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VT ablation: New Developments and Approaches

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Opinion Statement

Over the past decade, catheter ablation has emerged as an important therapeutic option for ventricular tachycardia (VT) in both patients with and without structural heart disease. In patients without structural heart disease, catheter ablation serves as sole therapy for the treatment of VT. For those with structural heart disease, VT ablation has generally been reserved for patients who experience ICD therapies, and particularly those who fail antiarrhythmic agents. With the growing number of patients with implantable devices as well as improvements in heart failure therapy resulting in improved survival among ICD patients, the overall number of patients needing therapy for VT continues to increase. The past years have witnessed significant advances in our understanding of the arrhythmic substrate in various cardiomyopathies, resulting in substrate-based approaches for targeted VT ablation. Further, the growth in better technologies and techniques for VT ablation, such as the use of percutaneous epicardial ablation, the innovation of multielectrode catheters for rapid mapping, the use of intracardiac echocardiography (ICE) for mapping unusual sites, and activation and entrainment mapping of previously unmappable VTs assisted by mechanical circulatory support devices, has overcome the limitations and greatly improved the success rates of catheter ablation. This review summarizes recent advances and novel approaches in both technology and techniques for catheter ablation of ventricular tachycardia.

Introduction

Ventricular tachycardia (VT) is one of the most significant causes of sudden cardiac death, commonly occurring in patients with underlying structural heart disease [1]. The goals of treating VT include restoring

normal heart rhythm, managing the underlying disease, and preventing future episodes. There are 3 management options for VT: implantable cardioverter-defibrillator (ICD) placement, antiarrhythmic drug (AAD) medication, and catheter ablation. In most VT patients with structural heart disease, ICDs remain the first-line treatment for primary and secondary prevention of sudden cardiac death (SCD) [2]. Although ICD therapies are lifesaving, ICDs have no influence on the substrate nor do they prevent the occurrence of VT. Moreover, repeated ICD shocks have been shown to decrease the quality of life by causing psychological impairment and post-traumatic stress syndrome and have been linked with higher rates of mortality and heart failure hospitalizations [3–5]. Antiarrhythmic medications such as amiodarone and beta-blockers can reduce the frequency of ICD interventions, albeit with disappointing efficacy and side effects [6, 7]. Over the past decade, radiofrequency catheter ablation has evolved as a promising treatment modality for ventricular tachycardia and has significantly reduced the burden of VT, and hence ICD, even in patients with advanced heart disease [8, 9•, 10–15]. Recent years have seen significant advances in both mapping techniques and ablation technology, coupled with better understanding of VT substrates in various cardiomyopathies. The success rate of catheter ablation is over 90 % in patients with otherwise normal hearts. In patients with structural heart disease, most commonly from post-infarct scar or cardiomyopathy, the success rate, as measured in terms of freedom from recurrent VT, ranges between 50 % and 75 % within the first 2 years. However, there is no evidence of reduction in mortality [16]. This review will focus on the most recent advances in preprocedural imaging and new mapping and ablation techniques for the management of recurrent VT.

Current indications for VT ablation

In the past, ablation was considered only after pharmacological options had been exhausted, often after the patient had suffered substantial morbidity from recurrent episodes of VT and ICD shocks. Advances in technology and understanding of VT substrates now allow ablation of multiple and unstable VTs with acceptable safety and efficacy, and the indications for VT ablation continue to expand and are recommended earlier in the course of the disease [9•, 14, 15]. Current indications of catheter ablation are idiopathic VT, scar-related VT with multiple ICD shocks, and VT storm. The ideal candidate for catheter ablation is the patient who has hemodynamically tolerated VT with well-circumscribed infarction and preserved ejection fraction. Current indications according to the 2009 EHRA/HRS Expert Consensus on Catheter Ablation of Ventricular Arrhythmias are shown in Table 1[8].

Preprocedural imaging

Preprocedural imaging is critical for patients undergoing VT ablation. Various imaging modalities, including echocardiography, nuclear imaging, and/or magnetic resonance imaging (MRI) or computed tomography (CT) imaging, can provide valuable anatomic and/or functional information prior to ablation [17, 18]. A number of studies published in past years have expanded the role of preprocedural imaging in the diagnosis and treatment of VT. Of note, MRI with late gadolinium enhancement (LGE) is able not only to localize the presence of scar but also to further characterize the distribution as involving the endocardium, midmyocardium, and/or epicardium [19]. When extensive midmyocardial or epicardial scar is identified, the likelihood of

Table 1. Indications for catheter ablation of ventricular tachycardia

Patients with structural heart disease (including prior MI, dilated cardiomyopathy, ARVC/D)

Catheter ablation of VT is recommended

1. for symptomatic sustained monomorphic VT (SMVT), including VT terminated by an ICD, that recurs despite antiarrhythmic drug therapy or when antiarrhythmic drugs are not tolerated or not desired;*
2. for control of incessant SMVT or VT storm that is not due to a transient reversible cause;
3. for patients with frequent PVCs, NSVTs, or VT that is presumed to cause ventricular dysfunction;
4. for bundle branch reentrant or interfascicular VTs;
5. for recurrent sustained polymorphic VT and VF that is refractory to antiarrhythmic therapy when there is a suspected trigger that can be targeted for ablation.

Catheter ablation should be considered

1. in patients who have one or more episodes of SMVT despite therapy with one of more Class I or III antiarrhythmic drugs;*
2. in patients with recurrent SMVT due to prior MI who have LV ejection fraction >0.30 and expectation for 1 year of survival, and is an acceptable alternative to amiodarone therapy;*
3. in patients with hemodynamically tolerated SMVT due to prior MI who have reasonably preserved LV ejection fraction (>0.35) even if they have not failed antiarrhythmic drug therapy.*

Patients without structural heart disease

Catheter ablation of VT is recommended for patients with idiopathic VT

1. for monomorphic VT that is causing severe symptoms.
2. for monomorphic VT when antiarrhythmic drugs are not effective, not tolerated, or not desired.
3. for recurrent sustained polymorphic VT and VF (electrical storm) that is refractory to antiarrhythmic therapy when there is a suspected trigger that can be targeted for ablation.

VT catheter ablation is contraindicated

1. in the presence of a mobile ventricular thrombus (epicardial ablation may be considered);
2. for asymptomatic PVCs and/or NSVT that are not suspected of causing or contributing to ventricular dysfunction;
3. for VT due to transient reversible causes, such as acute ischemia, hyperkalemia, or drug-induced torsade de pointes.

ARVC/D, arrhythmogenic right ventricular cardiomyopathy/dysplasia; ICD, implantable cardioverter defibrillator; MI, myocardial infarction; VT, ventricular tachycardia; VF, ventricular fibrillation

*This recommendation for ablation stands regardless of whether VT is stable or unstable or multiple VTs are present.

epicardial ablation to achieve arrhythmia control increases accordingly. In addition, LGE image-based simulation can be used to estimate potential ablation targets of scar-related VT [20].

Similar to MRI, preprocedural cardiac CT with delayed enhancement or positron emission tomography is another important methodology to provide accurate 3-dimensional anatomic and scarring images, which can be registered real-time with voltage substrate maps in procedural periods. Tian et al. [21] reconstructed 3-dimensional scar from the hypoperfusion areas in contrast-enhanced CT images and imported it into the Carto XP mapping system. They found that CT hypoperfusion correlated well with scar and border-zone areas. Komatsu et al. [22] studied regional myocardial wall thickness with contrast-enhanced multidetector CT in 13 post-infarction patients and integrated the CT images with high-density electroanatomic maps acquired during sinus rhythm. They found that myocardial wall thinning correlates to low-voltage regions and distribution of local abnormal ventricular activities. CT also has the ability to depict fatty tissue in patients with ARVD [23]. In patients who have a contraindication for MRI, CT may be another option for identifying VT substrate prior to ablation.

In addition, image-based simulation can be used to estimate potential ablation targets of scar-related VT [20]. This method centers around identification of the heterogenous zone (HZ), which is scar interspersed with normal myocardium that forms the structural basis for slowly conducting tissue. LGE- derived HZ [24] can be a powerful noninvasive tool for preprocedural planning of ablation procedures and has the potential to reduce procedure time and improve success of catheter ablation.

Advances in mapping techniques

Substrate mapping

Conventional mapping techniques in VT ablation include activation mapping, pace mapping, entrainment mapping, and 3-dimensional electroanatomic mapping. These mapping techniques can be used separately or combined for the determination the potential targets for catheter ablation. For patients with stable VT, activation and entrainment mapping during VT is important for identification of the critical circuit. Although this is ideal, clinical VT in the majority of patients is either noninducible or hemodynamically unstable, and multiple VTs are often induced, rendering conventional mapping techniques ineffective. To a certain extent, substrate mapping combined with pace mapping techniques during sinus rhythm have overcome these limitations [25]. The principle for substrate mapping is based on the identification of low-voltage and slow conduction areas, which may harbor possible reentry circuits. Using a 3-dimensional electroanatomic mapping system, point-to-point bipolar voltage mapping is performed in the ventricles to identify low-voltage areas that signify scar or fibrosis. In the ventricular endocardium, areas with bipolar voltage >1.5 mV are considered to be normal. Those with bipolar voltage <0.5 mV are areas of dense scar, whereas areas with voltage of 0.5–1.5 mV are the border zone between necrosis/fibrosis and the normal myocardial tissue [26•]. Following voltage mapping, ablation can be guided by substrate mapping alone, with linear radiofrequency lesions connecting the dense scar to the normal myocardium or anatomic barriers such as the valve planes. The critical isthmus often lies close to the VT exit site identified during pace mapping, and isolated late potentials in the low-voltage areas are often found in the border zones of ischemic or nonischemic scar indicating areas of slow conduction, which often form the VT critical isthmus [27–29].

Multielectrode mapping

Accurate and precise mapping of the substrate via point-by-point electroanatomic mapping is critical to the success of RF ablation. In recent years, novel multielectrode catheters have been developed to facilitate rapid acquisition of higher-resolution maps through simultaneous collection of data from multiple points in space. In addition to several old multielectrode catheters, such as the 64-electrode basket catheter (Constellation, Boston Scientific, Boston, USA) and multielectrode balloon array (EnSite Array, St. Jude Medical Inc., St. Paul, MN, USA), novel multielectrode catheters including the PentaRay high-density mapping catheter (PentaRay, Biosense Webster, Inc., Diamond Bar, CA, USA) and the duo-decapolar catheter

(Livewire, 2-2-2 mm spacing, St. Jude Medical, Minnetonka, MN, USA) have recently been used in VT mapping. Figure 1 shows high-density mapping with the PentaRay catheter.

Using the PentaRay catheter for the mapping of local abnormal ventricular activities in 35 patients with scar-related VT, Jaïs et al [30] found that the PentaRay was capable not only of providing high-density maps with clean electrical signals, but also in enabling careful monitoring of transmural response to ablation, which is particularly helpful in epicardial high-density mapping. Several recent studies also showed promising application of the multielectrode catheter [31, 32].

Epicardial Mapping

Epicardial mapping was first reported in 1996 in three patients with Chagas disease, and has lately become a necessary tool to target epicardial or intramural VT substrates. The epicardial VT substrate is more likely to be found in patients with nonischemic cardiomyopathy (NICM) or Chagas disease [33•]. In ICM-related VT, epicardial substrates are more frequently found in patients with prior inferior-wall myocardial infarction. In a recent multicenter study, the overall prevalence of epicardial circuits in patients referred for VT ablation was 13 % (121 of 913 procedures). The presence of epicardial VT substrate was observed in 41 % of patients with ARVC, 35 % of patients with NICM, and 16 % of patients with ICM [33•].

Patients being considered for epicardial ablation often have ECG or preprocedural image clues that indicate epicardial origin and/or have al-

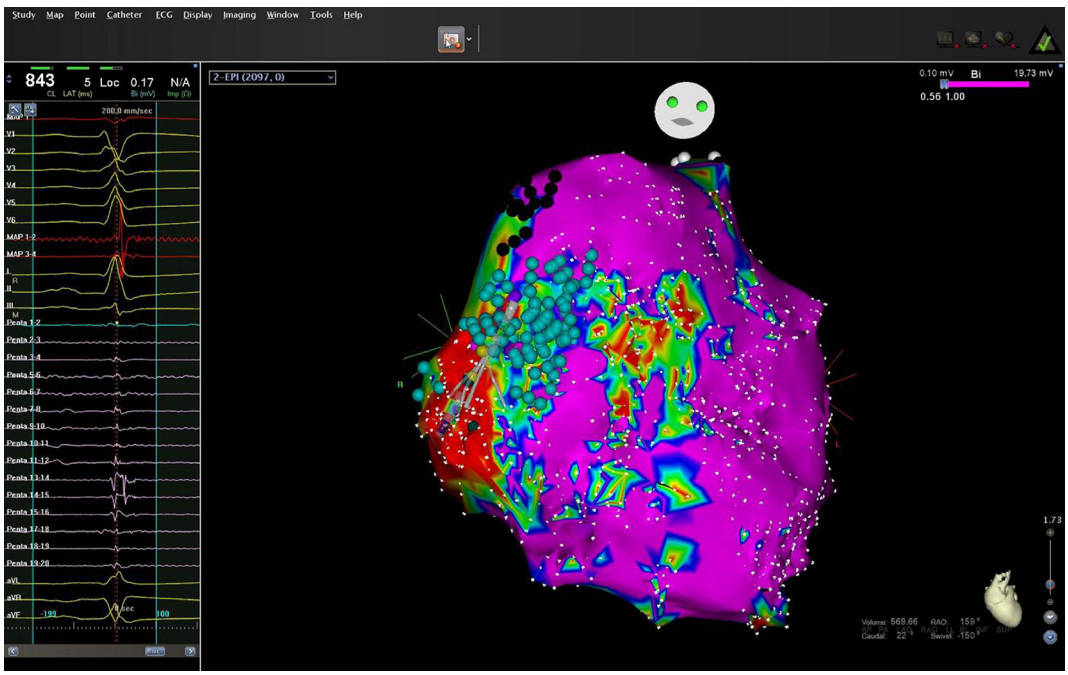

Fig. 1. Ultra high-density mapping of right ventricle using a PentaRay catheter showing dense basal inferior scar. Late potentials (LPs) during sinus rhythm seen on Penta13–15.

ready had a failed endocardial ablation procedure. Recent studies have shown that a local endocardial unipolar voltage (UV) <5.5 mV in the right ventricle (RV) and ≤8.27 mV in the left ventricle (LV) correlated well with epicardial low bipolar voltage areas [34, 35•]. The epicardial UV mapping also is useful for distinguishing scar from viable myocardium in the presence of fat [36].

Combined endocardial and epicardial mapping procedures are possible and would be expected to reduce the number of procedures required for patients with suspected epicardial VTs [37, 38]. The technique involves introducing the mapping catheter into the pericardial space using a subxiphoid pericardial puncture or minimally invasive surgical approach. Potential complications of this procedure are acceptable and generally safe in experienced centers. The most common complication is phrenic nerve injury. Rarer life-threatening complications, however, may occur occasionally, including RV perforation, RV to abdomen fistula, coronary artery vascular injury, laceration to liver tissue, and diaphragmatic bleeding [39]. Techniques to reduce the likelihood of complications include lifting the parietal pericardium away from epicardial surface by instilling air or saline and the inflation of an intrapericardial balloon into the pericardial space to avoid phrenic nerve injury, using cryoablation, when a coronary artery is close to the ablation target.

The success of epicardial ablation varies in different studies, depending upon the specific heart condition that caused VT. Della Bella et al. [40•] reported that acute prevention of VT inducibility was obtained in 71.6 % of 218 patients who received epicardial ablation in 20 experienced European centers, and that 68.6 % of these patients were free of VT recurrence after mean follow-up of 17.3 ±18.2 months. In patients with ARVC, Bai et al. [41] reported freedom from ventricular arrhythmias or ICD therapy in 84.6 % of patients treated with combined endo/epicardial ablation after a follow-up of at least 3 years. Tung et al. [42] recently reported that patients with ICM who underwent a combined epi/endo ablation had improved freedom from VT at 12 months compared with those who underwent endo-only ablation (85 % vs. 56 %). Although overall clinical recurrence remains high despite epicardial ablation, combined epi/endo ablation may improve the ablation success rate in some VT patients, particularly in those with ARVC and ICM.

Mapping of unusual VTs

In some patients with an unusual site of VT origin, such as idiopathic focal VT originating from papillary muscles (PAMs) or from giant basal aneurysm caused by chronic chagasic cardiomyopathy, the complex structure may pose difficulties in catheter manipulation. In these unusual cases, real-time 3-dimensional electroanatomical maps merged with preprocedural CT/MRI images are helpful for mapping and ablation [43, 44]. However, the real-time endocardium anatomy and catheter tip/myocardium contact cannot be visualized.

Intracardiac echocardiography (ICE) offers the unique ability to image the heart in real time during the course of the ablation procedure, and to both identify structures such as the papillary muscles and other obstacles to promote better navigation as well as to assess for catheter contact with the

myocardial wall during ablation [45, 46]. ICE can be safely used throughout invasive procedures for early detection of complications such as myocardial perforation/effusion to potentially avoid adverse events. In addition, ICE plays a role in assessing the epicardial substrate of VT in patients with NICM and delineating myocardial scar (wall thinning) and anatomic border zone in patients with ICM [47, 48]. The feasibility of integrating real-time ICE and electroanatomic mapping was demonstrated with the CartoSound system (Biosense Webster, Diamond Bar, USA). This new system contains an ICE catheter (SoundStar, Biosense Webster) that is equipped with an electroanatomic location sensor. By tracing endocardial surface contours on the imported ultrasound images, 3-dimensional reconstructions of the ventricle, including PAMs, can be created and merged to a CT/MRI reconstruction. Intracardiac ultrasound may reduce fluoroscopy and procedural time as well as improve outcome, and it is invaluable in the early detection of periprocedural complications, particularly in patients with unusual sites of VT origin.

Mechanical circulatory support devices: mapping of unmappable VTs

Mapping and ablation of hemodynamically unstable VTs is challenging, and procedural success in these VTs is much lower than in stable monomorphic VTs. Part of the problem is the inability to perform entrainment and activation mapping, which are crucial in identifying the critical isthmus of the VT. In addition, even in patients with tolerated VTs, anesthesia can produce severe hypotension, with potential deleterious effects. Surgically or percutaneously implanted mechanical circulatory support devices can provide hemodynamic support to allow for more detailed activation and entrainment mapping in patients with unstable VTs. The most common devices being used for mapping unstable VT include [49] (1) the percutaneous ventricular assist device (pVAD) (TandemHeart, Cardiac Assist, Inc., Pittsburg, PA, USA), (2) the Impella microcirculatory axial blood flow pump (Abiomed, Inc., Danvers, MA, USA), (3) the cardiopulmonary support (CPS) with bypass pump, and (4) the intra-aortic balloon pump (IABP). Venoarterial extracorporeal membrane oxygenation (ECMO) is also helpful in supporting the respiratory system in addition to providing circulatory support. The major complications related to these devices are aortic valve avulsion, vascular injury, hematoma/pseudoaneurysm/retroperitoneal bleeding after device removal, and stroke/systemic embolism.

Miller et al. [50] recently reported on 23 consecutive VT ablation procedures in 22 patients with structural heart disease and hemodynamically unstable VT. A total of 10 VT mapping and ablation procedures were performed with the support of the Impella 2.5 pVAD, and 13 procedures were performed either with an intra-aortic balloon pump (6 procedures) or with no device support (7 procedures). They found that VTs could be maintained and studied for a longer duration and that activation and entrainment mapping was also more often achievable without the need to terminate the VT in procedures supported with the Impella 2.5 pVAD. In a retrospective review of 13 consecutive patients with hemodynamically unstable VT who underwent TandemHeart-assisted ablation compared with 18 matched patients undergoing substrate-based VT ablation, Bunch et al. [51•] found a

greater number of monomorphic VTs induced in the pVAD group but no difference in inducibility after ablation. The freedom from implantable cardioverter-defibrillator (ICD) shocks/therapies for sustained VT was similar between groups.

Device selection is based primarily on availability, experience of the operator, extent of hemodynamic support required, and patient characteristics. Lü et al. [52] first compared the hemodynamic support effect among the Impella 2.5, peripheral cardiopulmonary bypass (CPB), and durable continuous-flow left ventricular assist device (CF-LVAD) (HeartMate II, Thoratec, Pleasanton, California, USA) in unstable VT ablation, and found that peripheral CPB and implantable LVAD could provide adequate hemodynamic support for successful ablation of unstable VT, while the Impella 2.5 was unable to provide sufficient support in some cases.

Although several retrospective studies suggest mechanical circulatory support device-assisted mapping and ablation could be achieved with acceptable safety and efficacy, no prospective randomized study has been conducted to compare the long-term efficacy of VT ablation between patients with and without mechanical circulatory support device-assisted mapping and ablation.

Other novel mapping and ablation techniques

Transcoronary ethanol ablation (TCEA) to obliterate the source of arrhythmia [53] is an option reserved for patients with deep intramural VT substrates that cannot be accessed with either an endocardial or epicardial approach. With an angioplasty wire, it is possible to record a unipolar electrogram from within the myocardium and to select the vessel in close proximity to the area of tachycardia origin. Injection of ultrasound contrast agent though the target coronary artery branch is helpful in verifying the ablation territory. If the VT can be terminated by infusing iced saline over the wire balloon positioned in the target coronary artery branch, the artery is suitable for ethanol injection. Tokuda et al. [53] performed transcoronary ethanol ablation in 27 high-risk VT patients, in a total 29 attempts, after failed endocardial and/or epicardial ablation, and found that TCEA prevented all VT recurrences in 36 % of patients and improved arrhythmia control in an additional 27 %. The efficacy of this technique may be limited by inadequate target vessels, collaterals, and recurrence of modified VTs. The major complications of TCEA include complete heart block, early ventricular arrhythmia, distant myocardial infarction from coronary complication, and death. The risks of transcoronary ethanol must be weighed against the potential benefits, as the complication rate is not trivial.

In addition to TCEA, other novel VT ablation techniques such as coil embolization, mapping from small branches of the coronary venous system, as well as ethanol infusion and bipolar radiofrequency ablation have recently been employed [54]. While these new techniques provide an important option for patients with specific types of VT, further studies should be performed to determine the safety and efficacy of these approaches.

Conclusions

The continuing improvement in VT ablation techniques has contributed significantly to both our understanding of the arrhythmic substrate and the suc-

cess of catheter ablation. The number of patients needing complex VT ablations is on the rise, thus driving the need for innovation and advancement in VT mapping and ablation technology. Indeed, a better understanding of these tools and the indications for their use will serve to improve procedural outcomes among patients with ventricular arrhythmias.

Compliance with Ethics Guidelines

Conflict of Interest

Dr. Zhiyu Ling and Dr. Adithya Hari each declare no potential conflict of interest relevant to this article. Dr. Harikrishna Tandri received a grant from NIH.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

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