How effective is ablation therapy for cardiac arrhythmias?

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Practice Points

- Catheter ablation procedures and outcomes have evolved considerably over the last 30 years.
- The vast majority of the regular supraventricular tachycardias can be safely and effectively ablated with current techniques.
- Medium-term success percentages are above 80% in paroxysmal atrial fibrillation (AF), but for patients with persistent and long-standing persistent AF the results are unsatisfactory.
- There are limited data regarding the cost–effectiveness of AF catheter ablation.
- In ventricular tachycardia ablation procedures, better lesions and a greater insight into the different arrhythmogenic mechanisms are needed in order to further improve the results.
- Patients should be informed about possible complications before they undergo catheter ablation.
- The use of robotics and contact force may help to improve the effectiveness of ablation therapy.
- Hybrid AF ablation combines the transvenous endocardial approach with the thoracoscopic epicardial approach resulting in better outcomes in patients with persistent AF.

SUMMARY Techniques for catheter ablation of cardiac arrhythmias have evolved considerably since their introduction into clinical practice 30 years ago. Catheter ablation has become the first-line therapy for many types of tachycardia, but the treatment of persistent atrial fibrillation and ventricular tachycardia in patients with structural heart disease remains challenging. New technologies and hybrid therapies have been introduced to further improve outcomes and effectiveness.

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Catheter ablation has dramatically changed treatment of tachyarrhythmias and has become first-line therapy for many tachycardias. Nonpharmacological management of refractory cardiac arrhythmias has progressed over the last 60 years from open chest arrhythmia surgery to catheter ablation procedures performed in an electrophysiology laboratory. Usually, both diagnosis and catheter ablation can be performed in a single procedure. Typically, three or four electrode catheters are positioned in the heart through percutaneous access (mostly femoral veins and/or arteries) to allow pacing and recording of intracardiac electrograms at important sites such as the right atrium, the His bundle region, the right ventricle and the coronary sinus. Some specific arrhythmias require a different access point. The efficacy of catheter ablation is largely determined by the correct identification of the vulnerable part of the arrhythmia circuit or focus and the subsequent destruction of this key site using electrode catheters and efficient energy sources.

This article will discuss the evolution of ablation techniques, the effectiveness of current procedures and future developments.

Evolution of ablation techniques

Catheters designed for intracardiac recording and stimulation were introduced in the late 1960s and, in 1967, both Durrer *et al.* [1] and Coumel *et al.* [2] reported the use of programmed stimulation to induce supraventricular tachycardia. However, at that time, surgery remained the first alternative for nonpharmacological therapy in the case of drug-refractory tachyarrhythmias. The description of programmed electrical stimulation while recording from multiple intracardiac electrodes by Wellens *et al.* in 1971, resulted in more comprehensive electrophysiological studies and important advances in surgical ablation techniques [3]. In 1981, Gonzalez *et al.* reported on an accidentally induced atrioventricular (AV) block by an electrode catheter in a patient that was undergoing an electrophysiological study following electrical cardioversion [4]. This procedural complication triggered cardiologists to search for tools in order to treat arrhythmias using transvenous catheters. It resulted in catheter ablation with direct-current shocks in 1982 [5,6]. In the 1990s, radiofrequency (RF) ablation replaced direct-current ablation because it had important advantages, such as the possibility to perform the procedure in conscious patients, fewer complications, the absence of damage to the catheter and the discrete nature of the resulting lesions [7,8]. RF current is alternating current that is delivered at cycle lengths of 300–750 kHz when used for catheter ablation and it creates lesions through thermal injury [9]. Acutely, this injury consists of a border area of inflammation and hemorrhage surrounding a central zone of coagulation necrosis. This evolves into a permanent lesion characterized by coagulation necrosis with a discrete border [10]. These anatomopathological findings are also the reason why arrhythmias can recur after apparently successful ablation. If the target tissue is not located in the central zone of necrosis but instead in the surrounding area consisting of inflammation, the arrhythmia may recur once that inflammation has resolved without necrosis [11]. For optimal ablation, the tissue temperature should be above 50°C to cause tissue necrosis but below 100°C in order to avoid formation of desiccated tissue and coagulated plasma on the electrode, which in turn may lead to thromboembolic complications [12,13]. The lesions created by typical RF ablation catheters that have a distal electrode 4 mm long, are relatively small (5–6 mm in diameter, 2–3 mm deep) due to the fact that the degree of tissue heating is inversely proportional to the radius to the fourth power [14–16]. To enhance the size of those lesions, one can rely on a larger electrode or saline-irrigated ablation catheters [17].

Alternative energy sources have been developed to overcome the limitations of RF energy like thrombus formation, pulmonary vein (PV) stenosis and barotrauma with ensuing cardiac perforation due to excessive tissue heating [18,19]. Catheter cryoablation is a relatively new technology based on the Joule–Thompson effect, whereby liquid N_2O at high pressure flows down the inner lumen of the catheter and evaporates at the tip into the outer shaft at lower pressure, causing freezing of the catheter tip. Tip temperatures of -60°C or less result in irreversible damage of the target tissue through formation of intra- and extra-cellular ice crystals and a microvascular injury effect [20]. Cryoablation lesions demonstrate preservation of tissue ultrastructural integrity and minimal endocardial surface disruption, resulting in a lower incidence of PV stenosis and thrombus formation compared with RF [21,22]. Despite its better safety profile, cryoablation has been associated with a lower success rate in AV nodal reciprocating tachycardia and AV reciprocating tachycardia ablation and higher recurrence rates [23]. Light amplification by stimulated emission of radiation (laser) can create large and deep lesions owing to its ability to be highly focused with subsequent energy scatter within the tissue. The clinical experience with this energy source remains scarce [24]. Other energy sources like high-frequency ultrasound and microwave did not gain widespread use due to a higher incidence of complications or lack of clinical utility [25,26].

Current effectiveness of catheter ablation procedures

The effectiveness of ablation therapy is not solely dependent on its ability to restore and maintain sinus rhythm in the long term. Other factors like complication rate and cost considerations may also play an important role. In this section, the arrhythmias that can be treated with ablation will be discussed with emphasis on effectiveness and its main determinants.

■ Supraventricular arrhythmias

Inappropriate sinus tachycardia

This arrhythmia is defined as a persistent increase in resting heart rate or sinus rate unrelated to, or out of proportion with, the level of physical, emotional, pathological or pharmacologic stress [27]. Enhanced automaticity of the sinus node and/or abnormal autonomic regulation has been proposed as the underlying mechanisms [28]. The treatment of this arrhythmia is symptom driven and sinus node modification (i.e., catheter ablation of the earliest endocardial activation during either spontaneous or isoproterenol-induced sinus tachycardia) is a therapeutic option in the cases refractory to β-blockers, calcium-channel blockers or ivabradine [29]. RF is the preferred energy source in this setting. Potential adverse effects include pericarditis, phrenic nerve injury, superior vena cava syndrome or a need for pacemaker implantation. Although short-term success rates are favorable (range: 76–100%), long-term outcomes remain disappointing (range: 25–65%) due to perseverance of symptoms, despite documentation of slower heart rates [30].

AV nodal reciprocating tachycardia

The re-entrant circuit in AV nodal reciprocating tachycardia (AVNRT) runs through the compact AV node and involves reciprocation between the fast pathway (located near the apex of Koch's triangle) and the slow pathway (extends inferoposterior to the compact AV node and stretches along the septal margin of the tricuspid annulus at the level of, or slightly superior to, the coronary sinus). During typical AVNRT the fast pathway conducts retrogradely and the slow pathway serves as the antegrade limb ('slow/fast' AVNRT). In 5–10% this circuit is reversed and the slow pathway conducts retrogradely ('slow/slow' and 'fast/slow'). Ablation of the slow pathway is the first-line invasive treatment for AVNRT. This approach, using RF, results in high procedural short- and long-term success (>98 and 95%, respectively) (Table 1) [31]. The most feared complication during this procedure is complete AV block due to the site of energy application but its occurrence is, fortunately, less than 1% [32]. Cryoablation can create reversible lesions when freezing at around -30°C (also known as cryomapping) and unwanted energy delivery at the compact AV node or His bundle due to dislodgment of the catheter is prevented by cryoadherence. Therefore, cryoablation holds the potential to further lower or even avoid the risk for permanent AV block and remains the preferred energy source in children or patients with complex AV node anatomy. However, the widespread use of cryoenergy for the ablation of AVNRT has been limited by a slightly lower long-term success rate [33].

Focal junctional tachycardia

This uncommon arrhythmia in adults is also known as junctional ectopic tachycardia and is characterized by abnormally rapid discharges from the AV node or His bundle due to abnormal automaticity or triggered activity [27]. Untreated patients may develop heart failure, particularly if the arrhythmia becomes incessant. Anti-arrhythmic drug (AAD) therapy with β-blockade or flecainide, is only variably successful [34]. RF catheter ablation can be curative by destroying the arrhythmogenic foci adjacent to the AV node but the risk of AV block is therefore significant (5–10%) [35]. This is the reason why RF ablation has not enjoyed widespread acceptance for definitive treatment of this arrhythmia and has mainly been reserved for patients who have significant cardiac compromise and have not responded to AADs. The advantages of

Table 1. Success rates for common types of regular supraventricular tachycardia.

	Acute success (%)	Long-term success (%)
AVNRT	98	95
AVRT	95	95
Focal AT	85–95	67–100
CTI-dependent atrial flutter	97	97
Non-CTI-dependent atrial flutter	90	41–100

AT: Atrial tachycardia; AVNRT: Atrioventricular nodal reciprocating tachycardia; AVRT: Atrioventricular reciprocating tachycardia; CTI: Cavotricuspid isthmus.

cryothermal ablation in patients with AVNRT (cryomapping and cryoadherence) support the use of this energy source for anatomic sites similar to those found in junctional ectopic tachycardia [36].

AV reciprocating tachycardia

The AV re-entrant circuit in this arrhythmia involves a connection other than the AV node, known as accessory pathway. They can be classified on the basis of their anatomic location along the tricuspid or mitral annulus and conduction properties. Accessory pathways capable of only retrograde conduction (i.e., from the ventricle to the atrium) are referred to as 'concealed', whereas those exhibiting antegrade conduction are 'manifest', demonstrating pre-excitation (delta waves) on the surface ECG. Delta waves are present in up to 0.25% of the general population [37]. The diagnosis of Wolff–Parkinson–White syndrome is reserved for patients who have both ventricular pre-excitation on their ECG and tachyarrhythmias, with AV reciprocating tachycardia being the most common one. Typical accessory pathways connect the myocardium of the atrium and the ventricle across the AV groove and have similar conduction properties to normal His–Purkinje tissue (rapid, nondecremental conduction). This feature explains the small risk of sudden cardiac death (0–0.6% per year) in patients with manifest pre-excitation, mainly due to rapidly conducted atrial fibrillation (AF) and subsequent degeneration to ventricular fibrillation [38]. Markers identifying patients at increased risk are:

- A shortest pre-excited R-R interval less than 250 ms during spontaneous or induced AF;
- A history of symptomatic tachycardia;
- Multiple accessory pathways;
- Ebstein's anomaly [27].

Invasive electrophysiological assessment for risk of sudden cardiac death is considered superior to noninvasive testing. Long-term AAD therapy to prevent accessory pathway-mediated arrhythmias, is based on agents that mainly modify AV node conduction or depress conduction across the accessory pathway. Today, RF ablation has obviated the need for AADs in many patients. Right free-wall accessory pathways and most septal accessory pathways are ablated along the tricuspid annulus or the right atrial septum using a venous approach. For left free-wall and left septal accessory pathways, a retrograde aortic or transseptal approach is used in order to advance the ablation catheter to the mitral annulus or left atrial septum. Ablation of accessory pathways in the posteroseptal region sometimes necessitates a subxiphoid percutaneous epicardial access [39]. The initial and long-term efficacy of catheter ablation for accessory pathways is approximately 95% [8,40]. Initial ablation failure and short- to medium-term recurrence occurs mostly in right free-wall and posteroseptal pathways [41]. The overall complication rate associated with catheter ablation of accessory pathways is lower than 1% [42]. Procedure-related mortality ranges from 0 to 0.2% [27]. Complete AV block and cardiac tamponade are the most common major complications. Inadvertent complete AV block occurs mostly in the setting of ablation of septal accessory pathways located near the AV node (up to 36%) [43]. The use of cryoablation for this type of accessory pathway results in slightly less long-term success (89%) but no permanent AV block was observed. The management of asymptomatic patients with pre-excitation remains controversial. Cardiac arrest is very rarely the first manifestation of the disease and the benefits of catheter ablation should be balanced against the risk for major complications [38,44].

Focal atrial tachycardias

Focal atrial tachycardias (ATs) are characterized by a focal origin with subsequent centrifugal spread and occur mostly in the absence of structural heart disease. Incessant forms may lead to tachycardia-induced cardiomyopathy. The sites of origin of those arrhythmias are clustered over specific anatomical regions. One of those regions in the right atrium is the entire crista terminalis and in the left atrium (LA) foci are frequently found in the PVs. The morphology of the P-wave on the 12-lead surface ECG, may be helpful for the localization of the site of origin of the focal AT [45]. AADs such as β-blockers and calcium-channel blockers, are indicated for acute treatment (conversion or rate control) and for prophylactic therapy. Catheter ablation is indicated in recurrent symptomatic focal AT or in incessant forms. Endocardial activation mapping (i.e., the process of integrating electrocardiographic data within a spatiotemporal framework with the purpose of defining the mechanism and activation sequence of arrhythmia) is the key to accurate localization of the site of origin of the arrhythmia, which is the cornerstone of successful ablation. Activation mapping includes the use of endocardial electrode catheters to identify the point of earliest atrial activation, whether or not this is in combination with 3D technologies that help in visualizing atrial anatomy and activation sequence. The acute success rates of RF catheter ablation are between 85 and 95% with a low reccurence rate (range: 0–33%) [46]. Major complications (cardiac perforation, phrenic nerve damage, sinus node dysfunction and AV block) are rare (1–2%) [27].

Macro re-entrant AT

Macro re-entrant ATs or flutters, in contrast to focal ATs, involve a large re-entry circuit. Because of the important impact on catheter ablation, they are referred to as cavotricuspid isthmus (CTI)-dependent or not.

CTI-dependent atrial flutter

This type of flutter accounts for about 90% of macro re-entrant tachycardias and is also known as 'typical atrial flutter' (AFL). Its re-entry circuit proceeds around the tricuspid annulus and involves the CTI (i.e., the isthmus between the tricuspid valve and the inferior vena cava). Depending on its rotation pattern around the tricuspid valve in the left anterior oblique view, a distinction is made between counterclockwise (the most common form, characterized on the ECG by negative flutter waves in the inferior leads and a positive flutter deflection in V1) and clockwise typical flutter (reverse typical flutter). Patients with AFL are at increased risk of thromboembolism and should therefore follow the same guidelines as AF patients regarding thromboprophylaxis [47]. The acute treatment might include atrial overdrive pacing, direct current or chemical cardioversion, or AV nodal-blocking agents. Catheter ablation of this arrhythmia involves the creation of a linear lesion with bidirectional block at the CTI. One prospective, randomized study has demonstrated the superiority of RF catheter ablation over oral AAD therapy in terms of rhythm control [48]. The long-term success rate for prevention of recurrent AFL is 97%, with 4–8% of patients requiring a repeat procedure. The rate of serious complications is 0.4%, with the most common being high-grade AV block [49,50].

Non-CTI-dependent AFL

The re-entry circuit in these types of flutters does not involve the CTI. These circuits most often arise in structurally abnormal hearts and include, among others, re-entry around surgical scars and circuits that develop after surgical or catheter ablation of AF. Especially the latter have become a relatively common finding late after catheter ablation of AF with extensive substrate modification (linear ablation and targeting of complex fractionated atrial electrograms [CFAEs]). The incidence of ATs after such a procedure ranges from 4 to 40% with a majority of non-CTI-dependent AFL, mostly around the mitral annulus or involving the roof of the LA [51]. The principles of acute treatment are the same as for CTI-dependent AFL. Catheter ablation of non-CTI-dependent flutter demands a tailored approach during which conventional mapping techniques, mostly together with 3D mapping systems, are used to identify a critical portion of the circuit (e.g., the isthmus between the mitral annulus and the left inferior PV in the case of a circuit around the mitral annulus) where it can be interrupted. Acute success rates exceed 90%, but recurrence rates vary from 0 to 59% depending on the underlying arrhythmia substrate [46].

AF

The prevalence of AF increases with age and it is the most common clinically important cardiac arrhythmia [52]. Total mortality and cardiovascular mortality are increased in patients with AF [53]. The most recent Heart Rhythm

Society (HRS)/European Heart Rhythm Society (EHRA)/European Cardiac Arrhythmia Society (ECAS) consensus statement recommends catheter ablation for:

- Symptomatic AF refractory or intolerant to at least one class 1 or 3 AAD (paroxysmal AF, class 1, level A; persistent AF, class 2A, level B; long-standing persistent AF, class 2B, level B);
- Symptomatic AF prior to initiation of antiarrhythmic therapy with a class 1 or 3 AAD (paroxysmal AF, class 2A, level B; persistent AF, class 2B, level C; long-standing persistent AF, class 2B, level C) [54].

The cornerstone of AF ablation is ablation of the ostium or antrum of the PV with the end point of electrical isolation of these veins from the LA. The rationale for this, is the seminal observation by Haïssaguerre *et al.* in 1998 that AF was almost always triggered by ectopic beats arising from the muscle sleeves of the PVs [55]. When PV isolation is successful, those ectopic beats cannot reach the LA because they are stopped at the region of scarring created during ablation.

The success rate of PV isolation in patients with paroxysmal AF is greater than 80% and the most frequent reason for AF recurrence is PV reconduction [56,57]. However, long-term results of catheter ablation for paroxysmal AF are less satisfying. In a recently published prospective study, sinus rhythm was maintained in 46% of patients after the initial procedure without AAD during a median follow-up period of 5 years [58]. According to the recent HRS/EHRA/ECAS consensus statement, success in AF ablation should be defined as freedom from AF/AFL/AT of greater than 30 s in duration off all AADs [54]. RF is the most frequently used energy source to perform PV isolation; the alternatives are cryoablation and laser [59,60]. To reach the PVs, one needs to cross the interatrial septum by transseptal puncture. Just before or after this puncture, heparine is administered to prevent thrombosis. Most of these procedures are performed using 3D electroanatomical mapping systems.

In patients with persistent (episodes lasting more than 7 days) or long-standing persistent AF (episodes longer than 12 months), PV isolation alone results in a success rate of 22% (in this study, success was defined as the absence of symptomatic AF off AADs at 5 months postprocedure) [61]. This is likely due to the fact that as AF progresses from paroxysmal to persistent, the atrial substrate itself may play a relatively more important role in AF maintenance [62]. Ablation of the atria is called 'substrate modification' and consists of linear lesions and/or ablation of CFAEs. Both are performed with RF. The creation of linear lesions was inspired by the surgical Cox maze procedure for AF [63]. These linear lesions are thought to prevent sustained multiple re-entry circuits by compartmentalization of the atria. The most frequently used linear lesions are the roofline (connecting both superior PVs) and the mitral isthmus line (from the left inferior PV to the mitral annulus). However, the creation of these linear lesions can be challenging and incomplete lesions may themselves become proarrhythmic and result in macro re-entrant circuits [64]. The ablation of CFAE gained interest after the publication by Nademanee *et al.* in 2004 [65]. CFAEs are defined as fractionated electrograms with two or more deflections and a mean cycle length under 120 ms. Nademanee *et al.* reported that at the 1-year follow-up (Holter and event recorder monitoring) after CFAE ablation alone, 93% of the patients with paroxysmal AF (4% with AAD), 87% of patients with persistent AF and 78% of patients with long-standing persistent AF (11% with AAD) remained in sinus rhythm. However, these results could not be reproduced by other groups. Also, the precise electrophysiological mechanism underlying CFAEs remains unclear. Sites of high-dominant frequency seem to be interesting ablation targets as well. In an animal model, these sites correspond to functional re-entry, also known as rotors [66]. Recently, localized rotors have been visualized in human AF by computational mapping [67]. This discovery is an important step towards a tailored substrate ablation, especially in patients with persistent AF. Catheter ablation procedures using PV isolation in combination with linear lesions and/or CFAE ablation in patients with persistent and long-standing persistent AF seem to result in a better outcome than PV isolation alone, but there is an important variation in success rates ranging from 11 to 75%, and the incidence of ATs after this type of procedure goes up to 40% [51,68]. There appears to be a slow but steady decline in arrhythmia-free survival, especially after catheter ablation for persistent AF [69].

The risk of a major complication was 4.5% and the risk of death was 0.15% in a recently published survey carried out on more than 16,000 patients undergoing AF ablation worldwide [70]. The most frequently reported major complications were cardiac tamponade (1.2–6%), cerebrovascular thromboembolism (0–2%), and PV stenosis (0.5–2%). Although there is nonrandomized data showing a reduction of stroke after AF catheter ablation, there is, to date, insufficient evidence to safely discontinue oral anticoagulation during maintenance of sinus rhythm after this procedure in patients at risk (i.e., risk for stroke as estimated by the currently recommended CHA_2DS_2-VASc score) [54] . There is no randomized trial large enough to answer the question as to whether or not AF catheter ablation reduces mortality. Several randomized trials showed a greater improvement in quality of life measurements in AF patients after catheter ablation compared with AAD treatment [54]. Finally, regarding cost–effectiveness, there are limited data available, suggesting that AF catheter ablation may be cost-effective in patients with at least one risk factor for stroke [54].

Ventricular arrhythmias

The majority of ventricular tachycardias (VTs) occur in the presence of structural heart disease that can result from myocardial infarction, replacement fibrosis in nonischemic cardiomyopathy and following cardiac surgery (e.g., after repair of tetralogy of Fallot). VT, in this setting, is based on re-entry due to surviving myocyte bundles within the scar promoting slow conduction and conduction block. Successful ablation relies on locating the area of scar and the narrow channels of slow conduction where ablation can stop the re-entry circuit. This type of VT can cause sudden cardiac death and patients need to be protected with an implantable cardioverter–defibrillator (ICD). In the absence of structural heart disease, VT (also termed idiopathic VT) or repetitive monomorphic ectopic beats are mostly due to a focal mechanism or interfascicular re-entry and typically originate, among other locations, in the outflow tracts of the right and left ventricle. During catheter ablation, the target tissue is the zone of earliest activation. In general, the incidence of sudden cardiac death in patients with VT without structural heart disease is extremely low.

Indications for VT ablation, based on the most recent HRS/EHRA expert consensus statement, are summarized in **Box 1** [71]. The most commonly used energy source for VT ablation is RF. 3D mapping systems are used in most cases to reduce fluoroscopy times and to visualize scar areas and endocardial activation. The left ventricle is usually approached retrogradely via the aortic valve but in many centers a transseptal approach is also used. In 10–15% of patients, VT originates epicardialy and demands an epicardial approach via a subxiphoid puncture [72]. This is often the case for VT in nonischemic cardiomyopathy and arrhythmogenic right ventricular cardiomyopathy.

The presence or absence of structural heart disease has a major impact on the outcomes of catheter ablation for VT. Indeed, ablation for VT associated with structural heart disease is a method to reduce recurrent VT and prevent ICD shocks rather than achieve annihilation of ventricular arrhythmia. In ischemic cardiomyopathy, the target VT is not acutely inducible anymore in up to 90% of patients and at 12 months follow-up, 50–88% of patients are free of any VT, with 30–100% continuing previously ineffective AAD [71]. In 67–81% of patients there is a >75% reduction in VT episodes. Long-term results after VT ablation in patients with previous myocardial infarction have also been reported; in a recent study, 58% of patients were free of VT after a mean follow-up of 39 months [73]. There is no significant effect on mortality and insufficient data to promote prophylactic VT ablation in ICD patients. There is only data from small single-center series concerning VT ablation in nonischemic cardiomyopathy, surgically repaired congenital heart disease and arrhythmogenic

Box 1. Indications for catheter ablation of ventricular tachycardia.

Patients with structural heart disease
- Symptomatic SMVT, including VT terminated by an ICD, reoccurring despite AAD therapy or when AAD are not tolerated or not desired
- Incessant SMVT or VT storm that is not due to a reversible cause
- Frequent PVCs, nonsustained VT or VT that is presumed to cause ventricular dysfunction
- Bundle branch re-entrant or interfascicular VT
- Recurrent sustained polymorphic VT and VF that is refractory to AAD therapy when there is a suspected trigger amenable to ablation

Patients without structural heart disease
- Monomorphic VT causing severe symptoms
- Monomorphic VT when AADs are not effective, not tolerated or not desired
- Recurrent sustained polymorphic VT and VF that is refractory to AAD therapy when there is a suspected trigger amenable to ablation

AAD: Anti-arrhythmic drug; ICD: Implantable cardioverter–defibrillator; PVC: Premature ventricular contraction; SMVT: Sustained monomorphic ventricular tachycardia; VF: Ventricular fibrillation; VT: Ventricular tachycardia.

right ventricular cardiomyopathy. Acute results are comparable with VT ablation in ischemic cardiomyopathy but recurrence rates, especially in arrhythmogenic right ventricular cardiomyopathy, are significant; the cumulative incidence of VT recurrence after a single procedure was 64, 75 and 91% at the end of 1, 2 and 3 years, respectively, in a trial on long-term efficacy of catheter ablation of VT in patients with arrhythmogenic right ventricular cardiomyopathy [74].

The outcomes for idiopathic VT catheter ablation are more favorable. Very frequent premature ventricular contractions (PVCs) can result in a reversible cardiomyopathy. Data from small case series, indicate an overall success rate >80% (success defined as complete abolishment of the PVCs on 24-h Holter by 3 months after ablation) and a subsequent improvement of the ventricular function [71]. Catheter ablation is considered first-line therapy for patients with bundle branch re-entry VT and is successful (defined as no symptomatic arrhythmia recurrence at 1 year after ablation and no VT on 24-h Holter monitoring) in almost all cases [71]. Acute success rate in catheter ablation of right ventricular outflow tract VT exceeds 80%, with a recurrence of arrhythmia in up to 5%.

Polymorphic VT and VF may be considered for ablation when they present as an arrhythmia storm refractory to AAD. These arrhythmias can be triggered by monomorphic PVCs from the Purkinje network after myocardial infarction, in Brugada and long QT syndromes, and in idiopathic VF patients. During catheter ablation, one tries to locate and destroy the source of these PVCs. Success rate exceeds 80% during a follow-up of 24 months (assessed by 24-h Holter and defibrillator memory interrogation), but these results were obtained in small series in expert centers [71].

Procedure related mortality ranges from 0 to 3% in patients with structural heart disease and is primarily linked to ongoing VT in case of failed ablation. Serious complications range from 0 to 4% in idiopathic VT, and from 3.8 to 8% in VT associated with structural heart disease [75]. Thromboembolic events occur in less than 3% of cases. The incidence of cardiac tamponade is 0.4–2.7%. This complication occurs mostly during ablation in the thin-walled right ventricle. Valvular injury is rare (1.9%) and mostly minor. AV block or newly developed bundle branch block has been described in less than 1–2% of VT ablation procedures. The most frequent vascular access complication is femoral pseudoaneurysma, and it occurs in up to 6% of procedures. Potential complications associated with epicardial VT ablation procedures are minor pericardial bleeding (30% of cases), injury to coronary arteries, injury to the phrenic nerve and pericarditis (30% of cases).

Future developments

■ Robotic catheter ablation

Two robotic systems have been developed to achieve superior catheter stability and reproducible catheter movements. The first is based on a magnetic navigation system and the second on a steerable sheath system. For the latter system, more complications were reported especially during the learning curve in low-volume centers [76]. Both systems are mainly used for AF and VT ablations. Success rates for robotic AF ablation are comparable with manual procedures and there is a significant reduction in fluoroscopy times [77]. The use of robotic systems may lead to better lesion formation and increased long-term success rates.

■ Contact force

One of the most important factors to achieve effective lesion formation using RF current, is the contact force (CF) between catheter tip and tissue. Excessive CF can lead to complications such as heart wall perforation and insufficient CF may result in ineffective lesion formation. Recently, novel ablation catheters with a CF sensor at the distal tip have been introduced into clinical practice. During AF catheter ablation, a CF above 20 g results in fewer AF recurrences [78].

■ Hybrid AF ablation

During this single procedure, the cardiac surgeon performs PV isolation and creates linear lesions epicardialy with a thoracoscopic approach. The electrophysiologist completes the lesion set endocardially if necessary and ablates AF foci outside the PVs and the posterior wall of the LA. This technique seems to result in lasting PV isolation and more efficient linear lesions. Defined according to the HRS/EHRA/ECAS consensus statement (freedom of AF/AFL/AT off AADs) 1-year success was 93% for patients with paroxysmal AF and 90% for patients with persistent AF. The combination of the transvenous endocardial approach with the thoracoscopic epicardial approach in a single AF ablation procedure, overcomes the limitations of both techniques and results in better outcomes [79]. However, these results need to be confirmed in prospective randomized trials.

Conclusion & future perspective

Catheter ablation procedures and outcomes have much evolved over the last 30 years. The vast majority of the regular supraventricular tachycardias can be safely and effectively ablated with current techniques. The outcomes for AF catheter ablation, however, are less impressive. Success percentages are above 80% in paroxysmal AF, but for patients with persistent and long-standing persistent AF, the results are unsatisfactory. To improve outcomes for this arrhythmia, we must have energy sources and ablation techniques that result in lasting PV isolation and persistent linear lesions, leading to less reconduction. This is confirmed by the results of the hybrid approach for AF. Besides more efficient ablation tools, we need a better understanding of the pathophysiology and underlying mechanisms of AF in order to tailor the therapy to the patient. In VT patients with structural heart disease, we also need better lesions and a greater insight into the arrhythmogenic mechanisms. Basic researchers, clinicians and industry have to join efforts in order to meet these needs.

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- ■■ of considerable interest

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