Radiofrequency ablation of cardiac arrhythmias: past, present and future

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Summary

The treatment of cardiac arrhythmias has been revolutionized by the ability to definitively treat many patients with radiofrequency catheter ablation, rather than requiring lifelong medication. This review covers the history of how this has developed and the methods used currently and explores what the future holds for this rapidly evolving branch of Cardiology.

Introduction

Radiofrequency ablation has revolutionized treatment for tachyarrhythmias and has become first-line therapy for many tachycardias. Non-pharmacological management of refractory cardiac arrhythmias has progressed over the last 60 years from arrhythmia surgery to high-voltage direct current catheter ablation from a standard external defibrillator, only to be superseded by radiofrequency ablation over the last 20 years.

This review article will discuss the emergence of radiofrequency ablation in the management of cardiac arrhythmias, summarize the technical aspects of current procedures, highlight the indications for radiofrequency ablation and discuss emerging technologies in catheter ablation.

The past

Catheters were first used for intra-cardiac recording and stimulation in the late 1960s, but surgical treatment for refractory tachyarrhythmias was the mainstay of non-pharmacological therapy. In 1967, both Durrer et al. and Coumel et al. described the ability to induce tachyarrhythmias using programmed electrical stimulation, and the use of cardiac surgery to treat these soon followed. In 1968, it was shown that surgical interruption of the Bundle of Kent (more commonly known as an accessory pathway now) could cure Wolff–Parkinson–White syndrome—the accessory pathway being initially localized with epicardial mapping.

For the first time in 1971, Wellens described programmed electrical stimulation while recording from multiple intra-cardiac electrodes, and over the following years the progress in electrophysiological studies was married with advances in surgical ablation. Atrial tachycardia was treated with excision of an arrhythmogenic focus, refractory supraventricular tachyarrhythmias managed with cryosurgery of the atrioventricular junction and cure of chronic atrial fibrillation (AF) was pioneered with the surgical Maze procedure.

It soon became clear that ablation could cure arrhythmias and transvenous catheter studies could accurately map the nature and anatomy of various arrhythmias. The first atrio-ventricular (AV) block induced by an electrode catheter was rather serendipitous when in 1981 Gonzales et al. reported on a patient that was undergoing an electrophysiological
study following defibrillation. Inadvertently, the defibrillating electrode accidentally came into contact with an electrode catheter situated in the bundle of His—resulting in a high-voltage discharge and damage to the surrounding endocardium.\(^\text{10}\) The ensuing complete heart block sparked a search for a technique to terminate arrhythmias using transvenous catheters.

Catheter ablation with direct current from a standard external defibrillator began to supersede surgery in the 1980’s. A shock was delivered between the distal catheter electrode and a cutaneous surface electrode; however, this high-voltage discharge was difficult to control and could cause extensive tissue damage. This technique was first used to manage refractory AF and supraventricular tachycardia by creating complete atrioventricular block.\(^\text{11,12}\) As operators became more skilled and electrophysiological mapping improved, direct current (DC) ablation was used to treat cases of Wolff–Parkinson–White, ventricular tachycardia and atrial tachycardia.\(^\text{13–16}\)

By the 1990’s, radiofrequency energy had supplanted direct current.\(^\text{17}\) This was mainly due to the high incidence of complications associated with the high-energy discharge such as impaired left ventricular function and cardiac rupture. In addition to this, radiofrequency ablation could be performed on conscious patients, formed discrete lesions and allowed termination of lesion formation if complications occurred.\(^\text{18–20}\)

Radiofrequency ablation of cardiac arrhythmias utilizes a sinusoidal high-frequency (500–750 Hz) current that creates lesions through thermal injury—a characteristic previously utilized by surgeons for cauterity. Resistive heating damages the tissue in direct contact of the catheter. Deeper and surrounding tissues are subsequently heated and damaged by conduction from this area.\(^\text{21}\)

The acute lesion consists of a border area of inflammation and haemorrhage surrounding a central area of coagulation necrosis. The presence of this border region may explain the recurrence of arrhythmias following the procedure because, this region may contain viable arrhythmogenic tissue that is non-conductive at the time of ablation but is able to conduct subsequently when it heals.

The size of the lesion created is determined through a balance between conduction of heat from the radiofrequency ‘electrode’ on the end of the ablation catheter (Figure 1) through to the tissue, and convective heat loss to the blood pool. In addition, the lesion size is proportional to the delivered power, the diameter of the distal ablation catheter electrode and the contact pressure of this electrode with the cardiac tissue.\(^\text{21}\)

There is a careful balance of the temperature that must be achieved for optimal ablation: the electrode-tissue interface must be \(\geq 50^\circ \text{C}\) to cause tissue necrosis, but at temperatures approaching \(100^\circ \text{C}\), a coagulum of denatured proteins and plasma forms on the catheter tip impeding the delivery of current. In addition to this technical difficulty, the formation of coagulum increases the risk of thromboembolic complications.\(^\text{22}\)

The present

Catheter ablation procedures are performed in an electrophysiology laboratory (a cardiac catheter laboratory with specific equipment for the electrophysiology work), with both diagnosis and ablation usually achieved together. ‘Electrode catheters’ are most commonly inserted percutaneously into the
femoral veins (although the internal jugular, or subclavian vein can sometimes be used) and orientated within the heart to allow pacing stimulation and intracardiac electrical signal recording at key sites—namely the right atrium, right ventricle, the area of the His bundle (in practical terms this equates to the AV node) and the coronary sinus (this sits between the left atrium and left ventricle and records electrical signals from both). If necessary, the left heart can be accessed through either an ‘antegrade’ transeptal puncture from the right atrium into the left atrium, or a ‘retrograde’ approach through the aortic valve via the femoral artery. The efficacy of catheter ablation is highly dependant on accurate identification of the site of origin of the arrhythmia. Once this site has been identified, an ablation catheter (typically 7 French in size with a tip electrode size of 4 mm) is positioned in direct contact with it and radiofrequency energy is delivered to ablate it. After 30–60 s, a lesion of 5-mm depth is formed, which is enough to destroy the full thickness of the atrial myocardium in that location. If necessary, the left heart can be accessed through either an ‘antegrade’ transeptal puncture from the right atrium into the left atrium, or a ‘retrograde’ approach through the aortic valve via the femoral artery. The efficacy of catheter ablation is highly dependant on accurate identification of the site of origin of the arrhythmia. Once this site has been identified, an ablation catheter (typically 7 French in size with a tip electrode size of 4 mm) is positioned in direct contact with it and radiofrequency energy is delivered to ablate it. After 30–60 s, a lesion of 5-mm depth is formed, which is enough to destroy the full thickness of the atrial myocardium in that location.

Current ablation systems allow for temperature monitoring and temperature control; valuable tools during radiofrequency ablation procedures as they provide important information regarding the adequacy of tissue heating, minimize the development of coagulum and maximize the lesion size. Newer technical modifications, such as a larger distal electrode and saline cooling of this electrode, have helped to minimize impedance rises and allow creation of larger and deeper lesions.

Clinical uses
There are three main indications for catheter ablation:

(i) Definitive treatment of symptomatic supraventricular tachycardia (SVT) due to atrioventricular re-entrant tachycardia (AVRT), atrioventricular nodal re-entrant tachycardia (AVNRT), unifocal atrial tachycardia or atrial flutter;

(ii) AF with lifestyle-impairing symptoms and failure of at least one antiarrhythmic agent; and

(iii) definitive treatment of symptomatic idiopathic ventricular tachycardia (VT). However, for VT in the setting of structural heart disease, catheter ablation is generally reserved for failure of drug-therapy or as adjunctive therapy in the setting of frequent implantable cardioverter defibrillator (ICD) discharges.

These arrhythmias that are amenable to ablation are discussed in more detail below (and in Table 1):

AVRT associated with the WPW syndrome or a concealed accessory pathway
This arrhythmia is due to an atrioventricular re-entrant circuit involving a connection other than the AV node, known as an accessory pathway. These congenital accessory pathways sometimes, but not always, give rise to arrhythmias and often present at a young age with rapid paroxysmal palpitations and an underlying narrow-complex tachycardia. There is also a small risk of sudden cardiac death in these patients, mainly due to rapidly conducted (‘pre-excited’) AF. This risk is best assessed by performing an electrophysiology study and, if

<table>
<thead>
<tr>
<th>Procedure</th>
<th>First procedure success rates (%)</th>
<th>Commonly occurring risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVT ablation (AVRT, AVNRT, atrial tachycardia)</td>
<td>90–95</td>
<td>PPM (&lt;0.5% in most but may be up to 5% if the abnormal pathway is very close to the AV node), thromboembolism (0.1%), tamponade (0.1%), death (0.05%), repeat procedure (5–10%)</td>
</tr>
<tr>
<td>AV node ablation and PPM insertion</td>
<td>99</td>
<td>Tamponade (0.1%), death (0.05%)</td>
</tr>
<tr>
<td>Atrial flutter ablation</td>
<td>90–95</td>
<td>PPM (&lt;0.5%), tamponade (0.1%), death (0.05%)</td>
</tr>
<tr>
<td>VT ablation (normal heart)</td>
<td>90</td>
<td>PPM (&lt;0.5%), thromboembolism (0.1%), tamponade (0.1%), death (0.05%), repeat procedure (5–10%)</td>
</tr>
<tr>
<td>VT ablation (structural heart disease, e.g. previous MI)</td>
<td>70–80</td>
<td>Thromboembolism (1%), tamponade (2%), death (0.5%)</td>
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<tr>
<td>Atrial fibrillation ablation</td>
<td>50–70 (with more than one procedure, success rates may be 80–90%)</td>
<td>Thromboembolism (0.5–1%), tamponade (2%), repeat procedure (25–40%), death (0.1%) PV stenosis (rare), atrio–oesophageal fistula (rare)</td>
</tr>
</tbody>
</table>

Figures shown are averages and there may be variation in individual cases.

PPM: permanent pacemaker; MI: myocardial infarction.
the risk warrants it, ablating the pathway even if the patient is asymptomatic. Successful identification and ablation of these accessory pathways are performed by identifying the earliest ventricular activation with conduction through the pathway and/or the earliest atrial activation during ventricular pacing. This should correlate to the location of the accessory pathway, and it is localized using a diagnostic catheter initially on the tricuspid or mitral valve annulus. Following this, the precise location of the pathway is identified with the ablation catheter and radiofrequency ablation can begin. Electrophysiology studies usually follow this procedure to ensure complete ablation of the accessory pathway.29

**AVNRT**

This is the commonest cause of regular narrow complex tachycardia in patients with normal hearts. In these patients, the AV node is functionally divided into two longitudinal pathways, usually one slowly and one fast conducting, that form the re-entrant circuit. The presence of two pathways in the AV node is seen in ~30% of all people and it is only a relatively small number who then go on to have the correct set of circumstances to allow tachycardia to start. In the majority of patients, during AVNRT, antegrade conduction occurs to the ventricle over the slow pathway and retrograde conduction occurs over the fast pathway. Ablation of this arrhythmia targets the slow pathway, which is found inferior to the His bundle, close to the mouth of the coronary sinus (Figure 2).30 Special care is taken to ensure that AV block does not occur, and ablation is followed by a full repeat electrophysiology study to ensure that there is no AV nodal damage.31,32

**Atrial tachycardia**

Focal atrial tachycardia results from the atrial cells with enhanced automaticity that generate impulses at a greater rate than the sinoatrial node. In order to ablate this focus, the arrhythmia must be induced and localized to the site of earliest atrial activation.29 Once localized, the ablation catheter electrogram (local electrical signal) should be ahead of the onset of the P-wave on the surface electrocardiogram—ablation at this point provides successful termination of the arrhythmia in >90% of patients.

**Atrial flutter**

The most common form of atrial flutter involves a single re-entrant circuit with circus activation in the right atrium around the tricuspid valve annulus with an area of slow conduction located between the tricuspid valve annulus and the coronary sinus ostium (Figure 3). This was the first re-entrant arrhythmia to be fully characterized.33

The diagnosis of atrial flutter is confirmed using pacing manoeuvres in the right atrium and coronary sinus and ablation is performed with a line of ablation between the inferior vena cava and the tricuspid valve to interrupt the circuit. Post-ablation, pacing manoeuvres can confirm that the substrate required for the circuit has been interrupted in both directions. Accurate ablation is associated with recurrence of <5%.34 Ablation of atrial flutter is a low risk/high success procedure and is increasingly used first-line by Electrophysiologists.
In patients without structural heart disease, the most common forms of VT are right ventricular outflow tract (RVOT) VT or fascicular VT (Figure 4). These are very amenable to ablation, although RVOT VT is a more focal rather than re-entrant arrhythmia. The success rates for ablation of ‘normal heart’ VT are much higher than those in patients with structural heart disease because, in the latter the substrate for VT (scar) often continues to develop over time. VT ablation for patients with structural heart disease therefore tends to be reserved for those patients in whom medical therapy has failed to adequately control the arrhythmia. This may be undertaken after only one drug has been tried, e.g. a beta-blocker, but more commonly it is after other drugs such as amiodarone have been used. Also, it may be performed in patients with implantable cardioverter defibrillators who are getting repeated shocks form their device due to VT that cannot be controlled with medication. Well tolerated VT, preferably of single morphology, is most amenable to radiofrequency ablation in this patient population. In order to identify the re-entrant circuit, VT is normally induced by pacing manoeuvres (if the patient is not already in VT) and for this reason, it is ideal if it is haemodynamically well tolerated. The re-entrant circuit is identified through a combination of pacing manoeuvres, and matching the resulting electrocardiogram (ECG) to the clinical VT picture. Once the re-entrant pathway has been identified, radiofrequency ablation at the critical, slow-conducting component of the pathway will often render the VT non-inducible. It is also possible to perform ablation of haemodynamically unstable VT using other techniques but success rates may be slightly lower.

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**Catheter ablation of the AV junction with permanent pacemaker implantation to establish rate control in refractory AF**

One of the difficulties with treating AF is in achieving adequate ventricular rate control. Where this
cannot be achieved with standard pharmacological measures (β-blockers, digoxin, etc.), the AV node itself can be ablated. This results in little or no ventricular rhythm subsequently so a pacemaker is implanted. This is a very effective treatment but it needs to be noted that atrial fibrillation will still occur, but the fast ventricular rates should not. Furthermore, this usually renders the patient completely dependent upon the pacemaker and therefore is not attractive as a treatment option in younger patients.36

Catheter ablation to cure AF

The cure of AF is the ultimate goal of invasive electrophysiology—it is complicated primarily because of the multiple triggers involved in the generation of AF.37 Ablation of AF relies on attempts to remove these triggers, as well as preventing potential atrial re-entrant circuits forming.

The first descriptions of successful catheter ablation using radiofrequency for AF were from Haissaguerre et al.38 They identified that AF was triggered in a large number of patients from the pulmonary veins draining into the left atrium and ablation at these trigger sites abolished AF. However, this was associated with a significant risk of pulmonary vein (PV) stenosis (~3%).39 As a result, further developments involved electrically isolating arrhythmogenic tissue around the pulmonary veins by ablation outside the ostia of the vein (avoiding the risk of PV stenosis)—so called circumferential PV isolation (Figure 5).40

PV isolation is effective for a large percentage of paroxysmal AF patients but more persistent AF is now recognized to have triggers outside the PVs, possibly involving multiple circuits. Changing the atrial substrate in order to prevent sustained multiple re-entry circuits was the aim of the surgical Maze procedure. This can now be performed endocardially through compartmentalization of the left and right atria with linear ablations (Figure 6).41 The main problem associated with this procedure is the duration of the procedure (~4 h), but improvements in catheter technology and non-fluoroscopic mapping have made this more readily available and quicker (Figure 7). Also, because of the extensive ablation required, there is a higher chance of recovery of tissue that will then allow AF to occur again so these patients often need repeat procedures.

Current guidelines suggest referral for consideration of invasive intervention for rhythm control of atrial fibrillation in patients who have failed medical therapy, have lone AF, or have ECG evidence of another underlying electrophysiological disorder (i.e. pre-excitation).

(http://www.nice.org.uk/nicemedia/pdf/CG036niceguideline.pdf)

Complications

The occurrence of complications varies depending on the procedure being performed. Serious complications are rare for most ablation procedures (death, myocardial infarction or stroke 0.05–0.01%) although the stroke risk with curative AF ablation is slightly higher.42,43 Heart block requiring a permanent pacemaker occurs on average in 0.5% but the risk does depend upon the tissue being ablated and its proximity to the AV node. Other
forms of thromboembolism, including systemic embolism, pulmonary embolism occur very rarely. Complications related to vascular access are more common (2–4%) and cardiac trauma/perforation leading to tamponade may occur (1–2%). Phrenic nerve damage may be seen but pacing manoeuvres can be used to identify the phrenic nerve’s location to help avoid it. Radiation exposure is kept to a minimum but the dose varies depending upon several factors including case complexity (see below). With AF ablation, specifically, pulmonary vein stenosis may be seen. The stroke risk is higher because of extensive ablation in the arterial system (left atrium) at 1% on average, but other potentially fatal complications such as atrio-oesophageal fistulae are extremely rare.

**Radiation exposure**

Radiofrequency ablation procedures require fluoroscopy, and the amount of radiation exposure depends on the equipment and the technique used. Acute skin injury is rare and can be avoided by minimizing radiation exposure. Radiofrequency ablation usually can routinely be accomplished with <20 min of fluoroscopy for most arrhythmias. For longer procedures, the use of non-fluoroscopy catheter location techniques,
Figure 6. In some patients with AF, PV isolation alone is not enough. These schematic diagrams show typical lesion patterns for (i) ostial/segmental PV isolation, (ii) wide area circumferential ablation with compartmentalization/linear ablation and (iii) electrogram-guided ablation in a postero-anterior (PA), left lateral (LLat) and antero-posterior (AP) view.

Figure 7. Mapping system image showing a 3D representation of the left atrium (in this case, a cardiovascular magnetic resonance scan has been used). A catheter is seen in the PV, and an ablation catheter (Ablation) at the antrum of the PV. Electro-anatomical mapping systems are now commonly used for ablation of complex arrhythmias such as AF. These systems have the advantage of allowing the operator to record positions that the ablation catheter has been to and to minimize fluoroscopy dose with visualization of the ablation catheter and its movement in real time. The main disadvantage is that the system depends upon a ‘reference’ (often another catheter in the body or a patch on the patient’s skin) and if this moves then the entire accuracy of the system is lost and the study may have to be restarted.
using either magnetic (i.e. CartoTM) or electrical fields (i.e. Ensite NavXTM) for mapping of catheter position, has reduced fluoroscopy time and radiation dose to both patient and staff. These systems allow the real time visualization of the catheters in the heart, based on either electromagnetic localization or the measurement of impedance changes and work using patches attached to the skin of the patient prior to the procedure (Figure 7).

The future

Improving mapping techniques

The newest versions of the mapping systems have been designed with features that may permit better radiofrequency ablation lesion formation. The most promising of these is the ability to measure contact force of the catheter tip with the tissue, which directly correlates with lesion formation. Whether this will translate into higher success rates, particularly for AF ablation, remains to be seen. Other improvements revolve around creating more user-friendly platforms with advanced software for some of the components of the procedures.

New catheter designs

Apart from new designs in handles, one of the major developments in recent years has been the ability to cool the catheter tip while ablation. This reduces dissipation of heat into the blood, enabling more efficient energy delivery to the tissue, potentially with lower power settings. The most common design involves a series of holes in the catheter tip through which saline is irrigated during ablation (so called ‘irrigated tip’ catheters) (Figure 1). For AF ablation, the need to speed up and simplify the process has led to the development of catheters that cannot only record electrical activity in the pulmonary veins, but also can deliver radiofrequency energy around multiple poles simultaneously. These catheters use bipolar radiofrequency energy (in addition to the standard unipolar energy), which means that the powers required are lower for equivalent lesion formation (Figure 8).

Remote/robotic catheter ablation

The long time required for these procedures can be physically demanding for operators. Systems have been developed that allow the operator to manipulate the radiofrequency ablation catheter from a control panel that is remote from the patient (usually in the control room). This not only offers the advantage of reducing radiation exposure to the operator and making it more comfortable for them by not wearing lead gowns, but also the catheter stability may be improved that may translate into better lesion formation and long term success.

Other energy sources

Cryoablation

Completely contained within a specialized ablation catheter, liquid nitrous oxide released into the tip rapidly cools adjacent tissue. The temperature initially falls to −30°C, resulting in reversible block. At this point, the electrophysiological impact can be determined prior to decreasing the temperature to −60 to −80°C for 4 min, resulting in permanent damage.

Microwave

Microwave creates thermal energy-like radiofrequency but unlike radiofrequency, the mechanism is dielectric. Electromagnetic radiation is converted to kinetic energy. These waves can get into tissue from virtually any distance and therefore is particularly useful for penetrating scars. This has not been proven to be clinically very useful.

High frequency ultrasound

Vibration energy is propagated as a mechanical wave. When this wave hits an absorbing medium such as tissue it is converted to heat. High frequency
ultrasound (HiFu) may be used to focus energy to create lesions at a particular distance from the transducer, penetrating through any tissue in between. Recent studies have suggested that this form of energy is associated with a higher risk of complication, mainly perforation.57

Light amplification by stimulated emission of radiation

The ability of Light amplification by stimulated emission of radiation (laser) light to be highly focused means that large, deep lesions can be created by subsequent energy scatter within the tissue. A number of different lasers have been tried including argon, Yag and diode.58,59 Clinical utility remains to be demonstrated in larger studies.

Summary

Radiofrequency ablation of cardiac arrhythmias is now an established treatment for many patients. In many, it is increasingly considered as first line therapy as it is potentially curative and negates the need for long-term medication. The technology continues to develop in response to the needs of physicians performing these procedures, improving efficacy and safety. It is important that all physicians are aware of what is available in terms of treatment as arrhythmia is common and often initially presents to doctors who are not specialists in cardiac electrophysiology.

Conflict of interest: None declared.

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