Intracardiac echocardiography (ICE) is increasingly used to facilitate catheter ablation of ventricular arrhythmias (VA). It allows intraprocedural recognition of myocardial substrate, optimization of catheter-tissue contact, identification of anatomical barriers to ablation, and early recognition of complications. In the era where the 3-dimensionality of substrate for VA is increasingly recognized, ICE is invaluable in identifying scar topography in the endocardial, midmyocardial, and epicardial layers. ICE assists in identifying endocavitary structures that are a common source of VA in idiopathic and structural heart disease. Furthermore, as substrate imaging of the right ventricle has not been optimized with other imaging modalities, ICE offers a unique opportunity to visualize substrate in this chamber. Real-time substrate identification can be particularly useful where there are contraindications to use of other imaging modalities or the images are obscured by artefact in the presence of cardiac device leads. In this review we provide a step-by-step guide in the techniques used to image ventricular arrhythmia substrate with ICE. We also discuss the benefits and limitations of this technique in comparison to other imaging modalities.

**KEYWORDS** Intracardiac echocardiogram; Ventricular arrhythmia; Catheter ablation; Substrate; Cardiac imaging

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**Introduction**

Substrate identification with pre-procedural imaging is limited in patients with pre-existing devices for ventricular arrhythmias (VA). Contraindications for magnetic resonance imaging (MRI) scanning are common and computed tomography (CT) interpretation of septal substrate with device leads in situ can be difficult. Intraprocedural imaging with intracardiac echocardiography (ICE) is being increasingly used in electrophysiology procedures for real-time substrate assessment. Substrate assessment with ICE is based on imaging regions of scar and wall motion abnormality. dense scar is defined as regions with high echogenicity, wall thinning, akinetic motion, or, more subtly, the absence of systolic wall thickening (Graphical Abstract).

The use of ICE during VA ablation can reduce or eliminate fluoroscopy requirements (essential for zero-fluoroscopy approaches) and support avoidance and early detection of procedural complications. ICE can be a valuable adjunct to electroanatomic mapping (EAM) for real-time localization of arrhythmogenic substrate in epicardial and midmyocardial substrate, common in nonischemic cardiomyopathy (NICM), allowing planning of mapping and ablation. ICE imaging allows visualization of catheter contact where there are anatomical barriers to endocardial ablation including substrate in regions of aneurysms and papillary muscles. Additionally, MRI and CT substrate identification in the right ventricle (RV) has not been optimized; therefore ICE offers a unique opportunity to visualize substrate in this chamber. In this review, we describe the techniques for ICE catheter manipulation to allow acquisition of ventricular anatomy, identification of endocavitary structures, and identification of substrate for VA. We also discuss the benefits and limitations of this technique in comparison to other imaging modalities.

All work was performed according to protocols approved by the Western Sydney Local Health District Human Research Ethics Committee.

**Utility of ICE in ablation of VAs**

The primary mechanism for ventricular tachycardia (VT) in patients with structural heart disease is reentry within and around regions of fibrosis or scar. These arrhythmogenic areas can be identified by cardiac imaging and mapping.
KEY FINDINGS

- Intracardiac echocardiography (ICE) is increasingly used to facilitate catheter ablation of ventricular arrhythmias (VA).
- ICE displays myocardial substrate which is seen as high echogenicity, wall thinning, akinetic motion or absence of systolic wall thickening.
- The outcomes of ICE use for substrate identification during VA ablation should be evaluated.

VT substrate in NICM is often epicardial and/or midmyocardial. Standard EAM techniques can lack specificity for identifying epicardial or midmyocardial substrate. In these situations ICE is an important adjunct to EAM for real-time imaging and localization of arrhythmogenic substrate. 

Identification of substrate not easily accessed or ablated from the endocardial cavity can prompt the operator to use epicardial access or alternative techniques such as the use of hypotonic irrigants, or simultaneous unipolar or bipolar ablation. 

Midmyocardial or epicardial scar of the LV is indicated by the presence of localized hyperechogenicity with or without associated regional wall motion abnormality that persists after reducing the gain on ICE imaging. 

This increased echogenicity has been shown to correlate with endocardial unipolar abnormalities and regions of late gadolinium enhancement on cardiac MRI.

The benefit of ICE for endocardial VT ablation in ischemic cardiomyopathy (ICM) lies in facilitating catheter visualization and positioning where there are anatomical barriers to effective ablation. This is specifically useful in the following locations: anteroapical aneurysms, particularly when they contain chronic calcified thrombus; ischemic substrate within papillary muscles (especially when co-localized within a scarred and/or tethered postero medial papillary muscle); and basal inferior aneurysms where the superior-posterior LV process and cardiac crux are difficult to outline.

Techniques for ICE imaging of VA substrate

Catheter manipulation

Manipulations of current phased array ICE probes consist of clockwise or counterclockwise rotation, probe advancement/withdrawal, and utilization of 4-way steering via the deflection mechanism at the catheter handle. As shown in Figure 1A–1D, the probe can be deflected in 4 directions: “anterior,” “posterior,” “left,” and “right.” The location of piezoelectric crystals is on the side of the probe, close to its tip. With the AcuNav™ and SoundStat™ catheters ( Biosense Webster, Irwindale, CA) and the Viewflex™ (Abbott, Abbott Park, IL), the piezoelectric crystal orientation aligns with the anterior deflection mechanism of the catheter. When looking at the image of the ultrasound (ULS) system, shown in Figure 1, if the handle icon is on the left, the distal part of the field of view is closest to the tip of the catheter and the proximal field of view is closest to the handle. With anterior deflection, the field of view will be deflected toward the catheter handle; posterior tilt field of view will be away from the catheter handle. The left tilt will move the field of view toward a horizontal position leftward to the catheter handle and right tilt in the opposite direction.

Settings for use

We have found that with ICE, imaging quality is dependent on a combination of catheter positioning, imaging settings on the ULS, and the patient’s rhythm. Positioning of the catheter is an adaptive process, based on the individual patient

Intraprocedural ICE image integration has been shown to reduce fluoroscopy times during arrhythmia ablation and nonfluoroscopic VA ablation is feasible with the use of ICE. ICE can safely guide transseptal puncture without the use of fluoroscopic imaging. The use of intraprocedural ICE assists with avoidance and early recognition of procedural complications. This is achieved by allowing imaging and tagging of critical structures, such as coronary artery ostia to avoid adjacent ablation, aortic atheroma to avoid embolization during retrograde aortic access to the left ventricle (LV), and intracardiac thrombus to avoid embolization during mapping and ablation. ICE also facilitates early detection of pericardial effusions and helps visualize the sheath in the pericardial space during pericardiocentesis.

In comparison, ICE can be routinely accessed and allows real-time imaging of cardiac structures during ablation procedures. This can be achieved without reconfiguration of the laboratory or acquisition of specific equipment as would be required for a setting compatible with MRI. ICE images can be integrated with 3-dimensional (3D) EAM into a single clinically useful dataset with both anatomic and electrophysiologic information to help guide ablation procedures. The integration may be facilitated by automated software. Although integration with 3D EAM can also be achieved with CT and MRI images, these images must be acquired prior to the procedure and may be subject to reduced accuracy of image integration owing to a change in intravascular volumes between the time of radiological image acquisition and the time of the procedure. The 3D EAM and ICE mapping can be further complemented by merging with other imaging such as CT, MRI, positron emission tomography (PET), or single-photon emission computed tomography (SPECT), to clarify anatomy, substrate, and metabolic activity.

Intracardiac echocardiography (ICE) is increasingly used to facilitate catheter ablation of ventricular arrhythmias (VA).
anatomy and the presence of intervening foreign bodies. Diagnostic catheters, pacing leads, and mechanical valves can all cause an artefact in the field of view and should be avoided where possible (Supplemental Figure 1). Diagnostic catheters can be overcome by small adjustments of left or right deflection to move the orientation of the beam slightly away while maintaining the view of interest. Optimizing the image settings of the ULS is important; depth, frequency, power, and level of time gain constant all need to be optimized before beginning. Another consideration for optimizing the image quality is the rhythm of the patient. Frequent ectopy can be difficult when interrogating small anatomical regions like the ostium of coronary arteries. The change in contraction can cause the catheter to bounce, losing position and the image. Fixed atrial, ventricular, or atrioventricular pacing can stabilize the catheter to optimize image quality.

**Standard anatomical imaging**

**Imaging of right ventricle**

Ventricular imaging may commence at the “home view.” The home view is defined as an imaging position from the right atrium (RA), visualizing the tricuspid annulus and a long axis of the RV. Commonly the free wall of the right ventricular outflow tract (RVOT) is seen in this position without any deflections of the catheter. Depending on the angle of the inferior vena cava, a small adjustment with posterior tilt will open this view if initially directed inferiorly. Small rotations clockwise will show the aorta and in the far field of the beam a more septal aspect of the RVOT (Figure 2A–2C). Small rotations counterclockwise will show the lateral border of the tricuspid annulus and more of the free wall of the RV. Depending on the depth setting you may experience dropout of the RV apex from this location and would benefit from imaging in the RV for greater detail to the RV apex. An ideal position for imaging the RV apex is at the RVOT or RV infundibulum level. This level positions the catheter tip just beyond the tricuspid valve leaflets, and without any deflections on the catheter enables clean rotation clockwise and counterclockwise to image the majority of the right and left ventricles. To attain this position starting from the RA, anterior deflection is placed on the catheter, imaging the inferior wall of the RA and the cavotricuspid isthmus (CTI). On fluoroscopy the catheter will look close to a horizontal position in a right anterior oblique view. Over-deflecting should be avoided so as to not catch a prominent inferior tricuspid annulus or the CTI region. The catheter is then advanced slowly until imaging shows the catheter beyond the tricuspid leaflets. Once beyond the leaflets, all anterior deflection is released. The catheter should now nestle between the tricuspid leaflets and posterior basal RV, pointing toward the RVOT but not into it. If any RV ectopy is observed, the catheter is withdrawn slightly until ectopy ceases. At this position, counterclockwise rotation of the catheter will allow imaging of the inferior RV through to the free wall of the RV (Figure 3A–3C). The superior aspect of the beam will be toward the apex and may observe the moderator band and RV papillary muscles from this view (Supplemental Figure 2A–2F). Further counterclockwise rotation will show the free wall of the RVOT and the pulmonary valve (Figure 3G–3I).

At this position withdrawing the catheter, if not already visible, will show a cross section of the right coronary artery (RCA) and the tricuspid annulus. This can be useful when attempting to visualize the ostium of the RCA to aid in identifying its course and where it attaches. Imaging the ostium of the RCA at this location is not clear though (coronary imaging is discussed in detail below).
From the RVOT level, interpretation of the intraventricular septum (IVS) is difficult as the catheter abuts the septum itself. Several techniques can be used to visualize the septum fully; posterior deflection to move away from the septal position, and returning to the RA and using a right deflection, will place the beam at a horizontal position (Figure 2D–2F).

Clockwise rotation will show additional anterior wall and IVS. Alternatively cannulating the coronary sinus (CS) will also allow detailed imaging of the IVS.

Operator care needs to be observed with ICE catheter placement in the thin-walled CS. Ultimately imaging without either a diagnostic catheter or LV lead is optimal to minimize

Figure 2  Imaging with intracardiac echocardiography (ICE) catheter from the right atrium (RA). A–C: Progressive clockwise rotation from starting position in RA. Left panel electroanatomical mapping (EAM) reconstruction in left anterior oblique (LAO) of left ventricle (LV) in gray, right coronary cusp (RCC) green reconstruction, left coronary cusp (LCC) pink reconstruction. Right panel corresponding ICE images are as follows: A: The RA, right ventricle (RV), aorta (Ao), and right ventricular outflow tract (RVOT) are visible. B: RA, Ao, RVOT, and the muscular intraventricular septum (IVS) are visible. C: RA, left atrium (LA) and mitral valve (MV), coronary sinus (CS), and basal LV are visible. D–F: Imaging from RA with right deflection applied and progressive counterclockwise rotation. Left panel EAM reconstruction of RV and LV in right anterior oblique (RAO). Right panel corresponding ICE images are as follows: D: RA tricuspid valve (TV). RV, and LV with IVS. E: RA TV, RV, and LV with IVS. F: RV, device lead in the RV apex, and musculature of the inferior LV. G,H: Fluoroscopy showing ICE catheter in RA. G: RAO image. H: LAO image.
the risk of complications such as perforation or LV lead dislodgement. If the catheter is positioned in the CS ostium and anterior deflection was used to cannulate the CS, the beam is likely to be pointing inferiorly or posteriorly. Counterclockwise rotation of the catheter will bring the ventricles into view from the inferior ventricle to the free wall and apical RV, moderator band, and then superiorly toward the RV and RVOT (Figure 4A–4F).

**Figure 4** Imaging the left ventricle (LV) and right ventricle (RV) from the coronary sinus (CS). A: Inferiorly directed beam visualization of the inferior basal wall of RV and LV. B: Inferior beam visualization to apex of both LV and RV with intraventricular septum (IVS). C: Low mid RV imaging with free wall RV insertion point of moderator band shown at green arrow. D: Mid RV imaging with moderator band shown at green arrow. E: Low right ventricular outflow tract (RVOT) imaging and anterior basal LV with left atrium (LA) and mitral valve (MV) in near field. F: RVOT and aorta (Ao) / left ventricular outflow tract (LVOT), with near-field anterior wall LA. G,H: Fluoroscopy showing intracardiac echocardiography catheter in CS. G: Right anterior oblique image. H: Left anterior oblique image.

**Imaging of left ventricle**
Imaging of the LV is a continuation of the RV views (Figure 5A–5I). From the level of the RV infundibulum, clockwise rotation of the catheter will reveal an intramuscular view of the IVS and then the apical septum. Progressive rotation clockwise will reveal the posteromedial papillary body and then the anterolateral papillary body with visualization simultaneously of the inferior and lateral aspects of the LV.

**Figure 5** Left ventricle (LV) imaging from right ventricle (RV) infundibulum level. Left panel electroanatomical mapping reconstruction of RV and LV in left anterior oblique. Right panel corresponding intracardiac echocardiography image. A–I: Progressive clockwise rotation from the RV infundibulum level starting at the inferior RV, intraventricular septum, and apex views and finishing at the level of the aortic cusps.
Further clockwise rotation allows visualization of the mitral valve, and the anterior and lateral walls of the LV, after the papillary muscles have passed out of view. With continued clockwise rotation, a level will be reached where the mitral valve is not clearly observed and the LV outflow tract (LVOT) will commence visualization. At this point the beam is superiorly directed above the mitral valve and displays the aortomitral continuity region and ventricular summit. Clockwise rotation will display the aortic annulus.

Identification of the papillary muscle heads requires multiple views to adequately define the separate attachments of the chordae (Supplemental Figure 3A and 3B). Rightward deflection of the catheter while a papillary muscle is in view and then rescanning with clockwise and counterclockwise rotation is frequently applied to confirm the multiple heads of the papillary muscle.

The anterior wall of the mid and apical LV can be missed. Slight advancement of the catheter into the RVOT, carefully watching for catheter ectopy, enables a view of the mid and apical LV. Alternatively, leftward deflection can be used while pointing into the RVOT and then rescanning clockwise and counterclockwise. If the mid and apical LV is still not visualized, the catheter should be repositioned to another location like the RV body or CS for visualization. As mentioned in imaging of the RV, if cannulation of the CS occurs with an anterior deflection, the image is likely to be of inferior or posterior views of the LV. Counterclockwise rotation will bring the LV into view from the inferior ventricle and posterior medial papillary to apex. Continuing counterclockwise allows visualization of the anterolateral papillary and to periaortic regions (Figure 4A–4F).

**Imaging for coronary arteries and aortic cusps**

Imaging of the aortic cusps begins from the RV infundibulum position, viewing the LVOT/aortomitral continuity region. Clockwise rotation enables a short axis with the 3 aortic cusps in view. Dependent on depth into the RV, a part of the posterior right coronary cusp (RCC) and the noncoronary cusp (NCC) may not be visualized; slight withdrawal of the catheter increases RCC/NCC visualization. In identification of cusps from the RV infundibulum position, the left coronary cusp is the furthest away, the RCC is near the distal edge of the beam, and the NCC is near the proximal edge of the beam. Small clockwise catheter rotation at this site will allow visualization of the ostium of the left main coronary artery (LMCA) with a long axis of the vessel (Supplemental Figure 4A and 4B and Supplemental Video 1). The RCA is difficult to visualize from the RV infundibulum position owing to its close proximity to the catheter tip. Ideally, repositioning the catheter away from the septum is required to image the RCA clearly (Supplemental Figure 5A). Alternatively, continued clockwise rotation of the catheter can be used, from the position where the LMCA is visualized to a location where the ascending aorta and pulmonary valve are observed. At this location, a cross section of the RCA can be viewed within the right atrioventricular groove. Continued clockwise rotation may be required to obtain this view. Once identified in cross section, the RCA can be tracked back toward the RCC with counterclockwise rotation of the catheter to identify the ostium of the vessel.

Ideally, a long axis of the RCA should be identified, as it provides the best representation of the ostium connecting in the RCC. The catheter is returned to the mid RA, and rightward deflection is applied, enabling imaging of the tricuspid valve, RA, and RV. The beam position is in a more horizontal plane, between a 45- and 80-degree deflection. With this orientation, rotation of the catheter clockwise will allow visualization of the aorta (catheter advancement may be required). Clockwise and counterclockwise rotation at this point will allow identification of the RCA ostium (Supplemental Figure 5B). Another position for imaging the RCA in its long axis is from the CS. With the beam directed superiorly from the CS, a long-axis view of both the RCA and LMCA can be achieved (Supplemental Figure 5C).

**Imaging for scar and wall motion abnormality**

Signal intensity on ICE was shown to correlate with regions of scar by voltage criteria identified on EAM.4 Most of the circuitry for reentrant VAs arises from regions within 5 mm of myocardial scar, which can be visualized on ICE as thinned aneurysmal regions.21 We characterize dense scar as regions with high echogenicity compared to surrounding tissue, wall thinning, akinetic/hypokinetic motion, and lack of thickening through the systolic period (Supplemental Figure 6 and Supplemental Video 2). Visualization of the full wall shows the endocardial, midmyocardial, and epicardial layers of scar (Figure 6A–6C). Wall motion abnormality is defined as hypokinetic, akinetic, or dyskinetic motion.

Imaging for scar and wall motion abnormality requires positioning of the probe for multiple views and visualizing the full thickness of myocardium. Adjustments to image depth may be required if a position does not allow visualization of the full extent of myocardium. A single position is not ideal for imaging all aspects of scar. In our experience, imaging only from the RV infundibulum level often misses or reduces the interpretation of the near-field septal aspect (Supplemental Figure 7A and 7B, Supplemental Videos 3 and 4).

With an increase in the number of VA ablation procedures for NICM, localization of substrate in the basal septum and periaortic region is critical, and thus visualization of this region is paramount. Initially positioning of the catheter at the RV infundibulum provides the majority of the anatomy and has been shown to identify scar in the lateral wall (Figure 7A–7D). Rotation clockwise images the oblique apical aspect of the septum and continued rotation through to the aortic cusps will allow visualization of the inferior and lateral walls of the left ventricle and enable interpretation of the papillary muscles for scar and for wall motion abnormalities.
In some instances, the papillary muscles need to be carefully interpreted for substrate that may involve focal echogenicity on the papillary body, intramuscular extension, or total papillary infarction (Supplemental Figure 8A–8C). Rarely, VAs may be associated with muscle bundles with high echogenicity and akinesis connected to papillary structures (Supplemental Figure 8D). When viewing the mitral valve, one should observe for substrate near the basal attachments of leaflets.

From the RV infundibulum, interrogation of the periaortic and basal septum for scar and wall motion is challenging. Posterior tilt and withdrawing of the catheter slightly may assist visualization of the periaortic basal septum from this position. Visualization of the periaortic basal septum is best achieved from the CS (Supplemental Figure 7A).

An anterior apical aneurysm of the LV is easily visualized from the RVOT, but this position often misses part of the anterior wall of the LV (Supplemental Figure 9). To visualize anteroapical septal scars, appropriately advancing the catheter while imaging superiorly, or using posterior deflection, and scanning through with clockwise and counterclockwise manipulation will reveal this region. For apical imaging, often we find this can be performed by repositioning the catheter completely into the RV body, as described previously. With the catheter located in the low RV body position, imaging of the anterior LV wall is easier to accomplish. Septal scarring and wall motion detection is best visualized from the CS (Supplemental Figure 7A). Interpretation from this position is only required at a location 1–2 cm from inside the CS ostium or from a sufficient depth into

Figure 6  High echogenicity at differing myocardial layers. A: Endocardial scar (red arrow), which also has an epicardial component (green arrow). B: Midmyocardial scar; edge of scar (red arrows), then progresses to midmyocardial and epicardial scar (blue arrows). C: Epicardial scar (red arrows). LV = left ventricle; RV = right ventricle.

Figure 7  Imaging from the right ventricle infundibulum for lateral wall scar. Right panels show electroanatomical mapping reconstruction, left ventricle (LV) (gray), and intracardiac echocardiography (ICE) scar (brown). Left panels show ICE image of corresponding location. A–D: Progressive counterclockwise rotation from basal LV toward apex. Imaging shows a transmural thickness scar at the lateral base, with progressive imaging toward the apex showing the scar moving epicardially in the mid LV and progressing into the midmyocardial area at the apical extension. Images courtesy Dr S. Agarwal, Royal Papworth Hospital, Cambridge UK. LA = left atrium; LCC = left coronary cusp; NCC = noncoronary cusp; RCC = right coronary cusp.
the CS that will enable clockwise and counterclockwise rotation of the catheter without the catheter being displaced into the RA. Alternatively, if the CS is small, positioning the catheter in the LA through a transseptal puncture can be performed; however, an 8F ICE catheter needs to be used if the LA is entered using a sheath.

Ideally, cannulation of the CS with the catheter using the posterior deflection mechanism will enable the catheter beam to be directed superiorly and reduce the amount of rotation required for adequate viewing of the septum. With the beam directed superiorly, the periaortic and LV summit region can be visualized for substrate (Figure 8A–8F). At this orientation, clockwise rotation will image toward the LV body and obtain a long-axis view of the LV. Counterclockwise rotation will image the aorta and LV outflow tract, subvalvular periaortic region, and basal septum. Both the LV and RV sides of the septum can be visualized at this position.

One location that is inadequately imaged at both the RVOT and CS locations is the inferoseptal process of the LV. Imaging of this location is routinely performed from the RA, rotating clockwise from the starting position of the RA, RV, and tricuspid valve. Slight left and right adjustments may be needed to improve image quality (Supplemental Figure 10A and 10B, Supplemental Video 5).

RV imaging for scar is difficult owing to the normally thin myocardium; thinning therefore cannot regularly be used as a visual marker of scar. Echogenicity on the free wall of the RV can also be difficult owing to the thin myocardium and proximity to the pericardium, which often obscures interpretation. This is not an issue on the septum, however. In some instances, echogenicity and thinning can be observed, commonly after surgical intervention (Supplemental Figure 11 and Supplemental Video 6) or in arrhythmogenic right ventricular cardiomyopathy. Instead, wall motion abnormality and the lack of wall thickening can be used for substrate identification in the RV (Supplemental Figure 12 and Supplemental Video 7). Imaging from the RVOT provides ideal views of the inferior and free walls of the RV. Using counterclockwise rotation will allow visualization from the inferior to high free wall of the RV. The catheter can be advanced or withdrawn for more basal or apical imaging of the RV.

The CS is the preferred site for septal visualization of the RV. From the CS and the low RV, the RVOT can also be imaged for substrate (Supplemental Figure 13 and Supplemental Video 8).

**Limitations of ICE in VA ablation**

Although the importance of ICE in VA ablation is recognized, there is a lack of consensus guidelines regarding its routine use. There are several limitations to this technique...
that should be mentioned. Firstly, as with most radiological techniques, the image quality varies between studies and is often dependent on patient anatomy and tissue-specific characteristics. In the context of VA ablation, the image quality may be impaired by artefact resulting from sheaths, catheters, and intracardiac devices. Satisfactory image acquisition is dependent on operator experience, particularly for locations that are difficult to acquire. There is a learning curve required to master various techniques, such as imaging from the CS.

ICE imaging is performed at the time of the procedure. Therefore, it cannot be used for preoperative scar localization and planning for the procedure and appropriate access. ICE images obtained require integration with 3D EAM and this process can be time-consuming and subject to human error, even when the imaging software is able to partly automate this process. 3D EAM construction using fast anatomical mapping is not electrocardiogram-gated, unlike ICE, which may result in small discrepancies in the geometry produced.

The cost of the ICE catheter may also be an obstacle to adoption of this technology in some centers and countries. Finally, additional venous access is required for ICE and this marginally increases the risk of vascular access complications.

Alternative imaging techniques

Cardiac magnetic resonance imaging

Cardiac magnetic resonance imaging (CMR) has unique benefits in identifying cardiomyopathies and structural abnormalities that are invaluable to planning catheter ablation for VA. Late gadolinium enhancement (LGE) in CMR visualizes scar with precision. Critical VT isthmuses are located within these areas of LGE. The ability to determine the distribution and transmurality of scar helps distinguish NICM from ICM. Furthermore, scar pattern and inflammation can be used to distinguish NICM etiologies. CMR can assist with the diagnosis of arrhythmogenic right ventricular cardiomyopathy, as it can detect RV wall motion abnormalities.

CMR is obtained prior to the procedure and the knowledge of scar architecture allows forward planning of access route. First-line epicardial access can be obtained based on this information and has been shown to improve outcomes. Additionally, CMR has the ability to detect pericardial abnormalities that reflect pericardial adhesions and foreshadow difficulty with catheter manipulation.

CMR is limited by the presence of cardiac devices in a large proportion of patients presenting for catheter ablation of VA. Modern cardiac devices are MRI compatible. CMR use in this context has been demonstrated, although cases of tissue heating and software malfunction have been reported. Despite the potential for CMR in patients with cardiac devices, the disadvantage remains the image degradation owing to artefact. The use of wideband pulse sequence for LGE imaging on CMR has been shown to improve the effect of artifact in the majority of cases. However, this protocol is not available at all centers. Finally, in severe renal impairment, gadolinium use confers a risk of nephrogenic systemic fibrosis and alternative imaging techniques are preferred.

Multidetector cardiac computed tomography

Multidetector cardiac computed tomography (MDCT) has a limited role in identification of VA substrate and can be used in patients in whom CMR is contraindicated. MDCT use in characterization of scar has been described. Scar on MDCT is defined by wall thinning, hypopattenuation, decreased perfusion, and hyperattenuation. Hypoperfusion demonstrated good correlation with scar and border zone areas. MDCT-identified scar has been shown to correlate to arrhythmogenic substrate in postinfarct VT. Despite the presence on implantable devices, there was good segmental concordance between CT and EAM. Unfortunately, there was less robust correlation with scar in NICM.

MDCT is very valuable in planning of catheter ablation of VA, as it has a higher spatial resolution than CMR. It is therefore the preferred technique for detailed anatomy such as coronary arterial and venous systems and phrenic nerve, which need to be avoided. It also provides well-defined views of epicardial fat, which causes poor contact of epicardial catheters and, in turn, unreliable mapping and ineffective ablation. Pericardial thickening or calcification can be detected with this technique, indicating adhesions that complicate pericardial access. Another advantage of MDCT is in detailed assessment of LV thrombus. The current guidelines advise that the presence of laminated thrombus is undesirable but ablation may proceed with caution, whereas mobile thrombus is a contraindication to ablation.

Nuclear imaging

The function of nuclear imaging in VT substrate identification is complementary to alternative imaging techniques. The specific advantages of SPECT and PET imaging include identification of inducible ischemia and silent ischemia, identification of active inflammation, distinguishing scar from viable tissue, and revealing regions with abnormal metabolic activity and sympathetic innervation. Critical VT isthmuses have been shown to be located within or in close proximity to scar on thallium-201 SPECT and PET. However, image integration studies with EAM have shown variable correlation of scar location. Overall, nuclear imaging techniques have been superseded by CMR or CT, as they do not provide sufficient anatomic detail.

Postimaging processing (ADAS-VT and MUSIC)

Advanced processing software has recently refined substrate localization on preprocedural imaging. There are 2 commonly used software platforms: ADAS-VT (Galgo Medical SL, Barcelona, Spain) and MUSIC (Liryc-Université de Bordeaux/Inria-Sophia Antipolis, France).

ADAS-VT uses pixel signal intensity to characterize myocardial fibrosis in 3 dimensions within the layers of the myocardium. This can distinguish between dense zones of fibrosis and border zones, and allows identification of
conduction channels. Targeting ADAS-VT-identified channels for ablation improves immediate and medium-term success rates while reducing radiofrequency lesions and delivery time. Wideband CMR sequences have been used to image patients with implantable cardioverter-defibrillator and used for ADAS-VT. This technique had good accuracy in identifying conduction channels compared to those on EAM. The accuracy was comparable to that of ADAS-VT-identified channels on conventional CMR in patients without implantable cardioverter-defibrillator.

MUSIC fuses multimodality imaging sequences into a single dataset. This can be used to generate 3D volume files that are in turn integrated with EAM. Previous studies have defined the structural substrate in both ICM and NICM as wall thinning on MDCT and LGE on CMR. Image registration is performed after mapping and prior to ablation. This can take up to 45 minutes in cases where MDCT and CMR data are combined. There was good agreement between substrate identification on MDCT and CMR with low-voltage EAM, although this was higher in ICM than NICM, particularly for MDCT-defined substrate. The use of MUSIC was an independent predictor of VT-free survival after catheter ablation for post–myocardial infarction VT. Another major benefit to MUSIC is the ability to include coronary arteries and phrenic nerve in image integration. This may obviate repeated iodine contrast injections and time-consuming pacing protocols, although further evidence is required.

Future directions

To date, there is no published study comparing substrate visualization with ICE and EAM voltages or MRI-identified substrate. The SoundScar study (ClinicalTrials.gov identifier NCT03862339) is currently recruiting, as a prospective, nonrandomized, single-arm study assessing the accuracy of ICE characterization of arrhythmogenic substrate in patients with ischemic cardiomyopathy undergoing VT ablation.

ICE imaging positions have been previously described at the RVOT, RA, and RV. In our experience, imaging from the CS in addition to these positions is required for all areas to be adequately sampled for substrate identification. This allows visualization of endocardial, mid-myocardial, and epicardial scar locations, while also being able to identify intracavitary structures and potential substrate within these. Consistent ICE imaging from all positions is required for comprehensive substrate assessments; therefore, uniformity of imaging across all laboratories is required.

Wall motion abnormality and wall thickening are qualitative assessments. Strain assessment has become routine practice in transthoracic echocardiography. Strain measurements can measure inhomogeneous ventricular contraction and subtle electromechanical changes and has been associated with an increased risk of VA in ischemic and nonischemic cardiomyopathies. Intraprocedural techniques for use and validation in ICE are needed.

Conclusion

ICE contributes considerably to the VA ablation procedures. It permits intraprocedural imaging of myocardial substrate in the context of VA ablation while also allowing observation of catheter contact where there are anatomical barriers and early recognition of complications. Further research is needed to clarify the correlation of substrate appearance on ICE to substrate identified by EAM in different cardiomyopathy etiologies. Furthermore, the outcomes of ICE use for substrate identification during VA ablation procedures should be evaluated, as this technique undoubtedly has multiple advantages.

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Authorship: All authors attest they meet the current ICMJE criteria for authorship.

Appendix

Supplementary data

Supplementary data associated with this article can be found in the online version at [https://doi.org/10.1016/j.hroc.2022.06.006].

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