

Catheter Ablation of Supraventricular Arrhythmias: State of the Art

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Introduction

The era of catheter ablation for the treatment of arrhythmias began in 1981, when Dr. Melvin Scheinman performed the first atrioventricular junction ablation using direct-current shocks in a patient with drug-refractory atrial fibrillation and an uncontrolled ventricular rate.¹ Because of the barotrauma associated with intracardiac high-energy shocks, direct-current catheter ablation played only a limited role in the treatment of arrhythmias. With the advent of radiofrequency catheter ablation in the late 1980s, the range of arrhythmias amenable to catheter ablation and the number of patients who could be treated safely by catheter ablation vastly expanded. In the past decade, radiofrequency catheter ablation has become firmly established as first-line therapy for paroxysmal supraventricular tachycardia and typical atrial flutter. Furthermore, although still in an evolutionary phase, catheter ablation to eliminate atrial fibrillation has been demonstrated in the past 5 years to be feasible and clinically useful. The intent of this article is to review the current status of catheter ablation for the treatment of paroxysmal supraventricular tachycardia, atrial flutter, and atrial fibrillation.

Paroxysmal Supraventricular Tachycardia

Atrioventricular Nodal Reentrant Tachycardia

The most common mechanism of paroxysmal supraventricular tachycardia is atrioventricular nodal reentrant tachycardia. When radiofrequency catheter ablation first was used to eliminate atrioventricular nodal reentrant tachycardia, the fast atrioventricular nodal pathway was targeted. Fast pathway ablation was associated with a success rate ranging from 80% to 90% and a risk of high-grade atrioventricular block ranging from 0% to as high as 21%.²⁻⁴

Fast pathway ablation was replaced in short order by slow pathway ablation, because of its greater efficacy and lower risk of high-grade atrioventricular block.^{3,5-7} In the initial reports, the success rate of slow pathway ablation ranged from

98% to 100%, and the incidence of high-grade atrioventricular block was only 0% to 1%.^{5,6}

To ablate the slow pathway, radiofrequency energy is applied at posteroseptal right atrial sites near the ostium of the coronary sinus. An anatomic approach can be used to create a line of block in the posterior septum, or target sites can be selected based on electrogram characteristics.^{3,5-7} Discrete potentials between the atrial and ventricular electrograms in the posterior septum of the right atrium that may represent activation of the slow pathway were found to be a useful guide to ablation.^{5,6} The most efficient technique for identifying slow pathway ablation sites may be a combined anatomic-electrogram mapping approach, in which energy is applied at posteroseptal sites where there is a small atrial-ventricular electrogram ratio and a fragmented or multicomponent atrial electrogram.⁸ Because electrograms with these characteristics can be recorded near the tricuspid annulus at sites that are distant from the slow pathway,⁹ the region that is explored with the ablation catheter should be limited to the posterior septum, near the coronary sinus ostium.

When a conventional, 4-mm-tip ablation catheter is used with a temperature feedback system, typical settings consist of a maximum power of 50 W and a maximum temperature of 55° to 60°C. Effective slow pathway ablation sites almost always display an irregular accelerated junctional rhythm during an application of radiofrequency energy.¹⁰ The junctional ectopy is not specific to successful ablation sites and also occurs commonly during ineffective applications of radiofrequency energy in the posterior septum.¹⁰

It is important to monitor ventriculoatrial conduction during the junctional ectopy. High-grade atrioventricular block is heralded by ventriculoatrial block, and atrioventricular block usually is avoided by the immediate termination of radiofrequency energy delivery upon the first instance of ventriculoatrial conduction delay or block.¹⁰

Another technique for avoiding atrioventricular block is to deliver the radiofrequency energy during atrial pacing at a cycle length that is short enough to override the junctional rhythm. The atrioventricular interval is monitored during applications of radiofrequency energy, and energy delivery is aborted if the atrioventricular interval prolongs. If atrial pacing at a cycle length short enough to override the junctional ectopy results in atrioventricular Wenckebach block even before the onset of radiofrequency energy delivery, either isoproterenol or atropine can be used to shorten the atrioventricular block cycle length and maintain 1:1 atrioventricular conduction during pacing.

If slow pathway ablation cannot be achieved in the posteroseptal right atrium, it may be worthwhile to deliver radiofrequency energy at sites in the proximal coronary sinus, close to the ostium. Rarely, successful slow pathway ablation may require an application of energy on the left side of the posterior septum, along the mitral annulus.¹¹

The optimal endpoint for slow pathway ablation is the complete elimination of slow pathway conduction. However, complete slow pathway ablation may not be necessary to achieve a successful clinical outcome. If atrioventricular nodal reentrant tachycardia was inducible before ablation, residual slow pathway function with a single atrioventricular nodal reentrant echo is an acceptable endpoint.^{6,12} Although there may still be evidence of dual atrioventricular nodal pathways, the recurrence rate of atrioventricular nodal reentrant tachycardia during follow-up is no higher than when there is complete slow pathway ablation, provided there is no more than a single atrioventricular nodal echo beat, even during infusion of isoproterenol.¹²

Some patients with atrioventricular nodal reentrant tachycardia have a first-degree atrioventricular block during sinus rhythm, suggesting the possibility of absent anterograde fast pathway conduction and a high risk of complete atrioventricular block if the slow pathway is ablated. However, in patients with first-degree atrioventricular block, the atrial-His interval usually remains stable or shortens after slow pathway ablation.^{13,14} The fast pathway may be affected by an electrotonic interaction with the slow pathway, and elimination of this effect by slow pathway ablation often shortens the effective refractory period of the fast pathway.¹⁴

The initial studies of patients undergoing slow pathway ablation were published in the first half of the 1990s.³⁻⁷ Since then, several years of experience in large numbers of patients have accrued. To obtain an accurate view of the outcomes obtained in contemporary practice, several electrophysiology laboratories (see Acknowledgments) were surveyed for their results of slow pathway ablation during the 5-year interval from 1997 to 2002. In a pooled sample size of 8,230 patients with atrioventricular nodal reentrant tachycardia, a repeat ablation procedure was necessary in 1.3% of patients, and the long-term success rate in eliminating atrioventricular nodal reentrant tachycardia was 99%. High-grade atrioventricular block requiring implantation of a pacemaker occurred in 0.4% of patients. These results confirm the highly favorable risk-to-benefit ratio of radiofrequency slow pathway ablation.

Recent studies have demonstrated that slow pathway ablation can be performed by transvenous catheter cryoablation.^{15,16} Two potential advantages of cryoablation over radiofrequency ablation are catheter stability during ablation and the reversibility of atrioventricular block.¹⁵ However, given the high success rate and low risk of radiofrequency slow pathway ablation, it may be difficult to demonstrate a clinical advantage of cryoablation over radiofrequency ablation of atrioventricular nodal reentrant tachycardia.

Because of a very favorable risk-to-benefit ratio, radiofrequency catheter ablation of atrioventricular nodal reentrant tachycardia has become the treatment of choice for most patients with atrioventricular nodal reentrant tachycardia who are symptomatic enough to require therapy. Many patients may elect to undergo radiofrequency catheter ablation as first-line therapy, to avoid bothersome symptoms of tachycardia and/or the need for antiarrhythmic drug therapy.

Orthodromic Reciprocating Tachycardia

The second most common mechanism of paroxysmal supraventricular tachycardia is orthodromic reciprocating tachycardia using an accessory pathway in the retrograde direction. In 1984, in the first report of catheter ablation of an accessory pathway, a 200-J shock was delivered near the ostium of the coronary sinus to ablate a posteroseptal accessory pathway.¹⁷ A long-term success rate of 67% was achieved using direct-current shocks to ablate posteroseptal accessory pathways.¹⁸ Direct-current ablation of left- and right-sided accessory pathways also had only a modest success rate and was associated with a significant risk of serious complications such as myocardial rupture.¹⁹⁻²³ Direct-current ablation of accessory pathways therefore was usually limited to drug-refractory patients who had severe symptoms. When radiofrequency energy was substituted for direct-current shocks, catheter ablation of accessory pathways in all locations became feasible and relatively safe, and the selection criteria for the procedure were greatly broadened.

Accessory pathways most often are located in the free wall of the left ventricle. These accessory pathways can be mapped and ablated using either a retrograde aortic or transeptal approach. Advantages of the transeptal approach include better maneuverability of the mapping/ablation catheter and avoidance of the risk of arterial complications, such as dissection of a coronary artery.^{24,25} On the other hand, the transeptal approach introduces the risk of complications, such as coronary air embolism,²⁶ and may not allow firm tissue contact as easily as with the retrograde approach. In patients with a prosthetic aortic valve or a diseased aorta, the transeptal approach clearly is the preferred technique. However, in studies that have compared the retrograde and transeptal approaches, the overall success rates with both approaches have been similar,^{24,27,28} and in most cases the primary determinant of which technique to use is operator preference.

Approximately 20% of accessory pathways are posteroseptal in location, and these pathways are most often ablatable using a right-sided approach, with delivery of radiofrequency energy along the posteroseptal aspect of the tricuspid annulus or within the proximal portion of the coronary sinus. In approximately 20% of patients, the accessory pathway is located on the left side of the posterior septum, and these pathways are ablatable using either a transeptal or retrograde aortic approach, according to operator preference. Findings that suggest the need for a left-sided approach consist of an R/S ratio > 1 in lead V¹ (when there is overt preexcitation), a 10- to 25-ms increase in the ventriculoatrial (VA) interval in association with a left bundle branch block during orthodromic reciprocating tachycardia, and a Δ VA > 25 ms during orthodromic reciprocating tachycardia.²⁹

The next most common site of accessory pathways is along the right free wall. These accessory pathways can be approached from either the inferior or superior vena cava. When the inferior vena cava approach is used, long guiding sheaths that extend into the right atrium and that have distal configurations tailored to specific locations along the tricuspid annulus provide support for the mapping/ablation catheter and improve catheter stability.³⁰

Approximately 2% of accessory pathways are anteroseptal or mid-septal, and these accessory pathways may be challenging to ablate because of their proximity to the atrioventricular junction. Because cryothermal ablation minimizes the risk of

atrioventricular block, this approach may be preferable to radiofrequency ablation of accessory pathways that are located close to the atrioventricular conduction system.³¹ In a series of 20 patients with an anteroseptal or mid-septal accessory pathway who underwent cryothermal catheter ablation, a successful outcome was achieved without injury to the atrioventricular conduction system in all patients, although a second ablation procedure was required in 20% of patients.³²

Target sites for ablation of accessory pathways are identified by early ventricular activation relative to the delta wave onset (for manifest accessory pathways), by the earliest atrial activation in the retrograde direction (for any accessory pathway that conducts retrogradely), and/or by the presence of a high-frequency electrogram consistent with an accessory pathway potential.^{33,34} Free-wall accessory pathways often have an oblique course, and the site of earliest anterograde ventricular activation may differ from the site of earliest retrograde atrial activation.³⁵

Decremental anterograde conduction through a bypass tract occurs when there is either a decrementally conducting atrioventricular accessory pathway³⁶ or an atriofascicular accessory pathway.³⁷ Target sites for ablation of the former are identified in the same way as for standard accessory pathways. Atriofascicular accessory pathways are most reliably localized by identification of an accessory pathway potential during sinus rhythm or antidromic tachycardia, usually along the lateral, posterolateral, or anterolateral tricuspid annulus.³⁷

For most free-wall accessory pathways, complete bidirectional block can be achieved with a conventional, 4-mm-tip ablation catheter, using a power setting of 50 W and a temperature setting of 60°C. If the conduction block is transient, permanent accessory pathway block may be easier to achieve with an 8-mm-tip ablation catheter or with an irrigated-tip ablation catheter.³⁸

Between 5% and 17% of posteroseptal and left posterior accessory pathways have been reported to be epicardial and ablatable only within a branch of the coronary sinus (most commonly the middle cardiac vein), on the floor of the coronary sinus at the orifice of a venous branch, or within a coronary sinus diverticulum. These pathways may consist of connections between the muscle coat of the coronary sinus and the ventricle.³⁹ In the presence of a coronary sinus-ventricular accessory pathway, ventricular activation within a branch of the coronary sinus precedes endocardial activation, and coronary sinus muscle extension potentials usually are recorded in the venous branch, producing a pattern similar to an accessory pathway activation potential.³⁹

A conventional ablation catheter may completely occlude a branch of the coronary sinus, preventing cooling of the ablation electrode and resulting in high impedance when radiofrequency energy is delivered. This markedly reduces the amount of power that can be delivered and may result in adherence of the ablation electrode to the wall of the vein. An externally saline-cooled ablation catheter allows more consistent delivery of radiofrequency energy with less heating at the electrode-tissue interface. However, before delivering radiofrequency energy near or within a branch of the coronary sinus, coronary angiography should be performed to determine whether there are any branches of the right or left coronary artery in proximity to the ablation site. If there is a branch of the right coronary artery within 2 mm of the ablation site, there may be a high risk of coronary artery injury if radiofrequency energy is delivered (Warren Jackman, personal

communication). In this situation, it may be that cryoablation can be performed with little or no risk of coronary artery injury.^{31,40}

A small percentage of left free-wall accessory pathways also may be epicardial, requiring ablation from within the coronary sinus.^{41,42} Other types of unusual accessory pathways that cannot be ablated with a standard endocardial approach at the annulus also have been described. These include accessory pathways that connect the right atrial appendage to the right ventricle, successfully ablated using a transcutaneous pericardial approach⁴³ or by endocardial ablation over a large area,⁴⁴ and accessory pathways closely associated with the ligament of Marshall, ablated by targeting this ligament.⁴⁵ Rarely, a transcutaneous pericardial approach is required to ablate epicardial atrioventricular accessory pathways that are posteroseptal or right-sided (Fig. 1).

In early reports, the acute success rate of accessory pathway ablation ranged from 89% to 100%, with a recurrence rate of 3% to 9% and a long-term success rate of 85% to 100%.^{28,33,46-50} The complication rate ranged between 2% and 3%, with the most common complications being cardiac tamponade and atrioventricular block.^{28,33,46-50} In a trial of a temperature-controlled radiofrequency ablation catheter conducted at 18 institution between 1992 and 1995, successful ablation was achieved in 93% of 500 patients with an accessory pathway, with a higher success rate for left-sided (95%) than for posteroseptal (88%) or right-sided (90%) accessory pathways.²⁵ There was one death in that study (caused by dissection of the left coronary artery),²⁵ yielding a fatality rate of 0.2%. A survey of five university electrophysiology laboratories in 1998 indicated that a fatal complication had occurred in 0.08% of 3,856 patients who had undergone radiofrequency ablation of an accessory pathway.⁵¹ This mortality rate compared favorably with the annual risk of sudden death in the Wolff-Parkinson-White syndrome, estimated to be 0.05% to 0.5%.⁵²

A more contemporary view of the risk-to-benefit ratio of accessory pathway ablation is available by pooling the results of ablation between 1997 and 2002 in the electrophysiology laboratories surveyed for this article. In a total of 6,065 patients, and with a repeat procedure necessary in 2.2%, a long-term success rate of 98% was achieved. A serious complication (cardiac tamponade, atrioventricular block, coronary artery injury, retroperitoneal hemorrhage, or stroke) occurred in 0.6% of patients, with 1 fatality (0.02%). Therefore, the one-time risk of catheter ablation is considerably lower than the cumulative annual risk associated with the Wolff-Parkinson-White syndrome, and it is clear that the treatment of choice for patients with the Wolff-Parkinson-White syndrome who may be at risk for life-threatening arrhythmias is catheter ablation. In addition, the highly favorable risk-to-benefit ratio justifies the use of catheter ablation as first-line therapy for any patient with accessory pathway-dependent tachycardia that requires treatment.

Atrial Tachycardia

Atrial tachycardias may be focal or macroreentrant. Focal atrial tachycardia may be caused by abnormal automaticity, triggered activity, or microreentry^{53,54} and is characterized by centrifugal spread of activation away from a discrete site of origin, without electrograms spanning all of diastole.⁵⁵ In contrast, in macroreentrant atrial tachycardia, electrograms

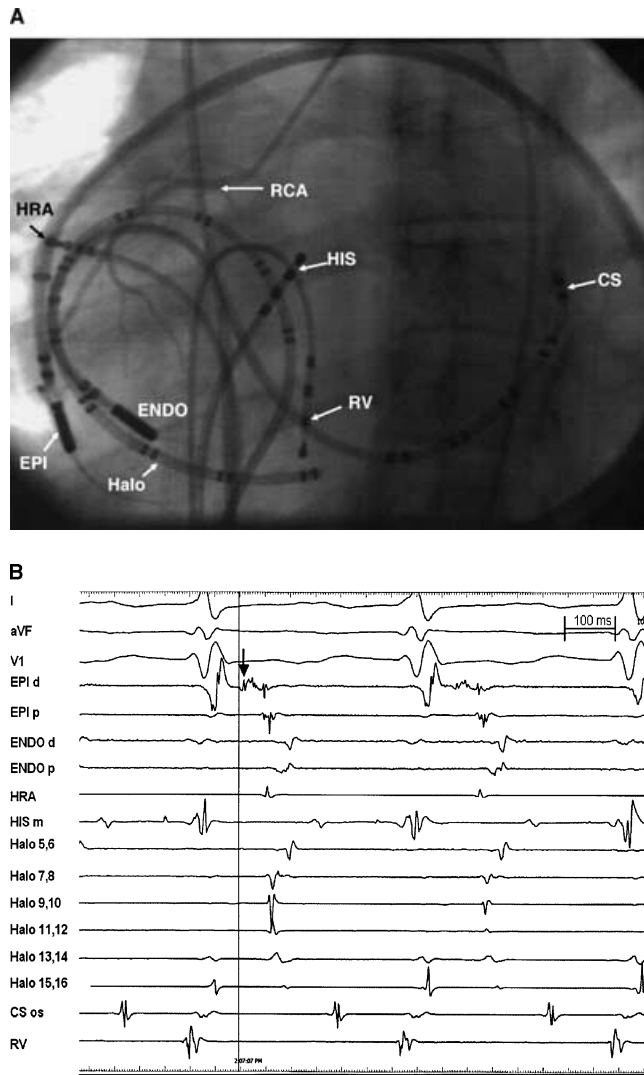


Figure 1. Right-sided epicardial accessory pathway ablated using a transcatheter pericardial approach. A: A 45° left anterior oblique fluoroscopic view of the catheters in the heart (CS, Halo, HIS, HRA, ENDO, RV) and pericardial space (EPI), and of the right coronary artery (RCA). The pericardial catheter (EPI) is at the posterolateral aspect of the tricuspid annulus. CS = coronary sinus; ENDO = endovascular; HIS = His bundle; HRA = high right atrium; RV = right ventricle. B: Intracardiac electrograms recorded by the catheters shown in panel A during orthodromic reciprocating tachycardia. A high-frequency potential compatible with an accessory pathway potential (arrow) was recordable only with the pericardial catheter positioned at the posterolateral aspect of the tricuspid annulus. Radiofrequency ablation at this pericardial site abolished accessory pathway conduction. The accessory pathway could not be ablated with endocardial applications of radiofrequency energy. (Figures courtesy of Dr. Kalyanam Shivkumar, University of California, Los Angeles, CA.)

are present throughout diastole. Macroreentrant atrial tachycardias, including incisional- or scar-related tachycardias, are much more closely related to non-isthmus-dependent atrial flutter than to focal atrial tachycardia and therefore are included in the discussion of atrial flutter.

Focal atrial tachycardias most commonly arise in the right atrium along the crista terminalis, near the tricuspid annulus, or near the coronary sinus ostium.^{56,57} Approximately 5% of focal atrial tachycardias arise in the left atrium, and these have been reported to occur most commonly along the superior or

inferior aspect of the mitral annulus^{58,59} or near the ostia of the pulmonary veins (Fig. 2).⁵⁸ Recent experience gained during catheter ablation of atrial fibrillation has indicated that focal tachycardias also may arise in the pulmonary veins,⁶⁰ superior vena cava,^{61,62} vein of Marshall,⁶³ or inferior vena cava.⁶⁴

Target sites for ablation of focal atrial tachycardias are identified by either activation mapping or pace mapping. It often is difficult to discern small differences in P wave morphology during pace mapping, and the activation sequence recorded by several multipole catheters is a useful surrogate for P wave morphology.⁶⁵ Mechanical interruption of an atrial tachycardia by the ablation catheter also has been demonstrated to be helpful in identifying an effective ablation site.⁶⁶

Identification of the earliest site of atrial activation during a focal atrial tachycardia may be facilitated by the use of various tools, such as a basket catheter,⁶⁷⁻⁶⁹ an electroanatomic mapping system (Fig. 2),^{58,70} or a noncontact mapping system.⁷¹

Because focal atrial tachycardias are relatively uncommon, there are no large series in the literature describing the results of catheter ablation of focal atrial tachycardia. In seven studies that included a total of 112 patients with focal atrial tachycardia, the short-term success rate of radiofrequency ablation was approximately 90%, 7% of patients had a late recurrence, and no serious complications were reported.^{54,65,66,72-75} However, these studies did not use either the three-dimensional mapping systems nor the 8-mm-tip or cooled-tip ablation catheters that are widely available today. With these sophisticated mapping tools and with ablation catheters capable of creating larger lesions than conventional ablation catheters, clinical failures more often are related to the emergence of new atrial foci than to the inability to ablate a particular atrial tachycardia.

Given the high probability of successful ablation and the low risk of serious complications, it is appropriate to consider the option of catheter ablation for any patient with an atrial tachycardia that is clinically significant and requires therapy. However, pharmacologic therapy is more appropriate if multiple atrial foci are present. In these patients, even if all of the atrial tachycardia foci are mapped and ablated, new foci may emerge later. In older patients with pleomorphic atrial tachycardia who are highly symptomatic and drug refractory, atrioventricular junction ablation/pacemaker may be more appropriate than attempts to ablate the multiple foci.

Atrial Flutter

Isthmus-Dependent Atrial Flutter

The most common type of atrial flutter is isthmus-dependent atrial flutter in which reentry is confined to the right atrium with the wavefront progressing either in a counterclockwise or clockwise direction across the cavotricuspid isthmus. In the initial reports of radiofrequency catheter ablation of isthmus-dependent atrial flutter, conventional ablation catheters were used and movement of the ablation catheter along the cavotricuspid isthmus was guided only by fluoroscopy. The endpoint of ablation in the early reports was termination of atrial flutter and/or the inability to induce the flutter by pacing. The acute success rates in these studies ranged

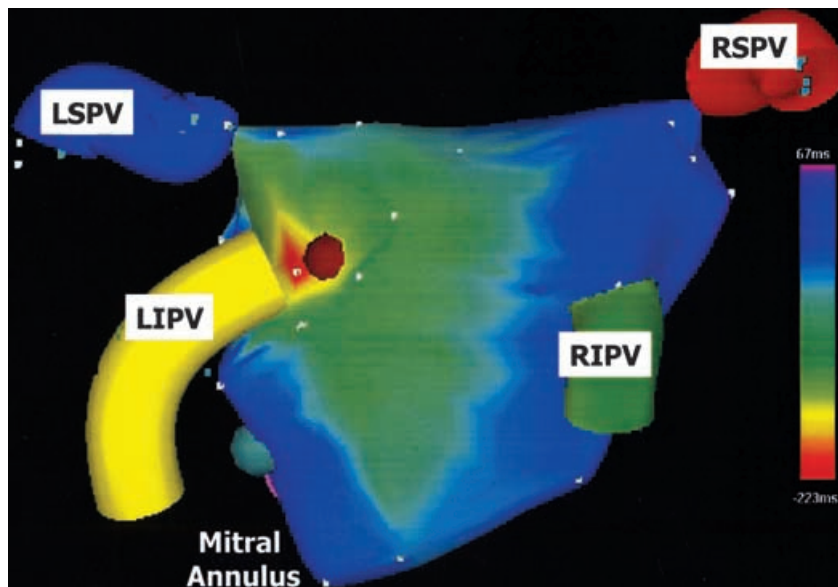


Figure 2. Activation map of a focal atrial tachycardia created with a three-dimensional electroanatomic mapping system. A posterior view of the left atrium is shown. Note that there is centrifugal spread from a focal area of early activation (red). The site of origin was near the ostium of the left inferior pulmonary vein. The dark red tag indicates the successful ablation target site. LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein.

from 77% to 100%, but recurrence rates usually ranged from 20% to 40%.^{50,75-77}

The recurrence rate of atrial flutter in the initial reports of radiofrequency ablation was high probably in large part because termination and noninducibility of atrial flutter are unreliable endpoints. Contributing to the more reliable outcome of catheter ablation of isthmus-dependent atrial flutter in contemporary practice are more accurate endpoints for the procedure. Recognition of complete isthmus block has been enhanced by several techniques, such

as a change in the atrial activation sequence along the lateral right atrium during coronary sinus pacing,^{78,79} differential pacing,⁸⁰ double potentials separated by at least 90 to 110 ms along the entire ablation line,⁸¹⁻⁸³ measurement of transisthmus conduction intervals,⁸⁴ and a change in electrogram polarity in the region of the isthmus during coronary sinus pacing.⁸⁵ In addition, although conventional catheter techniques suffice, complete isthmus block can be confirmed with the use of three-dimensional mapping systems.^{86,87}

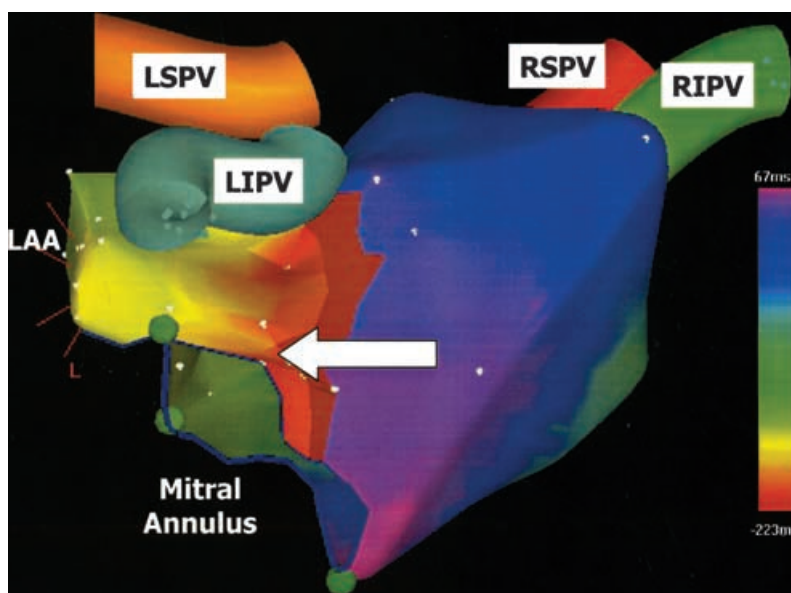


Figure 3. Activation map of a left atrial flutter created with a three-dimensional electroanatomic mapping system. A left posterior oblique view of the left atrium is shown. Note that the sites of earliest (red) and latest (purple) atrial activation are adjacent to each other, in the isthmus between the mitral annulus and the left inferior pulmonary vein. The white arrow indicates the direction of the wavefront across the mitral isthmus. An ablation line created in this isthmus successfully ablated the atrial flutter. LAA = left atrial appendage. Other abbreviations as in Figure 2.

In addition to more accurate endpoints for complete isthmus block, more precise localization and tracking of the ablation catheter along the cavotricuspid isthmus now is possible with a variety of nonfluoroscopic localization tools that facilitate the creation of ablation lines devoid of gaps.⁸⁶⁻⁹² Also available is phased-array intracardiac echocardiography,⁹³ which allows visualization of the pouches and recesses that commonly are present along the cavotricuspid isthmus and that sometimes make a complete line of block in the isthmus difficult to create.⁹³⁻⁹⁵

Advances in catheter design have enhanced the ability to create complete lines of block in the cavotricuspid isthmus. Because of the pouches, recesses, ridges, and trabeculations that may occur in the isthmus,⁹⁴ it often is advantageous to create lesions that are larger than those created with conventional 4-mm-tip ablation catheters. Radiofrequency ablation catheters that have an 8-mm distal electrode or a cooled- or irrigated-tip electrode allow the creation of larger lesions in both high- and low-flow regions. Several studies have demonstrated that complete isthmus block is more reliably achieved with an 8-mm-tip catheter⁹⁶⁻¹⁰⁰ and with a cooled- or irrigated-tip catheter^{99,101-104} than with a conventional ablation catheter. In a randomized study that compared the 8-mm-tip and cooled-tip catheters, complete isthmus block was achieved in 99% of 100 patients, with the efficacy of the two catheters being equally high.¹⁰⁵

Complete isthmus block also can be achieved by cryothermal ablation.¹⁰⁶ Although there is no reason to believe that cryothermal ablation will be more effective than radiofrequency ablation of the cavotricuspid isthmus, cryothermal ablation has the advantage of being less painful.¹⁰⁶

The cavotricuspid isthmus can be ablated using either a purely anatomic approach¹⁰⁷⁻¹¹² or an electrogram mapping approach that targets single potentials or narrowly split double potentials during atrial flutter or coronary sinus pacing.^{81,113} In a randomized comparison, the electrogram mapping approach was found to be more efficient than the anatomic approach if the first ablation line did not result in complete isthmus block.¹¹⁴

With the availability of precise catheter locator systems, more effective ablation tools, and accurate endpoints for ablation, the inability to successfully create complete isthmus block and to eliminate recurrences of isthmus-dependent flutter is unusual in contemporary practice. This is reflected in the pooled ablation results of the electrophysiology laboratories surveyed for this article. In a total of 7,071 patients with isthmus-dependent atrial flutter who underwent radiofrequency catheter ablation, a repeat ablation procedure was performed in 4% of patients, and the long-term success rate in preventing recurrent atrial flutter was 97%. The overall incidence of serious complications was 0.4%, with the most common complication consisting of atrioventricular block in 0.2% of patients. Other rare complications that have been reported include ventricular tachycardia¹¹⁵ and acute occlusion of the right coronary artery.¹¹⁶

In light of the high efficacy and safety of radiofrequency ablation for isthmus-dependent atrial flutter, catheter ablation is an appropriate therapeutic option for drug-refractory patients and for patients who prefer curative therapy to pharmacologic therapy. However, a large proportion of patients with atrial flutter also have had or will develop atrial fibrillation.¹¹⁷⁻¹²⁰ If treatment with a Class I or III antiarrhythmic drug suppresses atrial fibrillation but not atrial flutter, a hybrid

approach that combines catheter ablation of the atrial flutter with continued antiarrhythmic drug therapy often is effective in preventing recurrent atrial fibrillation.¹²¹⁻¹²³ However, in patients who have both atrial flutter and atrial fibrillation prior to ablation, the atrial fibrillation usually does not resolve after atrial flutter ablation.¹¹⁷⁻¹²⁰ Therefore, additional therapy for atrial fibrillation, either pharmacologic or catheter ablation, still may be necessary after atrial flutter is eliminated.

Other Atrial Flutters

Atrial flutters other than isthmus-dependent atrial flutter consist of right atrial flutters that are not isthmus dependent, left atrial flutters, and incisional atrial flutters. Because the pathophysiology and treatment of non-isthmus-dependent atrial flutter and macroreentrant atrial tachycardia are identical, they will be discussed together.

Right atrial flutter that does not involve the cavotricuspid isthmus is unusual, particularly in patients without a history of open heart surgery. In a series of 160 patients with right atrial flutter, only 4% were mapped to the right atrial free wall and did not use the cavotricuspid isthmus.¹²⁴ These atrial flutters were successfully eliminated by creation of an ablation line from a mid-lateral line of conduction block to the inferior vena cava.¹²⁴

Macroreentrant left atrial tachycardia and flutter also are unusual in patients without prior surgery or left atrial catheter ablation. In the largest series of left atrial flutters, detailed mapping in 17 patients, most of whom had structural heart disease but no history of heart surgery, demonstrated that there most commonly was macroreentry around the mitral annulus, pulmonary veins, and an electrically silent area.¹²⁵ Successful ablation was achieved with ablation lines between the mitral annulus and a pulmonary vein or an electrically silent area (Fig. 3).¹²⁵ Left atrial macroreentry also has been reported to involve the muscular coat of the coronary sinus and to be treatable by circumferential radiofrequency ablation within the coronary sinus.¹²⁶

Atypical right atrial flutter that occurs as a consequence of a surgical scar or suture line has been referred to as "incisional" flutter or tachycardia. Entrainment mapping and the postpacing interval are helpful in identifying critical components of the reentrant circuit.¹²⁷ These macroreentrant circuits usually can be abolished by transecting a critical isthmus with an ablation line extending from an area of scar to a naturally occurring anatomic barrier. The most common locations of the ablation lines used to treat incisional flutter/tachycardia are between a right lateral atriotomy scar and the inferior vena cava, superior vena cava, or tricuspid annulus.^{127,128} Success rates of 80% to 85% were reported in early studies that did not use three-dimensional mapping systems.^{127,128} A later study used a three-dimensional electroanatomic mapping system to demonstrate that macroreentrant right atrial tachycardias after surgery for congenital heart disease often utilize relatively narrow channels between scars.¹²⁹ Detailed voltage mapping allowed identification of the channels and elimination of the tachycardias, often with only a single application of radiofrequency energy.¹²⁹

In another study, the cavotricuspid isthmus was found to be part of the reentrant circuit in approximately 70% of patients with postoperative intra-atrial reentrant tachycardia.¹³⁰ Therefore, it is worthwhile to first evaluate the role of the cavotricuspid isthmus in an incisional flutter before

embarking on detailed activation or voltage mapping of the right atrium.

Patients who have undergone cardiac transplantation with an atrial anastomosis may develop an atrial tachycardia attributable to atrio-atrial conduction across the suture line separating the donor and native right atria.¹³¹ In addition to primary ablation of the arrhythmia in the native atrial remnant, these arrhythmias also may be eliminated by ablation of atrio-atrial conduction.¹³¹

Left atrial flutter may be a proarrhythmic complication of surgery or left atrial catheter ablation for atrial fibrillation. Many of these left atrial flutters use the isthmus between the mitral annulus and the left inferior pulmonary vein and can be eliminated by creating a line of block in this isthmus.¹³²

With the current availability of three-dimensional mapping systems, it is reasonable to expect a success rate of at least 90% when attempting to ablate non-isthmus-dependent atrial flutters. Therefore, catheter ablation is a reasonable option for drug-refractory non-isthmus-dependent atrial flutter or when it is the sole arrhythmia in a patient who prefers to avoid antiarrhythmic drug therapy. If the non-isthmus-dependent atrial flutter occurs following a surgical or atrial-based catheter procedure for atrial fibrillation, it is appropriate to treat the flutter pharmacologically before proceeding with catheter ablation, because these flutters may spontaneously resolve within 3 to 4 months after the surgical or catheter procedure.

Atrial Fibrillation

In the past several years, the most exciting developments in catheter ablation of supraventricular arrhythmias have occurred in the field of atrial fibrillation. The proof of concept for catheter ablation of atrial fibrillation was provided by John Swartz, who demonstrated that linear ablation lines made by contiguous applications of radiofrequency energy with a conventional ablation catheter in the left and right atria could eliminate atrial fibrillation.¹³³ However, because of the technically challenging nature of the procedure and a high complication rate, this type of ablation procedure was not adapted into clinical practice. Simpler and safer linear ablation procedures were attempted, generally with poor results.¹³⁴⁻¹³⁸

Role of Pulmonary Veins and Pulmonary Vein Isolation

A landmark study by Haissaguerre et al.⁶⁰ in 1998 focused attention on the importance of the pulmonary veins in the generation of atrial fibrillation. It was found that the premature depolarizations that trigger atrial fibrillation often arise in the muscle sleeves that surround the pulmonary veins. This seminal observation led to the technique of focal ablation within the pulmonary veins to eliminate the triggers of atrial fibrillation.¹³⁹⁻¹⁴¹ However, because of the multifocal nature of the triggers, the inability to identify all triggers in the course of a catheter ablation procedure, and the later emergence of new triggers, focal ablation within the pulmonary veins was associated with a high recurrence rate.¹³⁹ Another problem with the procedure was that it necessitated ablation within the pulmonary veins, creating pulmonary vein stenosis in 4% to 42% of patients.^{140,141}

The next major step in the evolution of catheter ablation of atrial fibrillation was the demonstration that the pulmonary

veins could be electrically isolated from the left atrium by ostial applications of radiofrequency energy guided by pulmonary vein potentials.¹⁴² Pulmonary veins can be electrically isolated by circumferential ablation at the ostium,¹⁴³ but when ostial ablation is guided by pulmonary vein potentials, complete isolation often is achieved with ablation at <60% of the ostial circumference.¹⁴⁴ This is because the muscle fibers that conduct impulses between the muscle sleeve and the atrium are not evenly distributed throughout the circumference of the ostium. Electrical isolation of a pulmonary vein by segmental ostial ablation not only eliminates the need for identification and mapping of individual triggers and serves as a safeguard against the future emergence of new triggers from a vein. It also reduces the risk of pulmonary vein stenosis by limiting the amount of ostial ablation needed to isolate a vein.

Pulmonary vein potentials are best recorded with a catheter that has 10 to 20 electrodes in a distal ring configuration or with a multitined basket catheter. Appropriate target sites for ablation are identified based on the earliest bipolar electrogram or the unipolar electrogram that has the steepest and largest intrinsic deflection.^{145,146} A randomized study showed that complete isolation of the pulmonary veins is achieved more quickly and efficiently when guided by unipolar electrograms than when guided by bipolar electrograms (Fig. 4).¹⁴⁷

Ostial pulmonary vein potentials may be buried within atrial electrograms recorded at the ostia of the pulmonary veins, and this may hinder the identification of appropriate target sites for ablation. The pulmonary vein potentials usually can be separated from the atrial electrograms either by pacing within the coronary sinus or left atrial

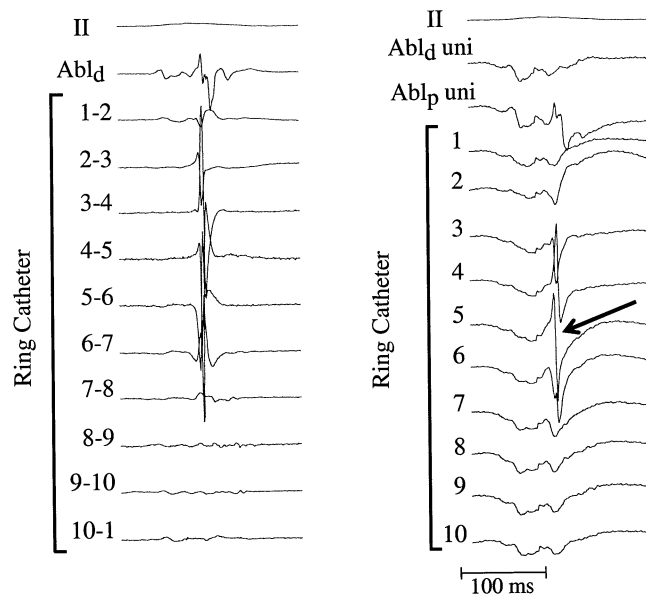


Figure 4. Bipolar (left panel) and unipolar (right panel) electrograms of pulmonary vein potentials recorded at the ostium of the right superior pulmonary vein with a ring catheter. Shown are lead II, bipolar and unipolar (uni) electrograms recorded with the ablation catheter (Abl), and multiple electrograms recorded with a ring catheter positioned at the ostium of the vein. In the bipolar recordings, the most appropriate ablation site is unclear. In the unipolar recordings, the most appropriate target site is easily identified to be at electrode 5 of the ring catheter, where the largest, steepest, and earliest intrinsic deflection is recorded (arrow). d = distal; p = proximal.

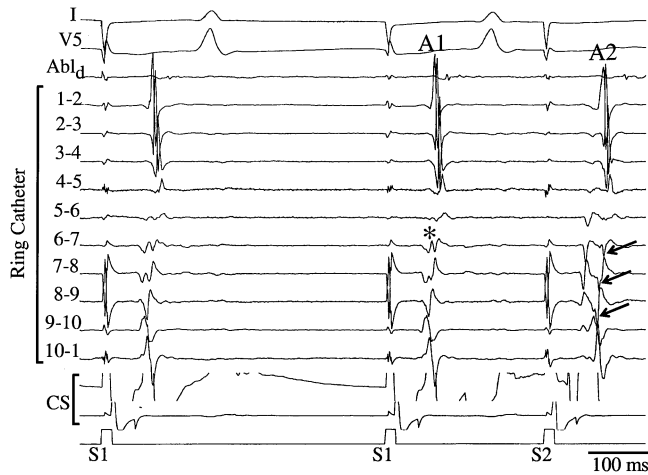


Figure 5. Use of an atrial extrastimulus to separate atrial and pulmonary vein potentials recorded with a ring catheter at the ostium of a left superior pulmonary vein. During coronary sinus (CS) pacing at a cycle length of 450 ms, the atrial and pulmonary vein potentials are fused (asterisk). A premature atrial extrastimulus (S2) results in separation of pulmonary vein potentials (arrows) from the atrial potentials. Abl = ablation catheter; d = distal.

appendage (in the case of the left-sided pulmonary veins)^{148,149} or by introducing an atrial extrastimulus during atrial pacing (Fig. 5).¹⁵⁰

The left atrial appendage often lies in close proximity to the left-sided pulmonary veins, and a potential that originates in the appendage may mimic a pulmonary vein potential. Pulmonary vein potentials can be distinguished from left atrial appendage potentials by pacing within the left atrial appendage.^{148,149}

The endpoint of segmental ostial ablation is the elimination of all pulmonary vein potentials, with complete conduction block in and out of the pulmonary vein (Fig. 6).

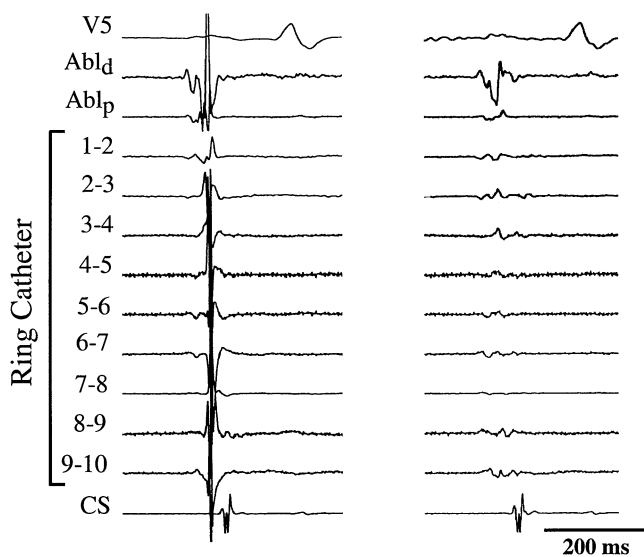


Figure 6. Endpoint of segmental ostial ablation. The ring catheter was positioned near the ostium of a left superior pulmonary vein, and multiple bipolar electrograms are shown before (left panel) and after (right panel) several ostial applications of radiofrequency energy. Note that all pulmonary vein potentials were eliminated. Abbreviations as in Figures 4 and 5.

In initial studies, when an arrhythmogenic pulmonary vein was isolated, the short-term success rate in eliminating paroxysmal atrial fibrillation ranged from 55% to 93%, depending on the number of arrhythmogenic pulmonary vein foci that were present.⁸⁰ However, as many as 54% of patients needed a repeat procedure because of residual triggers arising in other pulmonary veins or locations.⁸⁰

In addition to being a major source of premature depolarizations that trigger atrial fibrillation, the pulmonary veins may be important in maintaining an episode of paroxysmal atrial fibrillation. Intermittent bursts of rapid electrical activity in the pulmonary veins may serve as at least one of the drivers of atrial fibrillation.^{151,152} These bursts of pulmonary vein tachycardia have a high prevalence in the left superior, left inferior, and right superior pulmonary veins during episodes of paroxysmal atrial fibrillation, and this led to the approach of systematically isolating at least three pulmonary veins during the first ablation procedure, whether or not triggers were found to be arising in each vein.^{144,152} With this approach, symptomatic paroxysmal atrial fibrillation was eliminated, without the need for antiarrhythmic medications, in 70% of patients, and the percentage of patients requiring a repeat procedure dropped to 9%.¹⁴⁴

Pulmonary vein isolation has been performed with a conventional 4-mm-tip catheter, an 8-mm-tip catheter, or a saline-cooled or irrigated-tip catheter.^{153,154} In a study that compared the three types of catheters, the best results were obtained with the 8-mm-tip catheter.¹⁵⁴ However, in other studies, pulmonary vein isolation has been achieved reliably with a conventional 4-mm-tip catheter.^{144,152,155} It is possible that the deeper lesions created with an 8-mm-tip catheter increase the risk of pulmonary vein stenosis, and the type of ablation catheter that is associated with the most favorable risk-to-benefit ratio is unclear. When a cooled-tip or 8-mm-tip catheter is used, monitoring of microbubble formation by intracardiac echocardiography during applications of radiofrequency energy may reduce the risk of pulmonary vein stenosis and improve efficacy.¹⁵⁶

The triggers or driving mechanisms for atrial fibrillation may arise in other thoracic veins, including the vein of Marshall, superior vena cava, and coronary sinus, or in the left or right atrium.^{60,61,139,157-161} The ectopy that initiates atrial fibrillation has been demonstrated to originate outside of the pulmonary veins in as many as 28% to 47% of patients with paroxysmal atrial fibrillation.^{162,163} Therefore, if an ablation strategy for paroxysmal atrial fibrillation is limited to pulmonary vein isolation, it may be unrealistic to expect a long-term clinical success rate greater than approximately 70%, regardless of how reliably the pulmonary veins are isolated.

The pulmonary veins appear to play a much less important role in the generation of chronic atrial fibrillation than paroxysmal atrial fibrillation. This explains why pulmonary vein isolation by itself eliminates chronic atrial fibrillation in only 25% of patients.¹⁶⁴ Another problem with pulmonary vein isolation is that it is associated with a 3% to 5% risk of moderate-to-severe pulmonary vein stenosis.¹⁶⁵⁻¹⁶⁷ Because the ostium of a pulmonary vein may have a funnel configuration and may not be clearly definable, radiofrequency energy may inadvertently be delivered within the proximal portion of a pulmonary vein. Therefore, although it was an important step in the evolution of ablation techniques for atrial fibrillation, pulmonary vein isolation by itself has significant shortcomings.

Alternative Ablation Strategies

The limitations of pulmonary vein isolation have been addressed in several different ways. One approach has been to add an ablation line in the left atrium to segmental ostial ablation of the pulmonary veins. For example, the addition of an ablation line in the mitral isthmus, between the left inferior pulmonary vein and the mitral annulus, improved the success rate of pulmonary vein isolation for paroxysmal atrial fibrillation to 82% at a mean 6-month follow-up.¹⁶⁸ Furthermore, with the addition of one more ablation line across the left atrial roof, chronic atrial fibrillation was successfully eliminated in 60% of patients at a mean follow-up of 7 months.¹⁶⁹ A second approach has been to first isolate the pulmonary veins, then to search for and ablate triggers arising in other sites.^{163,170} In one study, this technique resulted in freedom from atrial fibrillation at 1-year follow-up in 80% of 75 patients, 88% of whom had paroxysmal atrial fibrillation.¹⁷⁰ However, in another study that used a strategy of targeting all ectopic foci within and outside of the pulmonary veins, the success rate at 22-month follow-up was a more modest 63%. A third approach has been to extend the targets for ablation from the ostia to the atrial tissue surrounding the pulmonary veins. With this approach, approximately 80% to 90% of patients were reported to have no further symptomatic atrial fibrillation at 14-month follow-up.¹⁵⁶

Left Atrial Ablation to Encircle the Pulmonary Veins

Another alternative to segmental ostial ablation has been to limit ablation to the left atrium. This technique involves the creation of circumferential ablation lines around the left- and right-sided pulmonary veins, 1 to 2 cm from the ostia of the veins, guided by a three-dimensional electroanatomic mapping system (Fig. 7).^{171,172} Ablation lines in the posterior left atrium and mitral isthmus often are also created (Fig. 7). The technique of circumferential left atrial ablation was first described by Pappone et al.¹⁷¹ In a group of 589 patients with paroxysmal or chronic atrial fibrillation, approximately 85% were free from atrial fibrillation at a mean of 900 days after circumferential left atrial ablation.¹⁷³ The most common serious complication of circumferential left atrial ablation has been pericardial tamponade, which has occurred in 1% of patients. Proarrhythmia in the form of left atrial flutter may occur within a few days of left atrial ablation in 5% to 10% of patients (unpublished data), and these flutters may require ablation if they do not resolve spontaneously within 3 to 4 months after the procedure.

Segmental ostial ablation to isolate the pulmonary veins was compared to the circumferential left atrial ablation strategy (Fig. 7) in a randomized study of 80 patients with paroxysmal atrial fibrillation.¹⁷⁴ The endpoint of the study was freedom from symptomatic atrial fibrillation in the absence of drug therapy, after a single ablation procedure. The circumferential left atrial ablation strategy was found to be significantly more effective than segmental ostial ablation, with success rates at 6 months of 87% and 67%, respectively. The average procedure duration with both approaches was approximately 2.5 hours.

It is logical that an extensive ablation procedure that has several possible mechanisms of action would be more effective than an ablation strategy that is limited to segmental ostial ablation. It is likely that segmental ostial ablation eliminates atrial fibrillation only by eliminating the triggers and drivers

of atrial fibrillation that arise in the pulmonary veins. The circumferential left atrial ablation strategy, including ablation lines in the posterior left atrium and mitral isthmus, has several possible mechanisms of action: (1) pulmonary vein isolation, at least to some degree; (2) elimination of anchor points for "mother waves," or rotors that may generate atrial fibrillation, at or near the left atrial-pulmonary vein junction¹⁷⁵⁻¹⁷⁷; (3) ablation of other potential trigger sites, such as the vein of Marshall and the posterior left atrial wall¹⁶³; (4) ablation of right-left atrial connections that may play a role in generating atrial fibrillation; (5) atrial debulking, to provide less space for circulating wavelets; and (6) atrial denervation. Some or all of these factors may explain why the circumferential left atrial ablation strategy is more effective than segmental ostial ablation for both paroxysmal and chronic atrial fibrillation.

Because atrial fibrillation is an independent predictor of mortality, it is conceivable that the elimination of atrial fibrillation may improve survival. The AFFIRM trial demonstrated that a rhythm control strategy conferred no survival advantage over rate control in patients with atrial fibrillation who had risk factors for stroke.¹⁷⁸ However, drug inefficacy and/or adverse drug effects easily could account for the absence of a survival benefit of rhythm control. In a recent study of 1,171 patients with symptomatic atrial fibrillation that were treated with either medical therapy or left atrial ablation, left atrial ablation was associated with a 55% reduction in major morbid events such as heart failure and stroke, and a 50% reduction in mortality. Because treatment allocation was not randomized, the results of this study cannot be considered definitive. Nevertheless, the study does suggest that elimination of atrial fibrillation may improve not only quality of life but also survival.

Current Role of Catheter Ablation of Atrial Fibrillation

Catheter ablation techniques for atrial fibrillation are still in an evolutionary phase, and the long term risk-to-benefit ratio is as yet unsettled. At this time, it seems appropriate to limit catheter ablation of atrial fibrillation to symptomatic patients whose quality of life has been impaired and who cannot be successfully managed with pharmacologic therapy. As the experience with catheter ablation of atrial fibrillation grows over the next few years, it is likely that the selection criteria also will expand.

Future Directions

After more than a decade of experience with radiofrequency catheter ablation of atrioventricular nodal reentrant tachycardia, accessory pathways, monomorphic atrial tachycardias, and atrial flutter, it seems safe to say that the vast majority of patients with these types of supraventricular tachycardia can be cured with very little risk of a serious complication. With success rates often in the upper half of the 90% to 100% range, one might question whether there is any need for further improvements in the catheter techniques used to treat these arrhythmias. However, until success rates reach 100%, there will continue to be room for improvement in ablation tools and refinement in ablation techniques. For example, cryoablation may prove to be a very useful alternative to radiofrequency ablation for epicardial accessory pathways that lie close to a coronary artery, or for mid- or anteroseptal accessory pathways that lie close to the atrioventricular

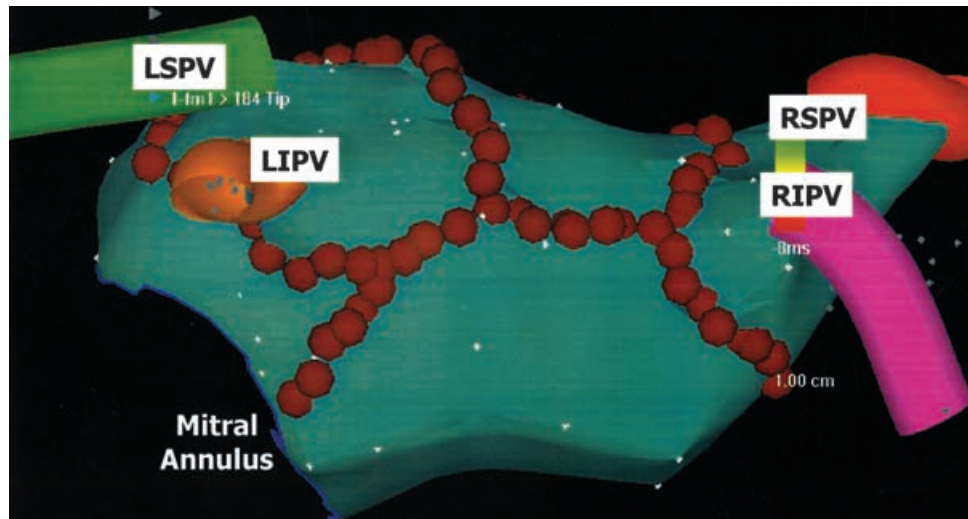


Figure 7. Circumferential left atrial ablation strategy. The posterior aspect of the left atrial shell created with an electroanatomic mapping system is shown. The dark red tags indicate ablation sites. The left- and right-sided pulmonary veins were encircled. Additional ablation lines were created in the posterior left atrium and across the isthmus between the mitral annulus and the inferior portion of the circumferential ablation line surrounding the left-sided pulmonary veins. Abbreviations as in Figure 2.

conduction system. Whether other energy sources, such as laser or ultrasound, will also find a niche in the electrophysiology laboratory is less clear, but possible.

High-intensity focused ultrasound provides the potential for ablating specific targets in the myocardium or atrioventricular conduction system from outside of the heart and potentially from outside of the thorax.¹⁷⁹ There are several technical problems that need to be overcome, but it will be interesting to see how the application of high-intensity focused ultrasound to ablation of arrhythmias develops over the next few years.

In the past few years, fluoroscopy techniques that limit radiation exposure have become commonplace,¹⁸⁰ and this has been beneficial to patients and electrophysiologists. Furthermore, the widespread availability of three-dimensional mapping tools has reduced our dependence on fluoroscopy and contributed to a reduction in radiation exposure, while improving the ability to map and ablate complex arrhythmias. Future developments in the area of imaging, such as real-time magnetic resonance imaging and “digital fusion” [the integration of an magnetic resonance image or computed tomographic image of the heart into a three-dimensional mapping

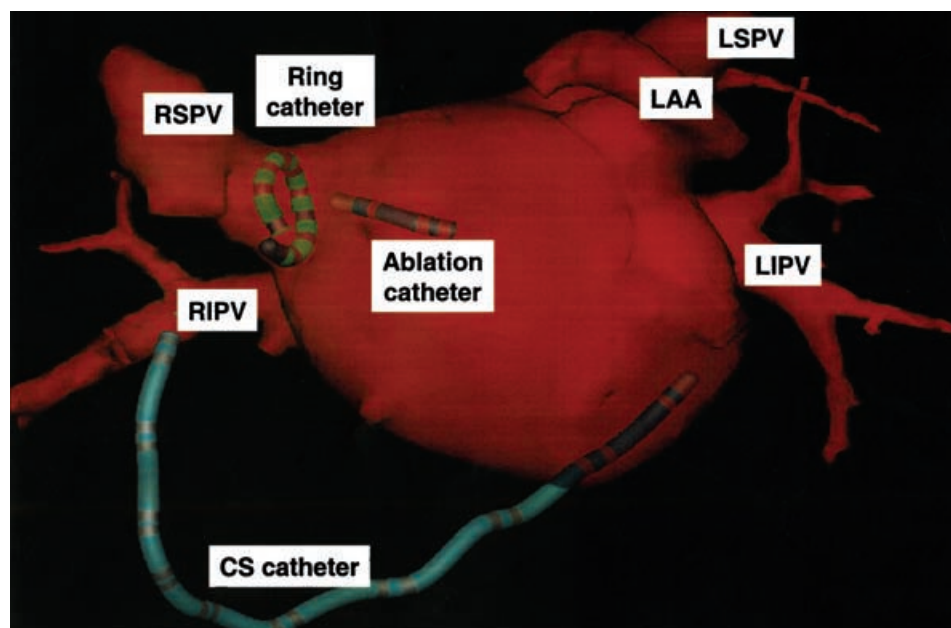


Figure 8. Example of “digital fusion” of a magnetic resonance image of the heart into a three-dimensional catheter localization system (NavX DIF™, currently under investigation.). Shown is an anteroposterior view of the left atrium, with a ring catheter in the right superior pulmonary vein, the distal portion of an ablation catheter in the left atrium, and a 20-pole catheter in the coronary sinus. CS = coronary sinus. Other abbreviations as in Figures 2 and 3. (Figure courtesy of Dr. Jasbir Sra, Milwaukee Heart Institute, Milwaukee, WI.)

system to provide an anatomically accurate image of a chamber (Fig. 8)], are likely to further reduce the need for radiation exposure to patients and operators.

A new approach to catheter ablation that currently is under development is the remote control of an ablation catheter using a magnetic guidance system in which a magnetic field is used for precise catheter navigation to an ablation target.¹⁸¹ The concept is intriguing, and initial studies have demonstrated that the remote control of an ablation catheter is feasible.¹⁸² The degree of incremental value of this new technology in clinical practice should become clear in the near future.

With regard to atrial fibrillation, by far the most complex and challenging supraventricular arrhythmia faced by interventional electrophysiologists, improvements in catheter ablation techniques will depend to a great degree on a better understanding of the mechanisms of this arrhythmia. The goal should be to learn how to eliminate atrial fibrillation with the minimum amount of ablation. However, because there are several possible mechanisms of atrial fibrillation, it is likely that there will be no minimum left atrial lesion set that will be effective in all patients with atrial fibrillation. Furthermore, although atrial fibrillation is curable in most patients by ablation in the left atrium, the atrial fibrillation at times may be generated in the right atrium and require ablation of gaps in the crista terminalis.¹⁸³ The challenge will be to learn how to recognize the various subtypes of atrial fibrillation and to tailor the ablation therapy accordingly. The development of ablation catheters that facilitate the creation of lines of block in the atria also may improve our ability to cure atrial fibrillation.¹⁸⁴

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