Ten years ago, the only available treatment modality for patients with drug-refractory supraventricular tachycardia was surgery. Surgical techniques included direct dissection or cryodesiccation of the His bundle for tachycardia control. During the past decade, catheter techniques have been introduced that replicate the surgical experience without the expense and morbidity associated with cardiac surgery. The first decade of catheter ablative therapy was directed primarily at disruption of the atrioventricular (AV) junction and, like the surgical approach, entailed the need for life-long cardiac pacing. In essence, this procedure served as a palliative procedure in that intractable supraventricular tachycardia was replaced by the need for permanent cardiac pacing. During the past 2 years, more specific ablative procedures have been introduced for patients with AV nodal reentry and for those with accessory bypass tracts in all locations. The latter procedures hold great promise for providing definitive cure for these patients. It should be emphasized that current catheter ablative procedures represent a direct outgrowth of impressive advances in our understanding of arrhythmia mechanism as well as in the ability to precisely define the anatomic components of the tachycardia circuits in patients with supraventricular tachycardia. The pioneer efforts of our surgical colleagues often served as the creative spark for development of newer catheter procedures. However, impressive gaps remain in both our understanding of basic mechanisms and our ability to locate critical components of the tachycardia circuit for patients with ventricular tachycardia. Hence, application of catheter ablative techniques to patients with ventricular tachycardia remains an important frontier for clinical electrophysiologists.

**Catheter Ablation of Atrioventricular Junction**

Ablation of the AV junction has become an accepted method for arrhythmia control for patients (without accessory pathways) with arrhythmias arising from atrial tissue. The basic technique involves positioning a multipolar electrode catheter across the tricuspid valve to record a His bundle potential. Initial experience involved use of high-energy DC electrical discharges from a standard defibrillator between the electrode showing the largest His bundle potential to a patch positioned over the left scapula. The patient received a brief general anesthetic agent before shock delivery. If AV block was achieved, a permanent cardiac pacemaker was inserted. The current efficacy rate for this procedure (using high-energy DC shocks) as reported from experienced centers is approximately 85%. High-energy DC discharges involve delivery of discharges of 2–3 kV associated with 40–60 A of current flow. The tissue destruction is thought to be due to disruption of cardiac membranes resulting from the intense electrical field. Disruption of the cardiac membrane allows influx of calcium and probably explains the observed contraction bands after application of this energy form. In addition, high-energy discharges are characterized by spotty rather than homogeneous tissue necrosis.

Although transient ventricular arrhythmias may occur immediately after the shock, the most significant in-hospital complication of this procedure is development of polymorphous ventricular tachycardia. These patients must therefore undergo continuous electrocardiographic monitoring for several days after the ablation. In our personal experience with 100 consecutive patients who underwent AV junctional ablative procedures, polymorphous ventricular tachycardia occurred in four. The clinical setting usually consisted of premature ventricular complexes that resulted in short-long sequences that preceded episodes of polymorphous ventricular tachycardia. This complication was readily reversed by increasing the ventricular paced rate. Furthermore, polymorphous ventricular tachycardia was observed in both those undergoing DC ablation (two patients) and those in whom radiofrequency energy (two patients) was used. In-hospital deaths due to polymorphous ventricular tachycardia, particularly in patients with very poor myocardial function, have been reported. It appears to be prudent to avoid use of class IA antiarrhythmic agents and to closely monitor
serum electrolytes in the postablative period. Careful attention to the paced ventricular rate is of prime importance. Other reported serious complications associated with high-energy DC discharges are uncommon (less than 1%) and include transient immediate postshock ventricular arrhythmias, myocardial perforation, and asymptomatic pericardial effusions.\(^{13}\) The most serious potential complication is the 1.5% incidence of sudden death that has occurred from 3 days to 6 months after high-energy DC ablation.\(^{13}\) This complication has mainly been reported for patients with organic cardiac disease.

In more recent years, alternative energy delivery systems have been applied, including radiofrequency energy\(^{14-16}\) and use of short-duration, nonarcing DC pulses.\(^{17-19}\) The advantages of these alternative systems are that energy is delivered without generation of large pressure waves; therefore, there is avoidance of barotrauma to the heart. Radiofrequency ablation has the added advantage of not requiring general anesthesia during application. Our current experience using radiofrequency energy in association with a large-tip (3 mm) electrode resulted in a 74% efficacy rate in producing complete AV block.\(^{20}\) A failed radiofrequency attempt does not preclude use of DC shocks during the same session. Failed radiofrequency attempts may result in difficulty in recording a clear-cut His bundle deflection and thus may complicate later application of high-energy DC shocks. One is advised to use anatomic landmarks outlined by markings on the fluoroscopic screen as a supplementary measure to guide application of the shocks. With this approach (i.e., initial radiofrequency followed by DC shocks if necessary), our overall success rate in our last consecutive 39 patients was 97%.\(^{21}\) To date, aside from episodes of polymorphous ventricular tachycardia (two patients), no other significant complication has been reported for those undergoing attempted radiofrequency ablation.

**Long-term Results of Atrioventricular Junctional Ablation**

Many prior reports have documented the safety and efficacy of catheter ablative procedures.\(^{22-26}\) Unfortunately, most of these reports comprise relatively few patients with short follow-up periods. Since high-energy DC ablation was first used in 1981, data with regard to long-term effects of induced AV block are becoming available. In a study of 49 consecutive patients treated with high-energy DC shock and followed for a minimum of 1 year (mean follow-up interval, 41±23 months), a number of interesting observations emerged.\(^{27}\) An improved quality of life, manifest by sustained improved exercise capacity or ability to return to work, was reported in 89% of those with no or minimal heart disease compared with a 67% improvement for those with significant organic cardiac disease. Similar data were reported by Kay et al.\(^{28}\) The use of antiarrhythmic drugs (mean failed agents before ablation, 5.5±2) was essentially eliminated after successful ablation. Dramatic decreases in health-care costs were realized for patients with drug-resistant atrial arrhythmias. These patients required a mean of 2.4±2 hospital admissions per year before ablation but only 0.3±0.5 admissions per year after this procedure. Each hospital stay was quite expensive because it usually required continuous electrocardiographic monitoring for several days as well as one or more attempted external DC cardioversion attempts. Furthermore, in five patients with depressed ejection fraction before ablation (27±7%), a significant improvement in systolic function after ablation (45±14%) occurred, which is compatible with the thesis that ablation was effective in abrogating a superimposed tachycardic myopathy.\(^{29,30}\)

**Choice of Long-term Cardiac Pacing**

Long-term cardiac pacing is required even after failed ablative attempts because failed attempts after DC ablation carry a high risk for later development of AV block.\(^{27}\) So far, two patients in our series of 100 patients developed acute pacemaker failure and symptoms of fatigue and dizziness owing to bradycardia. Both underwent uneventful generator replacement. In our early experience, most patients were treated with VVI pacemakers. During the follow-up interval, we found that 33% of patients initially treated with VVI units required upgrade to rate-responsive pacemakers.\(^{27}\) An important innovation, particularly for patients with paroxysmal atrial arrhythmias, is the use of DDIR pacemakers. In these patients, the pacemaker is programmed to allow AV synchrony during slower sinus rhythms with rate-responsive ventricular pacing supervening during more rapid atrial arrhythmias.

**Modification of Atrioventricular Nodal Function**

Ideally, one would like to modify AV nodal conduction to achieve arrhythmia control without producing complete AV block. This approach has been applied to patients with AV nodal reentry. This arrhythmia is thought to be mediated by dual AV nodal pathways, with arrhythmias generated by atrial premature complexes that block in one pathway (fast) but are capable of retrograde excitation of this pathway and initiation of a sustained supraventricular tachycardia.\(^{31}\) Many surgical groups have reported successful tachycardia control (without AV block) by either dissection or application of cryolesions around the AV node.\(^{32-34}\) Available surgical results suggest an efficacy rate of more than 90%, and the chief drawback appears to be inadvertent development of complete AV block, which in the largest reported surgical series was approximately 3%.\(^{32}\) Other surgical series have reported comparable success without development of AV block.

More recently, several catheter techniques have been introduced for AV nodal attenuation in patients with AV nodal reentry. The earliest catheter techniques involved application of high-energy DC shocks to the perinodal region.\(^{35-36}\) In the largest reported series using high-energy DC shocks, the success rate was approximately 85%, but the inci-
dence of inadvertent AV block was approximately 10%. Other groups have applied radiofrequency energy to achieve the same effects. In the largest reported series using radiofrequency energy, complete tachycardia cure was achieved in 32 of 37 patients, whereas inadvertent complete AV block occurred in three patients. In the present series, radiofrequency energy was applied by catheter to the anterior perinodal region just proximal to the region of the His bundle deflection. Postablation electrophysiological studies showed either complete disruption or major modification of fast pathway conduction (Figure 1). In contrast, Roman et al reported catheter application of radiofrequency-induced lesions in the posterior perinodal region anterior and inferior to the os of the coronary sinus and found that these lesions resulted in disruption of slow pathway conduction without producing AV block. The available experience suggests that the atrial breakthrough of the retrograde fast pathway occurs predominantly in the anterior perinodal region, whereas the slow pathway insertion appears to be associated with the posterior perinodal region. However, neither surgical nor catheter experience conclusively determines whether AV nodal reentrant tachycardia is solely relegated to the AV node or whether perinodal atrial fibers are critical components of the circuit. Given the intimate merging among the atrial muscles approaching the atrial anode, the issue of atrial participation in AV nodal reentry may not be resolvable with current techniques.

Regardless of the precise mechanisms of arrhythmia cure, the catheter technique using radiofrequency energy appears to be effective for the vast majority of patients with AV nodal reentrant tachycardia and to have largely obviated the need for surgery in drug-refractory patients. Furthermore, with further improvements in catheter design and experience, this technique holds great promise of becoming the initial therapy of choice for patients with symptomatic tachycardia due to AV nodal reentrant tachycardia. It must be appreciated that current techniques still carry a small risk of developing complete AV block with need for chronic pacing. It is not clear whether the risks of creation of AV block are different between surgical and catheter techniques. In addition, long-term follow-up data are needed (for both techniques) to assess long-term stability of AV conduction.

**Accessory Pathways**

Patients with accessory AV pathways suffer mainly from two types of tachycardia. The most common is designated orthodromic AV reentrant tachycardia and involves antegrade conduction over the normal AV node–His axis with retrograde conduction over the accessory pathway. In addition, these patients may suffer from life-threatening arrhythmias because of the development of atrial fibrillation in patients with accessory pathways with short refractory periods. These pathways connect the atrium with the ventricle by crossing the tricuspid or mitral anulus or anteroseptal or posteroseptal spaces. Excellent surgical approaches designed to ablate the accessory pathways have been introduced and shown to be highly safe and effective. The introduction of catheter techniques to ablate pathways in all locations has opened an exciting new chapter of treat-
ment of patients with accessory pathway–mediated tachycardia. The most common location of accessory pathways is over the left free wall. Patients with left free wall pathways are approached either using an atrial transseptal technique or by retrograde aortic catheterization43 (Figure 2).

The initial reports by Warin et al43 used high-energy DC shocks applied to the atrial insertion site of the accessory pathways. These researchers have reported impressive results with this technique, and these results have been replicated by Swartz et al.44 An alternative approach has been suggested by Jackman et al45 in which catheter-delivered radiofrequency energy is applied at the tricuspid or mitral anulus. In this technique, the electrode catheter is manipulated (retrograde left ventricular catheterization is used for left free wall sites) against the respective anulus over the putative site of the accessory pathway. The latter has been defined using classic endocardial mapping procedures as well as direct recordings from the Kent bundle. The impressive results of radiofrequency applications reported by Jackman et al45 have been confirmed by other groups.46,47 Right free wall pathways are approached from either the superior or the inferior vena cava using similar techniques. We have found it of value to more accurately locate the right-sided pathways by using an electrode catheter inserted into the right coronary artery, as suggested by Swartz et al44 (Figure 3). This is done because of the serious limitations of standard catheter techniques in accurately mapping pathways traversing the tricuspid anulus. Pathways traversing the posteroseptal space may be approached by application of high-energy shocks either just outside the coronary sinus or in close proximity to this structure.48

Initial reports for pathways in all locations using either DC shocks, which have been reported largely from France, or radiofrequency ablation, which have been reported from the United States, show comparable degrees of efficacy compared with the surgical approach. Complications with the catheter technique have been infrequent and largely associated with use of high-energy DC shocks. The most serious complication reported so far was the rare occurrence of sudden death after DC ablation; other reported complications include coronary spasm and myocardial perforation.49 To date, the incidence of serious adverse effects using radiofrequency application for accessory pathway disruption appears to be very low; one instance of spasm of the left circumflex coronary artery with development of acute myocardial infarction has been reported.46 In our experience using catheter ablation with radiofrequency applications to 50 consecutive patients, the efficacy rate is 88% and the only significant complication was one instance of pericardial tamponade that required urgent pericar-
diocentesis. It appears that the initial favorable catheter results are being more widely reported and that in the near future catheter techniques will probably obviate the need for cardiac electrosurgery for most patients with tachycardias incorporating accessory pathways.

**Catheter Ablation for Ventricular Tachycardia**

Catheter ablation of ventricular tachycardia foci remains the most demanding of the catheter procedures. The procedure involves induction of the tachycardia using standard techniques in the catheterization labo-
ratory. Monomorphic ventricular tachycardia is induced, and percutaneously introduced electrode catheters are manipulated to record from as many right and left ventricular endocardial sites as is practical, provided there is hemodynamic stability. The initial technique involved attempts at detection of the earliest ventricular electrogram relative to the surface recordings. At present, attempts are made to localize the critical slow zone of reentrant circuits by pacing near the suspected site of ventricular tachycardia origin (Figure 4). If ventricular pacing produces a QRS morphology identical to the spontaneous tachycardia (Figure 4, bottom panel) with the interval between pacing spike and QRS similar to the interval from diastolic potential to QRS, then these findings are interpreted as pacing within the critical slow zone. In addition, efforts are made to identify mid-diastolic potentials during tachycardia (Figure 5) and to entrain the tachycardia during pacing (Figure 5).

Once the putative site of origin of ventricular tachycardia is located, varying energy sources are then applied to this site in an effort to ablate the focus. The greatest amount of experience has been gathered using high-energy DC shocks applied to the endocardial site by a standard defibrillator. The shocks are usually delivered from the unipolar, distal electrode closest to the ventricular tachycardia site to a chest lead applied in closest approximation to the catheter electrode. An alternative approach has been suggested for ventricular septal foci. In this approach, the earliest left and right septal activations are detected by endocardial mapping. The catheters are manipulated so that the distal electrode of each catheter is positioned as close as possible to the site of tachycardia origin from both right and left septal surfaces. One or more shocks are delivered from one distal electrode to the other across the septum via a standard DC defibrillator. The reported use of radiofrequency application for patients with ventricular arrhythmogenic foci is limited.

The most comprehensive report detailing results of high-energy DC shock for patients with ventricular tachycardia comes from a voluntary international registry. In a final summary report involving 164 patients with ventricular tachycardia, the overall incidence of complete tachycardia cure (without need for supplemental antiarrhythmic agents) was 18%, and an additional 41% appeared to be improved with drug therapy. Unfortunately, there was a high incidence of serious procedure-related complications, including death. A total of 11 procedure-resulted deaths were reported and resulted from electromechanical dissociation, induction of nonresuscitatable ventricular arrhythmias, or progressive intractable heart failure. Other serious complications included major cerebrovascular accidents, myocardial perforation, or arterial thrombosis. Varying results have been reported from a number of investigators. Frank et al reported impressive successes using high-energy DC shocks, whereas more recent reports have described use of radiofrequency application for patients with ventricular tachycardia.

In contrast to the generally poor results reported for catheter ablation of ventricular tachycardia foci, certain ventricular tachycardia patient subgroups may respond very favorably to catheter techniques. Most impressive results have been reported, for example, for patients with bundle branch reentry. This tachycardia is more apt to occur in patients with very dilated hearts and electrocardiographic evidence of intraventricular conduction delay. The tachycardia mechanism usually involves antegrade conduction over the right bundle branch and retrograde conduction over the left bundle branch. Because the right bundle branch is a critical component of the tachycardia circuit, ablation of this structure should lead to tachycardia cure. The proximal right bundle branch is superficially draped over the right ventricular summit and is readily accessible to a catheter. The structure is further localized by recording a specific right bundle branch potential. Application of either high-energy DC shock or radiofrequency energy to the right bundle has been shown to be effective for tachycardia control. Others have reported successful application of catheter techniques to patients with tachycardia emanating from the right ventricle. Great care must be used in application of high-energy DC shocks to this region to avoid myocardial perforation.

**Summary and Future Directions**

Catheter ablation techniques have undergone remarkable evolutionary changes since their introduction approximately 10 years ago. Catheter ablation of the AV junction has essentially replaced the need for cardiac surgery in patients with drug-refractory supraventricular tachycardia. Ingenious catheter techniques are now applied for the common causes of paroxysmal supraventricular tachycardia. Catheter techniques have been refined to address reentry circuits in the atrium, atrioventricular junction, bundle branches, and ventricles. Catheter ablation techniques have been extended to include pulmonary vein isolation for atrial fibrillation, left atrial linear ablation for atrial flutter, and atrioseptal ablation for atrial tachycardia.
techniques devised for modification of the AV node in patients with AV nodal reentry have proven to be almost as effective as the surgical technique and should become the procedure of choice in drug-refractory patients, particularly if it can be shown that the incidence of inadvertent third-degree AV block is reduced. Considering the morbidity, expense, time to recuperate, and risk of death, a trial of catheter modification is preferable to surgery for patients with drug-resistant AV nodal reentrant tachycardia. Surgery can be used for failed catheter attempts. Similarly rapid strides have been accomplished using catheter techniques for destruction of accessory pathways. In many centers (including our own), catheter techniques are used as the procedure of choice for patients with drug-refractory supraventricular tachycardia due to AV node reentry or for patients whose arrhythmias incorporate an accessory pathway. Although indications for catheter techniques for patients with supraventricular tachycardia are still a matter of contention, my opinion is that catheter ablation is in general indicated whenever the physician feels that long-term drug therapy is required for arrhythmia control. This feeling is tempered somewhat for patients with AV nodal reentry or those with parahisian accessory pathways in view of the potential risk of producing complete AV block in these patients. The ablative procedures are in general not indicated for asymptomatic patients because the risk of sudden death or subsequent development of sustained arrhythmia is very low. Consequently, catheter techniques might be applied in exceptional instances to asymptomatic individuals with ventricular preexcitation and very short accessory pathway refractory periods who are engaged in high-risk professions or competitive sports.

Surgery is reserved for patients who fail to respond to catheter ablative therapy. In contrast, catheter ablative procedures should be applied with great caution to patients with ventricular tachycardia considering the limited reported efficacy and serious complications. Catheter ablation is generally reserved as the procedure of last resort for patients with intractable ventricular arrhythmias that are unresponsive to or unsuitable for either cardiac surgery or treatment with an internal defibrillator.

Future directions include development and refinement of catheters and energy sources, allowing wider applications of catheter techniques. Energy delivery systems avoiding the barotrauma associated with high-energy shocks will be increasingly used. In addition, radiofrequency or microwave energy delivery systems that avoid development of high impedance because of tissue surface-catheter interactions will soon become available. A number of novel catheter designs allow increased flexibility and effectiveness, particularly in treating patients with supraventricular tachycardia. We are rapidly approaching an era in which the typical patient with paroxysmal supraventricular tachycardia is studied and cured during the same session.64

An important goal is to develop techniques to reliably modify AV nodal conduction in patients with atrial fibrillation. Development of such techniques without the hazard of producing AV block may obviate the need for life-long drug therapy in patients with atrial fibrillation associated with rapid rate. In addition, there is a need for the development of a multiple electrode array catheter suitable for simultaneous mapping of multiple endocardial sites. The latter should greatly facilitate endocardial mapping in patients with ventricular tachycardia. Both a better understanding of specific arrhythmia mechanisms and development of improved mapping procedures are clearly needed for the next quantum leap in successful applications of catheter ablative procedures in patients with ventricular tachycardia.

The impressive strides achieved in the management of patients with supraventricular tachycardia with catheter techniques have enormous implications relative to patient management issues. It is difficult to justify continued medical therapy in terms of morbidity and expense for patients with atrial fibrillation who prove resistant to reasonable drug trials in view of the effectiveness and safety of the catheter techniques. For patients with drug-refractory reentrant supraventricular arrhythmias, the role of catheter ablation is clear cut. Catheter ablative techniques appear to hold particular promise for women of child-bearing age who require drugs that have a potential for fetal toxicity.

It is further anticipated that the more widespread use of catheter procedures will result in curtailment of surgical procedures. It appears prudent to limit cardiac electrosurgery to a relatively few experienced centers; it would be illogical to encourage proliferation of cardiac electrosurgical centers with the attendant enormous costs of electrical equipment and personnel when the patient pool requiring surgery is anticipated to shrink.

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