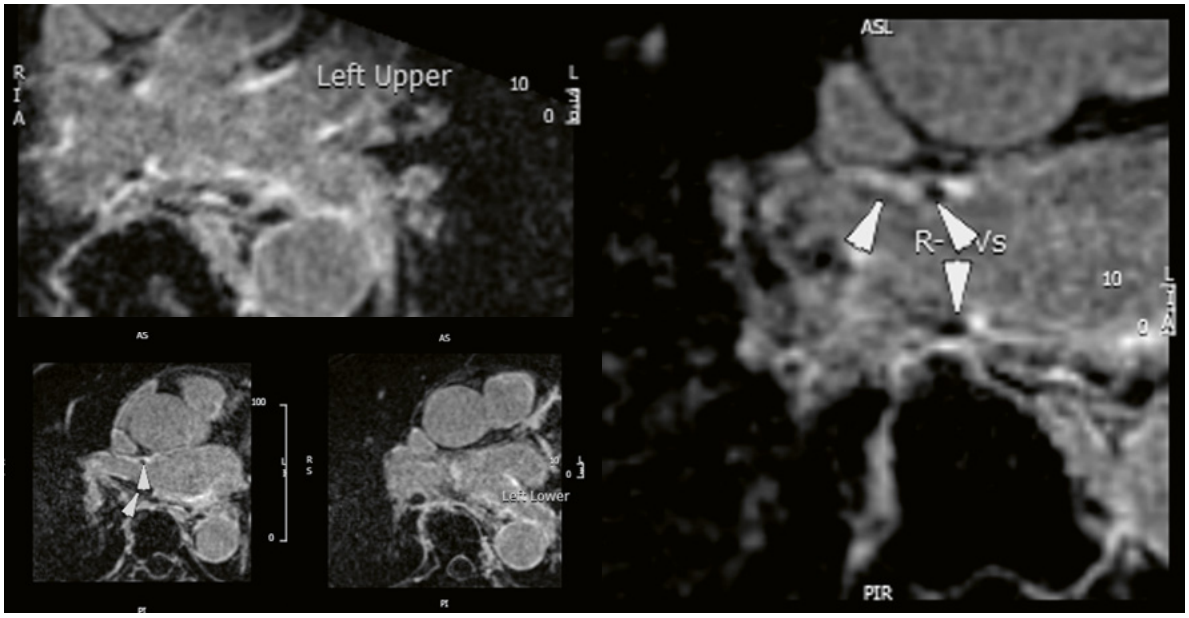
Novel techniques like the free-breathing, image-navigated isotropic high-resolution 3D LGE sequence with Dixon fat-water separation [20] introduce better spatial resolution and shorter scan times. Fat suppression improves diagnostic accuracy, which is crucial in thin structures like the atria. Sample images of post-ablation PV lesions are seen in Figures 6 and 7.

Challenges

LGE image signal intensity is very sensitive to poor ECG gating in arrhythmia, to artifacts from fat in the atrioventricular groove or epicardium, and to artifacts from respiratory motion. Additionally, volume averaging may represent a perfectly sharp but slanted scar border as "heterogeneous tissue" on LGE that affects the detection of VT corridors.



6 Post-ablation for atrial fibrillation imaging.
6A: Electroanatomical voltage maps showing the gaps in pulmonary vein isolation.
6B: PSI maps derived from 3D LGE whole-heart datasets showing complete agreement.



7 24 hours post-cryoablation for atrial fibrillation imaging. 3D LGE whole-heart imaging of the lesions using a novel iNAV Dixon fat-water separation sequence.

For patients with AF, cardioversion is often recommended prior to the study to improve image quality [32].

The time delay between contrast injection and image acquisition is crucial. Despite the lack of official consensus, LGE MRI acquisition is usually performed 15–25 minutes (atrium) or 7–15 minutes (ventricle) after injection of gadolinium contrast agent.

As mentioned earlier, novel motion-corrected whole-heart 3D water/fat LGE imaging has been introduced, showing good agreement with conventional breath-hold 2D LGE imaging. It offers higher spatial resolution and good image quality from a free-breathing acquisition with 100% scan efficiency and a predictable scan time [20].

Finally, a major limitation for arrhythmia patients is the presence of devices (ICDs, CRTs, pacemakers). This is because they can cause hyperintense image artifacts that partially or fully cover the area of interest. To avoid these artifacts, wideband MRI sequences have recently been developed that increase the bandwidth of the inversion and excitation pulse and reduce the incidence of artifacts.

Conclusion

Over the last decade, the technical development of high-resolution 3D whole-heart imaging has provided new insights into congenital heart disease and arrhythmia treatment, increasing diagnostic confidence, patient safety, and procedural success.

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