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Review

The Past, the Present, and the Future of Cardiac Arrhythmia Ablation

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ABSTRACT

The development and evolution of percutaneous catheter ablation for the treatment of cardiac arrhythmias has advanced significantly since the early days of direct current shock ablation, and in parallel with an increasing understanding about arrhythmia mechanisms. Because of the ever-changing landscape that is cardiac electrophysiology, the purpose of this review is to discuss the future of invasive arrhythmia management within the context of the history and contemporary practice of this cardiac subspecialty. Topics of discussion include: (1) the evolution of ablation technologies from direct current shock and radiofrequency to alternative energy sources such as cryothermal ablation; (2) the use and development of nonfluoroscopic navigation systems; (3) the progression of ablation toolsets and modalities; and (4) the advancement of ablation strategies and techniques, including ablation of complex atrial and ventricular dysrhythmias tailored to the individual patient.

RÉSUMÉ

Les techniques d'ablation par cathéter pour le traitement des arythmies cardiaques ont fait des progrès significatifs au cours des dernières années, parallèlement à une meilleure compréhension des mécanismes impliqués dans les différents types d'arythmie. Le but de cette revue est de se pencher sur l'avenir de l'électrophysiologie cardiaque invasive dans la prise en charge des arythmies, dans le contexte de la pratique contemporaine et de l'évolution constante de cette sous-spécialité de la cardiologie. Les sujets de discussion sont : 1) l'évolution des technologies d'ablation par radiofréquence et des autres sources d'énergie telle la cryothermie; 2) l'utilité et le développement de systèmes de navigation non-fluoroscopiques; 3) le progrès des outils et des différentes modalités d'ablation; 4) l'avancement des stratégies et des techniques d'ablation, y compris l'ablation de troubles du rythme auriculaire et ventriculaire complexe adaptés à chaque patient.

The development and evolution of catheter ablation for the treatment of cardiac arrhythmias represents a major accomplishment. Rarely have such significant advances in technology and technique been seen so rapidly and over such a short period of time. Catheter ablation procedures have been used worldwide in hundreds of thousands of patients. Since its clinical introduction in the early 1980s, the techniques and technologies surrounding cardiac catheter ablation have become increasingly complex, evolving significantly in parallel with an increasing understanding about arrhythmia mechanisms (Fig. 1). Because of the ever-changing landscape that is cardiac electrophysiology, the purpose of this review is discuss the future of invasive arrhythmia management within the context of the history and contemporary practice of this cardiac subspecialty.

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See page S440 for disclosure information.

Where We Have Been

The beginnings of invasive electrophysiology and catheter ablation

Invasive electrophysiology owes its early existence to a combination of critical developments in the late 1960s and early 1970s.[1-4] The combination of intracardiac catheter recordings of cardiac electrical activation (such as the His bundle activity described by Scherlag and colleagues in the late 1960s [Fig. 2]), and programmed stimulation techniques (described by Henrick Joan Joost Wellens in the early 1970s) led to significant advances in the understanding of tachycardia mechanisms (particularly Wolff-Parkinson-White syndrome, but also atrioventricular node re-entry and atrial flutter).[1,5] As a result of this greater understanding, open surgical techniques were developed for the treatment of various arrhythmia substrates including atrioventricular or accessory pathway mediated tachycardia,[6] ventricular tachycardia (VT),[7] and atrial fibrillation (AF).[8,9]

Because of limitations associated with the open surgical treatment of cardiac arrhythmias, percutaneous catheter ablation was developed in the early 1980s and has since

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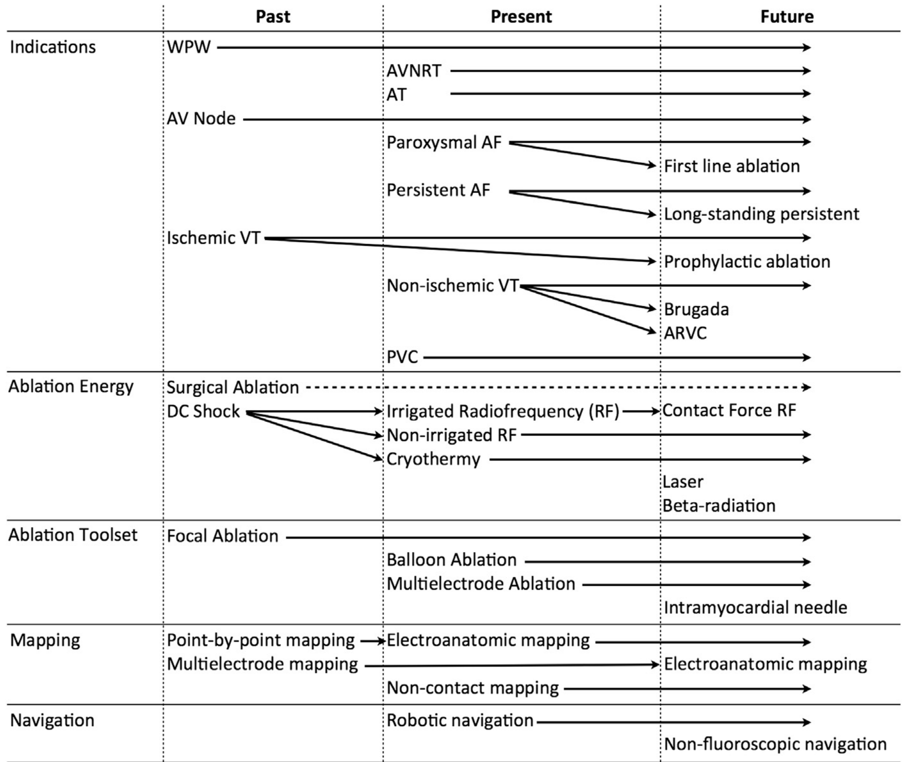

Figure 1. The evolution of invasive arrhythmia management: past, present, and future. With increasing knowledge and technological developments, the indications and techniques have expanded in parallel. AF, atrial fibrillation; ARVC, arrhythmogenic right ventricular cardiomyopathy; AT, atrial tachycardia; AV, atrioventricular; AVNRT, atrioventricular nodal rentrant tachycardia; DC, direct current; PVC, premature ventricular complexes; RF, radiofrequency; VT, ventricular tachycardia; WPW, Wolff-Parkinson-White syndrome.

revolutionized electrophysiology (Fig. 3).[10-12] Using high- and low-energy direct current shocks, the initial studies concentrated the use of this technique on reasonably well understood focal arrhythmia substrates such as the atrioventricular (AV) junction or His bundle (ie, complete AV node ablation), AV re-entrant tachycardias (ie, accessory AV pathways), and ischemic VT (ie, diastolic pathway or VT exit site).[10-15] Unfortunately, these early ablation procedures were long (> 4-8 hours), and of limited utility. Specifically, the risk of barotrauma and other significant complications (myocardial depression, proarrhythmia, unintended AV block, myocardial perforation, venous thrombosis, and sudden death) limited these procedures to patients with more malignant dysrhythmias or severe comorbidities.

Radiofrequency ablation

Technological advancements in the late 1980s led to the development of catheters capable of delivering continuous-wave unmodulated radiofrequency (RF) energy. This shift from direct current to RF ablation represented a major advance in invasive cardiac electrophysiology. Compared with direct current shocks, RF ablation offered the advantages of: (1) minimal discomfort during energy delivery (allowing the procedure to be performed in conscious patients); (2) absent skeletal- and cardiac-muscle stimulation; (3) relatively discrete ablation lesions with absent barotrauma; and (4) the potential for the premature termination of ablation in an effort to avoid impending complications.[16] As such, RF energy provided a reasonably low-risk treatment option, quickly supplanting open-heart surgery as the preferred invasive modality for the treatment of supraventricular and ventricular arrhythmias.

However, despite the rapid and widespread adoption of percutaneous catheter ablation, the early use of RF energy was not without its limitations. Although the standard RF ablation is appropriate for focal ablation in thin myocardium (eg, focal atrial tachycardia, accessory pathways, and AV nodal substrates) its use is limited by complications related to the use of high-power settings and/or high target temperatures when performing more extensive ablation in thicker tissues (ie, the ventricle), or ablation in the systemic circulation. Specifically, irreversible tissue destruction requires a temperature of $\geq 50°C$. However, the attainment of high temperatures at the electrode-tissue interface might result in carbonization, tissue desiccation, and/or plasma coagulation (charring and thrombus formation). These factors might increase the risk of perforation and/or thromboembolism.

In response, temperature- and/or energy-limited ablation was developed. Using temperature control, RF power delivery is regulated to maintain a constant electrode temperature (commonly 55°C or 60°C), which is thought to prevent electrode-tissue interface temperature from increasing to the point of creating an impedance rise, soft thrombus formation, and/or steam "pop." However, the ablation electrode temperature is dependent on the opposing effects of heating from the tissue and cooling by the blood flowing around the electrode at any given electrode temperature. As such, the reduced electrode cooling associated with the presence of low blood