Advances in Catheter Ablation for the Treatment of Cardiac Arrhythmias

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***Abstract*—RF catheter ablation has become the nonpharmacologic treatment of choice for refractory cardiac arrhythmias. Single carefully directed RF lesions are capable of curing most supraventricular tachycardias. Recent developments in cardiac mapping and lesion formation allow for the analysis and treatment of more complex arrhythmias. Such new technology should help to expand the number of patients successfully treated with catheter ablation.**

***Index Terms*—Cardiac arrhythmia, catheter ablation, RF ablation.**

I. Introduction

CATHETER ablation, using radio-frequency (RF) energy, has become the nonpharmacologic treatment of choice for patients with symptomatic cardiac arrhythmias [1]–[4]. Ablation is based upon the concept that removal of cardiac tissue that is either the focus or the critical portion of the arrhythmic circuit will result in a cure of the clinical arrhythmia. Initially, open-heart surgery was required. In 1969, Sealy and colleagues demonstrated that patients with Wolff–Parkinson–White syndrome could be cured of their clinical arrhythmias once their accessory pathway was surgically interrupted [5]. Although highly effective, surgical treatment of cardiac arrhythmias is not commonly employed due to the morbidity and potential mortality associated with open-heart surgery and cardiopulmonary bypass. RF catheter ablation offers a nonsurgical alternative. When RF current (unmodulated, 550 kHz) is passed to the tip of a standard intracardiac electrode catheter, a well demarcated lesion is formed at the interface between the catheter electrode and the myocardium. If this lesion is appropriately placed, a cardiac arrhythmia can be successfully treated.

In the last decade, catheter ablation has revolutionized the treatment of patients with cardiac arrhythmias. The success of this therapy depends upon two factors:

1) *cardiac mapping:* the ability to successfully characterize the arrhythmic circuit;
2) *lesion formation:* the ability to generate a lesion in the heart capable of abolishing the arrhythmia.

Supraventricular tachycardia generally results from an arrhythmic circuit that may be easily identified. These arrhythmias generally occur in patients who have structurally normal hearts. They have abnormal electrical pathways, but their heart is otherwise normal. The target sites for delivery of RF energy are determined by catheter mapping in the electrophysiology laboratory. During these studies, standard electrode catheters are placed fluoroscopically in the heart and electrical activity is recorded. The clinical arrhythmia is induced using programmed electrical stimulation, and the arrhythmia may be studied. Most supraventricular tachycardias occur over easily defined pathways. The critical portion of the tachycardia circuit may be ablated with a single RF lesion produced by delivering sufficient RF power (generally 25–40 W) to the tip of a standard 4-mm electrode catheter to achieve a target tip temperature of 65 °C for 30–60 s. More than 90% of patients with supraventricular tachycardias may be successfully treated with a minimum of complications [1]–[4].

Catheter ablation of supraventricular tachycardias is straightforward. First, single point-to-point mapping can easily identify the appropriate target site for RF delivery. Second, a single appropriately delivered RF lesion is often effective. In more complex arrhythmias, such as ventricular tachycardia postmyocardial infarction, the situation is not so straightforward. The arrhythmia circuit is more difficult to define, and the arrhythmia may not be cured with a single RF lesion delivered through a standard catheter. Generation of larger, deeper lesions or long continuous longitudinal lesions may be required for the treatment of more complex arrhythmias such as atrial flutter or ventricular tachycardia. Recent developments in cardiac mapping and RF delivery systems are helping to expand the scope of catheter ablation to these more complex arrhythmias.

II. Mapping Systems

New mapping systems are being developed in the hope of more rapidly and accurately defining the arrhythmic substrate. Mapping is the recording of the electrical activation sequence of the heart. Conventional catheter mapping of the heart utilizes a single electrode catheter, which is moved throughout the cardiac chamber. Endocardial signals are recorded and compared to a reference signal such as the P-wave or QRS complex on the surface electrocardiogram (ECG). Such point-to point mapping may be difficult and time consuming. In addition, single point mapping does not give a global view or anatomic view of chamber activation.

In order to overcome some of these limitations, new mapping systems are under current investigation. These include multielectrode arrays, noncontact electrodes, and nonfluoroscopic mapping by recognizing an electromagnetic field applied outside the body.

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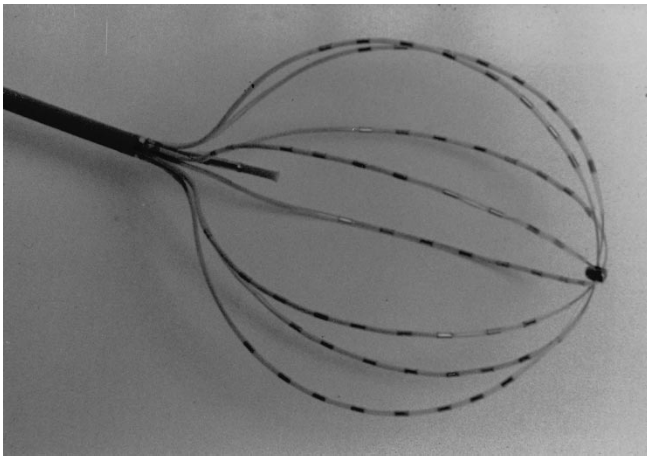

Fig. 1. Multielectrode “basket” catheter (Constellation, EP Technologies/ Boston Scientific).

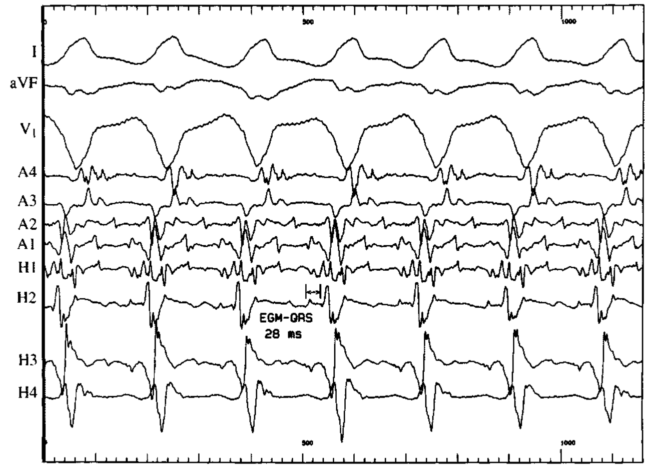

Fig. 2. Electrograms recorded from a multielectrode “basket” catheter located in the left ventricle of an animal during sustained ventricular tachycardia. Bipolar electrograms are recorded from two adjacent splines on the basket catheter (splines A and H and electrode pairs 1 to 4). Earliest presystolic activity is recorded 28 ms prior to the onset of the QRS complex at electrode pair H2.

A. Multielectrode Arrays

A multielectrode “basket” catheter has been developed by EP Technologies/Boston Scientific and Cardiac Pathways for human use (Fig. 1). The Constellation (EP Technologies, San Jose, CA) catheter consists of eight self-expanding nitinol splines mounted on an 8F 110-cm-long flexible shaft [6].

Each spline has eight symmetrically arranged electrodes, which permits a total of 32 bipolar pairs for recording or pacing. In this catheter, the interelectrode distance is 5 mm while the interspline distance is approximately 1 cm. The catheter is introduced into the heart by means of a custom designed guiding sheath. The collapsed basket is introduced into the guiding sheath and advanced into the heart. The sheath is then withdrawn allowing the basket catheter to expand to fill cardiac chamber, either the atrium or the ventricle. The basket catheter conforms to the shape of the cavity during both systole and diastole. Unipolar or bipolar electrograms may be regarded from any of the 64 electrodes. Electrograms are generally amplified and filtered at 30–500 Hz and displayed on a physiologic recorder.

Initial studies in animals demonstrated that the multielectrode “basket” catheter was capable of recording stable endocardial signals during rapid cardiac arrhythmias [6], [7]. Activation mapping during the arrhythmia with a multielectrode catheter permits rapid localization of early activation sites. (Fig. 2) Pacing maneuvers performed with the “basket” catheter may also help identify potential target sites for catheter ablation of the arrhythmia. Ablation of ventricular tachycardia guided by multielectrode catheters has been performed in animals and humans [7]–[9]. In addition, use of this catheter in the atrium has been effective in the analysis of complex atrial arrhythmias [10], [11].

The major advantage of a multielectrode “basket” catheter is that activation mapping data may be acquired from as little as a single beat of the tachycardia. The electrograms obtained are real-time signals and do not require special processing. In addition, the catheter itself may be inserted with standard cardiac catheterization techniques. Special recording equipment is not required. The data may be acquired using the standard recording equipment found in every electrophysiology laboratory. Disadvantages of a multielectrode “basket” catheter include the difficulty in analyzing multiple simultaneous signals and the difficulty in maneuvering other catheter electrodes within the “basket” framework. Development of computer algorithms for display and analysis of these signals is required for this system to develop widespread acceptance. In addition, electrode spacing limits the resolution of the system.

B. Noncontact Electrode Systems

The noncontact electrode system, developed by Endocardial Solutions (Ensite 3000; St. Paul, MN), utilizes a mathematical computation to determine endocardial activation from data provided from multiple electrodes on a noncontact balloon catheter placed in the heart [12], [13]. The system consists of an array catheter, a standard roving electrode catheter, and a computer interface unit that processes the signals and creates electroanatomic maps. The standard roving electrode catheter moves about the endocardial surface of the chamber that is to be mapped and is located by the array catheter to reconstruct chamber geometry. Computer processing constructs an electroanatomic map, reconstructing potentials arising from the endocardial surface, by combining information on chamber geometry, the known location of array electrodes, and noncontact electrode potentials at each electrode on the array.

The array catheter (Fig. 3) consists of a 9F central lumen catheter terminating in a pigtail tip allowing safe passage into the left ventricle. Within the chamber there are two ring electrodes. The array consists of a strand of 64 polyimide-insulated 0.003-in stainless-steel wires over a 7.5-ml balloon. The electrodes are created by laser removal of 0.025 in of insulation. When placed in the heart, the inflated balloon measures 1.8 × 4.6 cm.

In order to locate the tip of the roving electrode, a low-level 5.68-kHz current is passed to the distal electrode and returned to one of the ring electrodes on the array. The location of the roving electrode is determined by sampling this signal from each of the

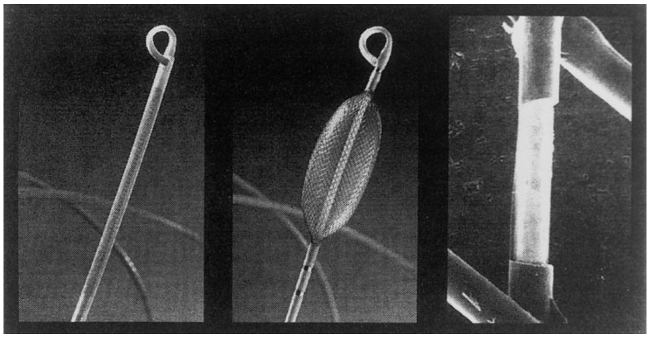

Fig. 3. Noncontact multielectrode catheter (Endocardial Solution, Inc.). The distal end of the array catheter is shown before and after inflation (left and center). At right is a magnified view of an electrode on the array. (Reproduced from [16] with permission.)

64 array electrodes. The surface of the chamber to be mapped is determined using the system's locator and X-ray fluoroscopy.

Noncontact endocardial potentials are derived from each of the 64 electrodes on the array. Taccardi was the first to apply a mathematical model to determine endocardial potentials with a noncontact probe [14]. Endocardial potentials are derived from the cavitary probe recorded electrograms by applying an "inverse solution" [15]. The mathematical formula for deriving these electrograms is based on the inverse solution to Laplace's equation using a boundary element method. This formula determines how a remote signal recorded on the noncontact catheter array would appear at its source. These derived electrograms correlate well with electrograms recorded by direct surface contact probes. *In vitro* studies have demonstrated that accuracy of the noncontact electrograms decreases at distances of greater than 40 mm from the center of the array. tachycardia as well as atrial arrhythmias [16]. Validation of this system has continued in clinical studies of sustained ventricular tachycardia. In studies of patients undergoing RF catheter ablation of sustained ventricular tachycardia, reconstructed electrograms obtained from the noncontact array correlated well with those electrograms obtained from standard contact electrode probes. This system has been utilized to safely map and guide ablation [17].

Advantages of the noncontact electrode system include the ability to create an activation map with a single beat of tachycardia. (Fig. 4) Therefore, mapping of rapid, hemodynamically unstable arrhythmias is possible. This may decrease procedure time and allow more patients with unstable arrhythmias to undergo ablation. Disadvantages include the difficulty in navigating a probe in a cardiac chamber that already contains the balloon array. The utility and accuracy of this system in clinical practice remains to be determined.

C. Nonfluoroscopic Electroanatomic Cardiac Mapping

The final system undergoing investigation is theCarto mapping system (Biosense, Tirat Hacarmel, Israel), which utilizes catheters instrumented with a sensor in the distal tip that senses an electromagnetic field [18]. The system simultaneously acquires electrograms from the catheter tip as well as its three-dimensional location. The mapping system reconstructs a three-dimensional electroanatomical map of the heart.

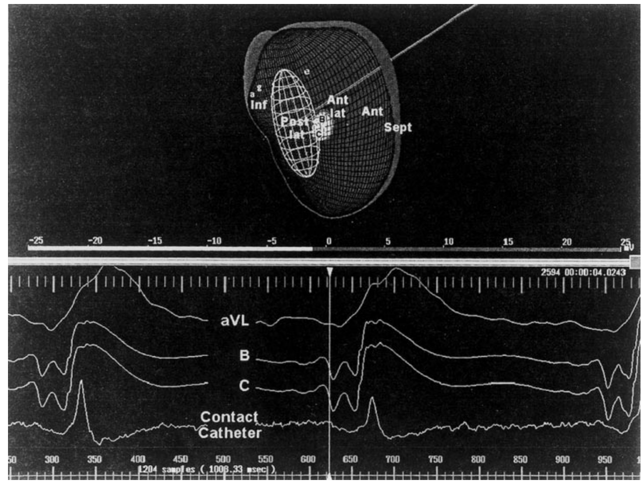

Fig. 4. Activation during sustained ventricular tachycardia as recorded from a noncontact catheter. The array catheter is displayed as a frame within the virtual endocardium Anatomic locations identified by fluoroscopy are identified. The map shows the exit site of the ventricular tachycardia as a white dot. The electrograms displyed below the map are the reconstructed electrograms from the exit sites B and C, surface lead avL, and an electrogram from a contact catheter located at a site remote form the origin of the arrhythmia. (Reproduced from [17] with permission.)

The system consists of a roving catheter, which is a standard deflectable catheter equipped with a miniature passive magnetic field sensor. Ultralow magnetic fields (5×10^{-6} to 5×10^{-5} T) are generated by a locator pad that is placed beneath the operating table. The locator pad consists of three coils that each generate a magnetic field. Since the field decays as a function of distance from the coil, the sensor in the tip of the roving electrode can measure the strength of the field. The field emitted from the locator has known temporal and spatial features allowing three-dimensional orientation of the sensor electrode.

The mapping procedure consists of moving the roving catheter under fluoroscopic guidance to multiple locations in the heart. The recorded electrogram at each site is displayed on a computer screen and oriented to a fiducial point in the cardiac cycle such as a P-wave or R-wave. By moving the recording catheter to multiple locations in the cardiac chamber to be mapped, an endocardial surface reconstruction may be created. The activation time at each site is color-coded. The computer displays an electroanatomic map of the heart (Fig. 5). Once this is created, the roving catheter may be moved to any anatomic site without the need for fluoroscopy. In addition, the catheter can be easily moved to sites that were previously tagged. Unlike mapping with the noncontact probe, this type of cardiac mapping is a sequential beat-to-beat approach.

In vitro and *in vivo* validation studies have shown reproducibility of location measurements to within 0.42 $\pm$ 0.05 mm [17]. Animal studies have shown that the system is accurate enough to guide a RF ablation catheter to within 2.3 $\pm$ 0.5 mm of a given target site. This suggests that RF energy could be targeted to multiple points without the need for fluoroscopy [19].

Multiple studies have shown the utility of this mapping system in clinical practice. These include activation mapping for accessory pathways, locating the site of a focal tachycardia,

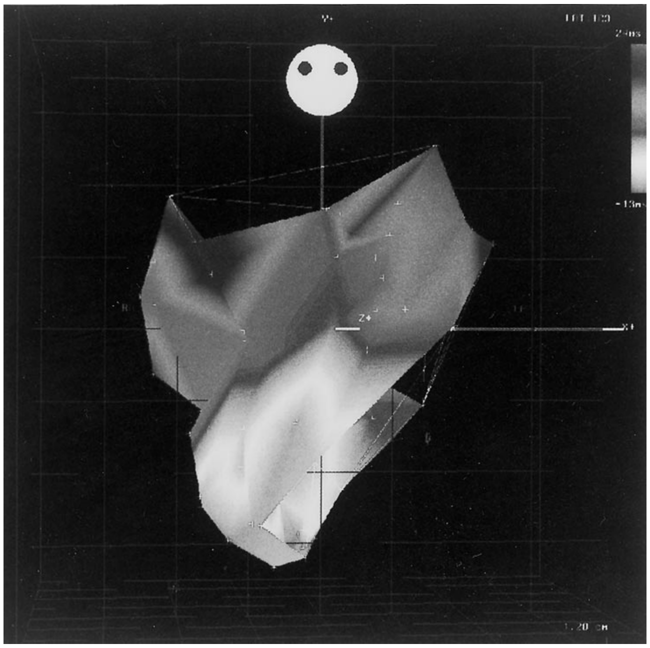

Fig. 5. Three-dimensional electroanatomic map of right ventricular activation in the swine produced by the Carto system. The map was constructed from multiple sampling points during sinus rhythm. This is an anteroposterior view of the right ventricle with the right ventricular outflow tract protruding anteriorly and to the left. The right ventricular apex is to the right and inferior. Activation starts along the inferior portion of the septum and proceeds toward the apex. (Reproduced from [18] with permission.)

determining anatomic boundaries for catheter ablation as well as gaps in linear ablation lesions [20]. Unlike other mapping systems, which give electrical information only, Carto provides an integration of both anatomic and electrical findings. Disadvantages of the Carto system include the complexity of the system and the time required to produce the electroanatomic maps.

As the complexity of cardiac ablation procedures increases, there is a need for more sophisticated cardiac mapping systems. The three systems described provide the operator with a more complete picture of endocardial activation. In the case of basket arrays, this is more complete activation maps from multiple electrodes. Noncontact arrays and nonfluoroscopic maps provide electroanatomic data. Future studies will determine the role of each system in clinical practice.

III. Lesion Delivery

Newer catheter systems are being developed to treat complex arrhythmias that are not amenable to simple single lesion placement. For example, in atrial flutter, a linear lesion between the tricuspid anulus and inferior vena cava is required to terminate the arrhythmia. In addition, ablation of other arrhythmias such as ventricular tachycardia postmyocardial infarction may require lesions that are deeper than those produced by standard catheters. An important disadvantage of RF ablation is the focal and discrete nature of the endocardial lesion. Previous studies have demonstrated that lesion formation is determined to a large extent by the nature of the electrode-tissue interface [21].

Large tip catheters, microwave catheters, and irrigated tip catheters are being developed to produce larger RF lesions

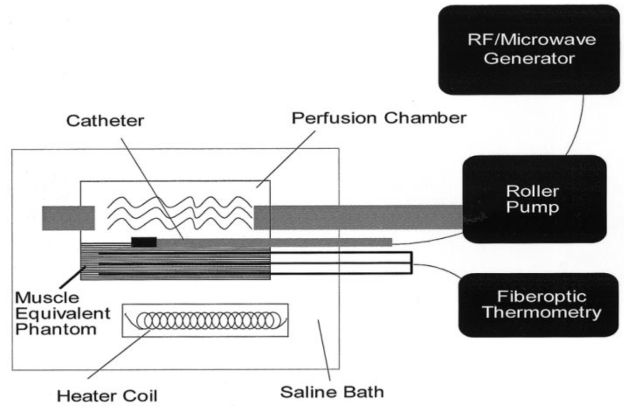

Fig. 6. Diagram of the flow-phantom model for the evaluation of cardiac ablation catheters.

[22]–[24]. We evaluated the influence of electrode tip size on lesion formation in an *in vitro* flow-phantom model [25] (Fig. 6). The flow-phantom model consisted of phantom material that simulates cardiac muscle suspended in a saline perfusion chamber. Muscle equivalent phantoms for microwave and RF were made from mixtures of TX150, polyethylene powder, NaCl, and water. Flow across the surface of the phantom, simulating blood flow, was controlled by a perfusion pump. Catheter design was tested by placing the catheter on the surface of the phantom material. Since cardiac lesion formation is dependent upon tissue heating, the temperature profile of each catheter will determine potential lesion size. Temperature measurements were made using a 12-channel Luxtron fiber-optic thermometry system. Fiber-optic probes were inserted at various depths in the phantom material.

Studies using this model demonstrated that lesion size is proportional to delivered power. Larger delivered power is necessary to optimize lesion size with an 8-mm versus a standard 4-mm RF electrode. If similar tip temperatures are achieved, the maximal lesion volume with an 8-mm electrode is approximately twice that achieved with a 4-mm electrode. A microwave catheter using a coaxial cable with an overall diameter of 2.413 mm terminating in a helical antenna was studied at 915 MHz [26]. This catheter produced a temperature profile similar to that of the smaller 4-mm standard RF electrode. This suggests that the microwave catheter tested would not produce cardiac lesions any larger than standard RF catheters. In addition, these studies demonstrated that there is a substantial cooling effect of cardiac blood flow across the surface of the catheter electrode. These data show that static phantom models will overestimate lesion size since lesion size is proportional to surface temperature.

In vivo studies have also shown that lesion size may be enlarged by increasing electrode diameter [23], [24]. These studies demonstrated that increased electrode size will enhance lesion volume provided sufficient RF power is delivered. For each electrode tested, power delivery was limited by the development of an impedance rise. An impedance rise was associated with tip temperatures in excess of 100°C and coagulum formation at the electrode surface. While the microwave catheter tested did not substantially improve lesion formation, microwave energy is still an attractive potential energy source for ablation since there may be volume heating without the limitations of RF energy that limit power delivery.

Modifications in electrode design have been studied in an attempt to deliver additional RF power without causing a rise in impedance. The irrigated tip catheter has undergone the most extensive evaluation. Wittkampf originated the concept of irrigating the tip of the ablation catheter with saline to cool the electrode-tissue interface and prevent a rise in impedance during higher power RF delivery [27]. The advantage of such a system is that higher RF power may be delivered, which produces larger and deeper lesions. Normally, blood flow will produce convective cooling of the catheter tip. With an irrigated tip electrode, a rise in impedance will not occur even if the catheter is in an area of relatively low blood flow.

Studies in a canine thigh muscle preparation have shown that RF lesions produced with a 5-mm irrigated tip electrode are deeper (9.9 ± 1.1 mm versus 6.1 ± 0.5 mm, $p < 0.01$) and wider (11.3 ± 0.9 mm versus 14.3 ± 1.5 mm, $p < 0.01$) than those produced by a conventional electrode [28]. Lesion volume was approximately 2.5 times larger with the irrigated tip electrode (700 ± 217 mm^3 versus 275 ± 55 mm^3, $p < 0.01$). Using fluoroptic thermal probes, these investigators were able to demonstrate that there was a higher temperature in the tissue at depths of 3.5 and 7 mm than there was at the tissue surface. This was in contrast to standard electrodes, where the surface temperature was always higher than the tissue temperature. With irrigated tipped electrodes, there was direct resistive heating deep in the tissue which produced a larger lesion.

Ablation for the common form of atrial flutter may fail due to an incomplete ablation line in the inferior vena cava tricuspid anulus isthmus. Jais and coworkers found that 13 of 170 patients referred for atrial flutter ablation had such an incomplete line of conduction block [29]. Using an irrigated tip catheter, they were able to create bidirectional conduction block, the marker of a successful ablation in 12/13 cases. These data suggest that this system may prove useful in cases resistant to standard ablation techniques.

The safety of this system has not been completely studied. Risk of coronary artery damage is possible since the lesion depth is greater. In addition, conventional RF delivery is limited by an impedance rise. Since the risk of an impedance rise is lessened due to the cooling effects of the tip irrigation, there is a greater chance of steam formation beneath the surface. A "tissue pop" could occur, causing cardiac perforation and tamponade. These safety concerns need to be addressed before the system gains widespread use.

Catheters capable of producing linear lesions are being developed. Using standard electrode technology, a linear lesion is produced by dragging the RF electrode in a straight line during constant or intermittent RF power delivery. Obviously, the ability to drag a catheter consistently along a straight line poses technical challenges. This technique also increases procedure time, as the operator must drag the catheter slowly along the ablation line. In order to overcome these limitations, new catheters that utilize coils or arrays rather than standard platinum electrodes have been designed. These catheters may prove to be useful in the treatment of atrial fibrillation where long linear lesions may be required. Such catheters are undergoing investigation but have yet to enter clinical practice [30].

IV. Conclusion

As we enter the new millennium, new technology in arrhythmia analysis and delivery of RF energy will allow for the treatment of more complex arrhythmias. Patients who are now resigned to life-long treatment with drugs or implantable devices may become candidates for RF catheter ablation treatment of their arrhythmias.

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