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CATHETER ABLATION OF ACCESSORY ATRIOVENTRICULAR PATHWAYS (WOLFF–PARKINSON–WHITE SYNDROME) BY RADIOFREQUENCY CURRENT

WARREN M. JACKMAN, M.D., XUNZHANG WANG, M.D., KAREN J. FRIDAY, M.D., CARLOS A. ROMAN, M.D., KRIEGH P. MOULTON, M.D., KAREN J. BECKMAN, M.D., JAMES H. MCCLELLAND, M.D., NICHOLAS TWIDALE, M.D., H. ANDREW HAZLITT, M.D., MICHAEL I. PRIOR, M.D., P. DAVID MARGOLIS, M.D., JAMES D. CALAME, R.N., EDWARD D. OVERHOLT, M.D., AND RALPH LAZZARA, M.D.

Abstract *Background.* Surgical or catheter ablation of accessory pathways by means of high-energy shocks serves as definitive therapy for patients with Wolff–Parkinson–White syndrome but has substantial associated morbidity and mortality. Radiofrequency current, an alternative energy source for ablation, produces smaller lesions without adverse effects remote from the site where current is delivered. We conducted this study to develop catheter techniques for delivering radiofrequency current to reduce morbidity and mortality associated with accessory-pathway ablation.

Methods. Radiofrequency current (mean power, 30.9±5.3 W) was applied through a catheter electrode positioned against the mitral or tricuspid annulus or a branch of the coronary sinus; when possible, delivery was guided by catheter recordings of accessory-pathway activation. Ablation was attempted in 166 patients with 177 accessory pathways (106 pathways in the left free wall, 13 in the anteroseptal region, 43 in the posteroseptal region, and 15 in the right free wall).

Results. Accessory-pathway conduction was eliminated in 164 of 166 patients (99 percent) by a median of three applications of radiofrequency current. During a mean follow-up (±SD) of 8.0±5.4 months, preexcitation or atrioventricular reentrant tachycardia returned in 15 patients (9 percent). All underwent a second, successful ablation. Electrophysiologic study 3.1±1.9 months after ablation in 75 patients verified the absence of accessory-pathway conduction in all. Complications of radiofrequency-current application occurred in three patients (1.8 percent): atrioventricular block (one patient), pericarditis (one), and cardiac tamponade (one) after radiofrequency current was applied in a small branch of the coronary sinus.

Conclusions. Radiofrequency current is highly effective in ablating accessory pathways, with low morbidity and no mortality. (N Engl J Med 1991; 324:1605-11.)

FOR more than 20 years, surgical ablation of the accessory pathway has served as definitive therapy for patients with the Wolff–Parkinson–White syndrome.[1-3] The successful introduction of percutaneous catheter ablation of the atrioventricular junction in 1982[4,5] stimulated interest in nonsurgical ablation of accessory atrioventricular pathways.[6-11] Initial approaches used, with moderate success, high-energy direct-current shocks delivered near the coronary-sinus ostium to ablate posteroseptal pathways[12-14] and to the endocardial surface of the tricuspid annulus to ablate right–free-wall pathways.[15-17] High-energy shocks were also applied, with very limited success, within the coronary sinus to ablate left–free-wall accessory pathways.[18] Warin and coworkers successfully ablated 94 percent of 254 accessory pathways in all locations by using an endocardial approach, which also eliminated the risk of perforating the coronary sinus.[19,20]

However, the use of high-energy shocks is associated with infrequent but serious complications, including cardiac perforation, cardiogenic shock, coronary-artery spasm, atrioventricular block, and late occurrence of ventricular fibrillation.[12-24] An alternative energy source, radiofrequency current, has been found to produce discrete lesions in animals without causing hemodynamic embarrassment, serious arrhythmias, or neuromuscular stimulation (eliminating the need for general anesthesia).[25] Further observations in animals suggested that radiofrequency current could safely produce lesions that would be successful in ablating accessory pathways.[26-29] Clinical experience in ablation of the atrioventricular junction[30-32] and case reports of ablation of accessory pathways[33-35] also support the potential safety and efficacy of this approach. The purpose of this study was to develop and evaluate catheter techniques for applying radiofrequency current to accessory pathways in different

From the Department of Medicine, University of Oklahoma Health Sciences Center, and the Department of Veterans Affairs Medical Center, Oklahoma City, Okla. Address reprint requests to Dr. Jackman at the University of Oklahoma Health Sciences Center, Department of Medicine, Cardiovascular Section, P.O. Box 26901, Rm. 5SP300, Oklahoma City, OK 73190.

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locations, as a means of increasing the safety of catheter ablation in patients with the Wolff–Parkinson–White syndrome.

Methods

The study population consisted of 166 patients with symptomatic tachyarrhythmias associated with an accessory atrioventricular pathway, including atrioventricular reentrant tachycardia and atrial fibrillation with a rapid ventricular response due to antegrade conduction over an accessory atrioventricular pathway. Patients were not excluded for any technical reason, including the presence of multiple pathways; previous unsuccessful surgical or catheter ablation; accessory pathways anticipated to be in difficult locations; or previous inability to enter the coronary sinus. Their ages ranged from 6 to 78 years (mean [±SD], 32.2±15.7 years). Five patients were nine years of age or younger. One patient had congenitally corrected transposition of the great vessels. Nine patients were not candidates for surgical ablation because they had dilated cardiomyopathy (six patients) or pulmonary disease (three). Seven patients had undergone unsuccessful surgical ablation of the accessory pathway, and four others had undergone unsuccessful catheter ablation by high-energy direct-current shocks.

The study protocol was approved by the Institutional Review Board of the University of Oklahoma Health Sciences Center. After providing written informed consent, each patient was studied in the post-absorptive state under heavy sedation with fentanyl (50 to 150 μg per hour) and midazolam (2 to 6 mg per hour). Oxygen saturation was monitored with a pulse oximeter. Five multipolar electrode catheters were inserted percutaneously into the right subclavian, right femoral, and left femoral veins and used for programmed atrial and ventricular stimulation and for localization of the accessory pathway. Accessory pathways were localized by recording accessory-pathway activation potentials from closely spaced electrodes positioned near the sites of earliest ventricular activation during antegrade accessory-pathway conduction (sinus rhythm or atrial pacing) and the sites of earliest atrial activation during retrograde accessory-pathway conduction (atrioventricular reentrant tachycardia or ventricular pacing).[36] To localize left–free-wall accessory pathways, an orthogonal electrode catheter was used in the coronary sinus.[37] To localize right–free-wall and septal accessory pathways, a catheter with a deflectable curve and closely spaced conventional electrodes was used to map the tricuspid annulus.[38]

A catheter with a large-tip electrode (7 French; length, 4 mm; surface area, 27 mm^2 [Mansfield–Webster Catheters, Boston Scientific, Watertown, Mass.]) was used for ablation.[32] The catheter has a deflectable curve for maneuvering beneath the mitral or tricuspid leaflets. For the first 96 patients, radiofrequency current (continuous wave, 550 to 750 kHz) was generated by a conventional electrosurgical unit (Bicap 4005, Microvasive Inc., Watertown, Mass.) modified with a transformer to increase voltage, and for the other 70 patients by a more powerful unit (Liz 88, American Cardiac Ablation, Foxboro, Mass.). Both units were coupled to a device that provided real-time monitoring of root-mean-square voltage, current, and impedance.[26,32] Radiofrequency current was delivered at 45 to 60 V (usually 55 V) between the large-tip catheter electrode and a standard adhesive electrosurgical dispersive pad applied to the chest wall. Energy was usually applied during sinus rhythm in patients with preexcitation, and during ventricular pacing or atrioventricular reentrant tachycardia in patients with accessory pathways that conducted only in the retrograde direction. When accessory-pathway conduction was lost within 10 to 15 seconds, the application of energy was maintained for 45 seconds but was terminated immediately in the event of an increase in impedance (resulting from formation of coagulum on the electrode[39]) or displacement of the catheter electrode. Intravenous heparin in a bolus dose of 10,000 U and an infusion of 1000 U per hour was administered to all patients requiring a catheter in the left side of the heart.

Left–Free-Wall Accessory Atrioventricular Pathways

After localization of a left–free-wall accessory pathway by electrodes in the coronary sinus, coronary arteriography was performed to identify branches of the left circumflex coronary artery near the ablation site. The ablation catheter was then inserted through the right femoral arterial sheath and advanced retrogradely into the left ventricle. The large-tip electrode was positioned beneath the mitral leaflet, high against the mitral annulus at the site of the accessory pathway (Fig. 1A). The proximity of the electrode to the annulus and accessory pathway was confirmed by recording a large atrial potential[26] and an accessory-pathway activation potential, respectively (Fig. 2A).

In the first eight patients, radiofrequency current was delivered between the large-tip electrode beneath the mitral annulus and a second large-tip electrode positioned in the coronary sinus, close to the accessory pathway. In the remaining 97 patients, radiofrequency current was delivered between the large-tip electrode beneath the mitral leaflet and a large skin electrode. If the large-tip electrode could not be adequately positioned beneath the mitral

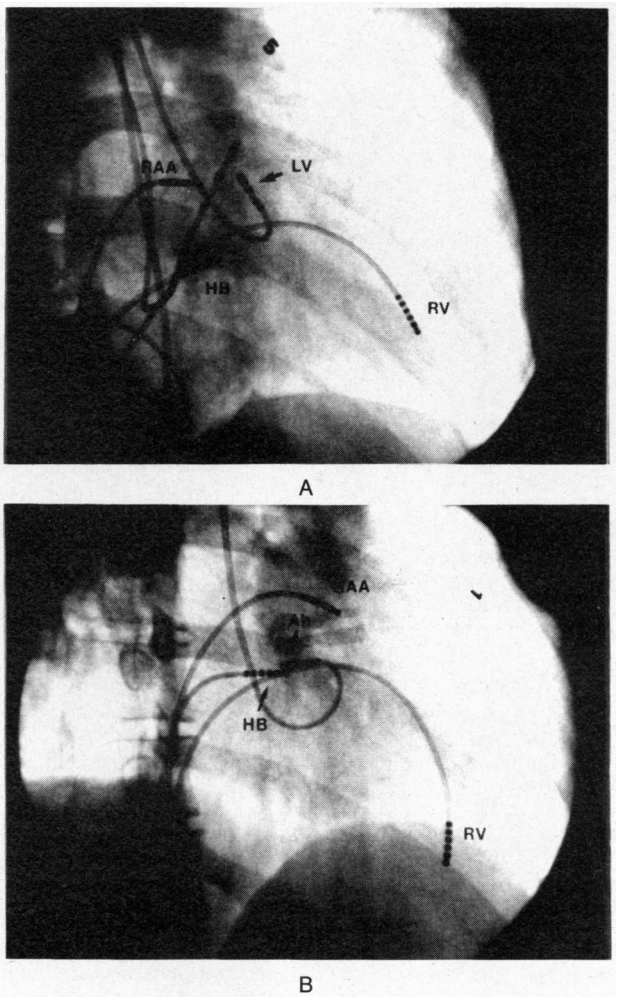

Figure 1. Catheter-Electrode Positions for Accessory-Pathway Ablation (Radiographs in 30-Degree Right Anterior Oblique Projection).

For ablation of a left anterolateral accessory pathway (Panel A), the ablation catheter (LV) was inserted through the right femoral artery and advanced into the left ventricle. The catheter tip was then curved, and the large-tip electrode was maneuvered beneath the mitral leaflet, high against the mitral annulus at the site of the accessory pathway. The small orthogonal electrodes on the coronary-sinus catheter (CS) were used for visual guidance of the ablation catheter to the correct region of the mitral annulus.

For ablation of an anteroseptal accessory pathway (Panel B), the ablation catheter (Ab) was inserted through the right subclavian vein, advanced into the right ventricle, curved beneath the tricuspid leaflet, and positioned 2 mm anterior to the His-bundle catheter (HB). The other two catheters were located in the right atrial appendage (RAA) and right ventricular apex (RV) and were used to stimulate the atria and ventricles, respectively.

leaflet, it was positioned against the mitral annulus above the leaflet or a catheter was placed across the interatrial septum through a patent foramen ovale, or by a transseptal procedure.

Anteroseptal Accessory Atrioventricular Pathways

Accessory pathways were classified as anteroseptal in location if the accessory-pathway activation potential and the His-bundle potential were recorded by the same close bipolar electrode (Fig. 3A). To minimize the risk of atrioventricular block, radiofrequency current was delivered on the ventricular side of the tricuspid annulus. The ablation catheter was inserted through the right subclavian venous sheath and curved beneath the septal or anterior tricuspid leaflet (Fig. 1B). If this approach was unsuccessful, an ablation catheter was inserted through the right femoral venous sheath and placed parallel to the His-bundle catheter.

Posteroseptal Accessory Atrioventricular Pathways

For posteroseptal accessory pathways, the ablation catheter was positioned in one of the following ways: (1) through the right femoral venous sheath, with the tip electrode placed against the tricuspid annulus or around the margin of the coronary-sinus ostium; (2) through the right femoral artery, with the tip electrode positioned against the mitral annulus, close to the septum, as in the approach used for left–free-wall pathways; or (3) through the right subclavian venous sheath, with the tip electrode positioned in a venous branch of the proximal coronary sinus (i.e., the middle cardiac vein).

Right–Free-Wall Accessory Atrioventricular Pathways

For right–free-wall accessory pathways, the ablation catheter was inserted through the right subclavian venous sheath and curved beneath the tricuspid leaflet, as in the approach to anteroseptal pathways. If this approach was unsuccessful, the ablation electrode was positioned above the tricuspid leaflet with a catheter inserted through either the right subclavian or right femoral venous sheath.

Multiple Accessory Atrioventricular Pathways

Two separate accessory pathways were considered to be present if sites where radiofrequency current affected accessory-pathway conduction were separated by more than 3 cm.

Post-Ablation Management

Thirty to 60 minutes after the final application of radiofrequency current, complete atrial and ventricular stimulation was repeated to verify the absence of accessory-pathway conduction and to exclude the presence of another accessory pathway and other arrhythmias, such as atrioventricular nodal reentrant tachycardia. Heparin administration was resumed 3 hours after the procedure and maintained for 48 hours in the first 27 patients with left–free-wall accessory pathways. Heparin was not administered after the procedure in the remaining patients. Transesophageal echocardiography was performed 18 to 72 hours after the ablation procedure to exclude thrombi at the ablation sites. Patients were discharged on the second day after ablation except for the 27 patients who received heparin, who were discharged on the third day after ablation. Patients were followed by the investigators or by the referring physician, and it was recommended that a follow-up electrophysiologic study be performed two to three months after ablation.

Results

A total of 177 accessory pathways were identified in the 166 patients. The locations and conduction prop-

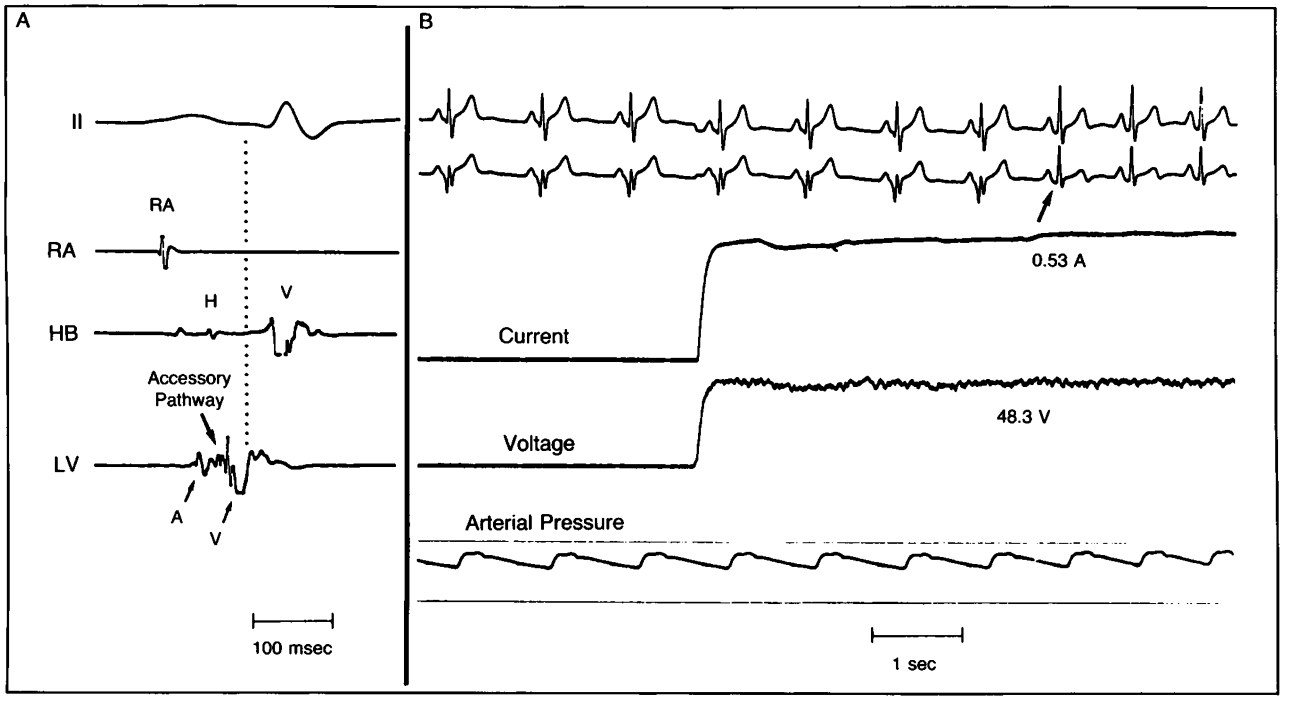

Figure 2. Ablation of a Posterior Left–Free-Wall Accessory Atrioventricular Pathway.

Panel A shows recordings from the ablation electrode during sinus rhythm. From the top, the tracings are Lead II (and Lead III in Panel B) and electrograms recorded from the right atrial appendage (RA), the His-bundle region (HB), and the ablation electrode (LV), which was positioned against the mitral annulus, beneath the mitral leaflet, as illustrated in Figure 1A. The large potential resulting from atrial activation (A) indicates proximity to the atrium and therefore to the mitral annulus. Note the distinct potentials resulting from accessory-pathway activation (large arrow). Left ventricular activation (V) began 20 msec before the onset of the delta wave (dotted vertical line). The tracings shown in Panel B were recorded when radiofrequency current was applied to the large-tip electrode on the left ventricular catheter at 48.3 V and 0.53 A (calculated power, 25.6 W). Accessory-pathway conduction ceased 3.9 seconds after the onset of the application of radiofrequency current (arrow), reflected by the lengthening of the PR interval and normalization of the QRS complex. Arterial pressure was unaffected by the application of radiofrequency current.

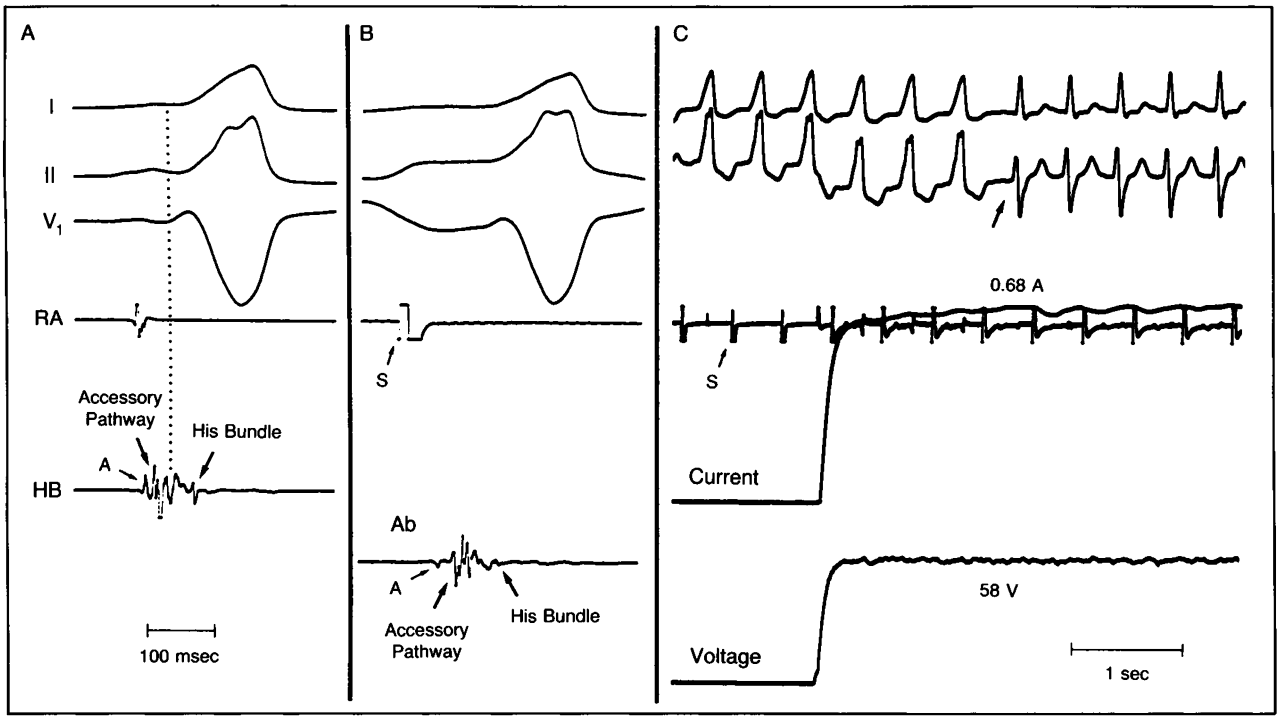

Figure 3. Ablation of an Anteroseptal Accessory Atrioventricular Pathway.

During sinus rhythm (Panel A), the bipolar electrode in the His-bundle region (HB, Fig. 1B) recorded activation potentials from both the accessory pathway and His bundle, indicating the close proximity of these two structures.

During right atrial (RA) pacing at a cycle length of 450 msec (Panel B; S denotes pacing-stimulus artifact), the ablation electrode (Ab) was positioned beneath the tricuspid leaflet, high against the tricuspid annulus and slightly anterior to the His bundle as in Figure 1B. At this site, the accessory-pathway activation potential is still prominent and the His-bundle potential is much smaller than on the electrogram recorded at the true His-bundle position. Note that the atrial potential (A) is smaller than on the His-bundle electrogram in Panel A, because the tip electrode approached the atrium from the ventricular side of the annulus.

In Panel C, radiofrequency current (power, 39.4 W) was applied to the large-tip electrode on the ablation catheter (Ab) during atrial pacing at cycle length 450 msec. Accessory-pathway conduction ceased 1.7 seconds after the onset of the application of radiofrequency current (arrow).

erties of the accessory pathways are shown in Table 1. Of the 177 accessory pathways, 106 (60 percent) were located along the left free wall, 13 (7 percent) in the anteroseptal region, 43 (24 percent) in the posteroseptal region, and 15 (9 percent) along the right free wall. Both antegrade and retrograde conduction were present in 126 pathways (71 percent). Conduction was present only in the retrograde direction in 40 pathways (23 percent), and only in the antegrade direction in 11 pathways (6 percent).

Accessory-pathway conduction was eliminated by the first ablation procedure in 174 of 177 accessory pathways (98 percent), including all left–free-wall, anteroseptal, and right–free-wall pathways (Table 2 and Fig. 2 and 3). Among the 43 patients with posteroseptal accessory pathways, the initial ablation procedure was unsuccessful in 2 patients and it markedly depressed antegrade and retrograde conduction in 1 other patient. The two patients with unsuccessful ablation underwent a second ablation procedure, which was successful in one. Successful ablation required a median of three applications of radiofrequency current at a mean power of 30.9±5.3 W delivered for a mean duration of 40.7±23.7 seconds (Table 3). Accessory-pathway activation potentials were recorded from the ablation electrode at 91 percent of the sites where ablation was successful. The procedure lasted a mean of 8.3±3.5 hours and included ablation of a second accessory pathway in 11 patients, atrioventricular nodal reentrant tachycardia in 4 patients, and ectopic atrial tachycardia in 2 patients. This procedure was also the initial diagnostic electrophysiologic study in approximately 35 percent of the patients. Despite its long duration, the procedure was well tolerated; patients slept throughout the procedure under heavy sedation. The application of radiofrequency current had no effect on the heart rate or blood pressure and produced little or no discomfort.

Table 1. Characteristics of Accessory Pathways.

Accessory-Pathway Location	No. of Patients	No. of Pathways	Antegrade and Retrograde Conduction	Retrograde Conduction Only	Antegrade Conduction Only
Left free wall	105	106	76	28	2
Anteroseptal	13	13	8	4	1
Posteroseptal	43	43	34	6*	3
Right free wall	14	15	8	2	5†
All locations	166‡	177	126	40	11

*Three of six pathways had long conduction times and incessant tachycardia (permanent form of junctional reciprocating tachycardia).

†Three of five pathways exhibited long conduction times with decremental properties (atriofascicular pathways).

‡Nine patients had two accessory pathways in different locations.

Table 2. Outcome of Ablation.

Accessory-Pathway Location	No. of Pathways	Initial Procedure			Recurrence of Conduction	Second Procedure		Final Outcome		
		Success*	Modification	Failure		Attempts	Success*	Success*	Modification	Failure
Left free wall	106	106	0	0	5	5	5	106	0	0
Anteroseptal	13	13	0	0	2	2	2	13	0	0
Posteroseptal	43	40	1†	2	6	8‡	7	41	1	1
Right free wall	15	15	0	0	2	2	2	15	0	0
All locations	177	174	1	2	15	17	16	175	1	1

*Successful ablation is defined as a total absence of antegrade and retrograde accessory-pathway conduction.

†Shortest RR interval between preexcited QRS complexes during atrial fibrillation increased from 150 msec to 270 msec.

‡The patient with modification of accessory-pathway conduction did not undergo a second procedure.

The patients have been followed for 1 week to 27 months (mean, 8.0±5.4 months). Preexcitation or atrioventricular reentrant tachycardia returned in 15 patients (9 percent) 1 day to 4.7 months (mean, 1.5±1.2 months) after ablation (Table 2). Recurrence of accessory-pathway conduction was apparent within the first two months in all but one patient. All 15 patients underwent a second ablation procedure, with elimination of accessory-pathway conduction in all. These 15 patients have subsequently been followed for 0.9 to 16.1 months (mean, 6.4±4.7 months), with no recurrence of preexcitation or tachycardia. A follow-up electrophysiologic study was performed more than 1 month after ablation (mean, 3.1±1.9 months) in 75 of the 164 patients with apparently successful ablation, including 9 of the 15 patients who had undergone a second ablation procedure for the recurrence of accessory-pathway conduction. Accessory-pathway conduction was absent in all 75 patients. Although the remaining 89 patients with apparently successful ablation did not undergo a late follow-up electrophysiologic study, 71 of these patients (80 percent) had preexcitation before ablation and no preexcitation during the follow-up period.

Four patients who had episodes of atrial fibrillation with preexcitation before ablation had a recurrence of atrial fibrillation without preexcitation after the procedure. Two of these patients had severe dilated cardiomyopathy, one of whom died of progressive heart failure four months after ablation. Antiarrhythmic drugs were administered to the four patients with a recurrence of atrial fibrillation and the two patients who had residual accessory-pathway conduction. The remaining 160 patients have not received antiarrhythmic drugs and are free of preexcitation, atrioventricular reentrant tachycardia, and atrial fibrillation.

Creatine kinase was measured in 147 patients after ablation. Both an elevated concentration of total creatine kinase and a high creatine kinase MB fraction (>5 percent) were found in 19 patients (13 percent). These patients had a peak total creatine kinase concentration of 5.38±2.8 μkat per liter (323±168 IU per liter) and a peak creatine kinase MB fraction of 0.495±0.73 μkat per liter (29.7±43.5 IU per liter). There was no electrocardiographic evidence of myocardial infarction in any patient.

Transesophageal echocardiography was performed within 72 hours of the ablation procedure in 128 patients. No thrombus was identified at the ablation site in any patient; however, thrombi were found in three patients in the high right atrium, in the left atrial appendage, and on the atrial side of the anterior tricuspid leaflet at a site in contact with a permanent-pacemaker lead. Only the thrombus in the high right atrium was believed to have resulted from the procedure. All three patients received a course of warfarin, and no patient had a thromboembolic event. No new mitral or tricuspid insufficiency was found. No new abnormalities of ventricular-wall motion were observed.

Complications other than the right atrial thrombus described above occurred in five patients. Complete atrioventricular block followed ablation of a posteroseptal accessory pathway in a patient with congenitally corrected transposition of the great vessels. This patient presented with rapid atrial fibrillation with

Table 3. Characteristics of Successful Ablation.

Accessory-Pathway Location	No. of Radiofrequency-Current Applications		Values for the Successful Application of Radiofrequency Current*					
	Range	Median	AP Potentials Recorded (%)	Voltage	Current	Power	Impedance	Duration
				volts	*amperes*	*watts*	*ohms*	*seconds*
Left free wall	1–59	2.0	98 (92)	54.0±8.9	0.56±0.08	30.8±5.5	99.9±19.3	41.2±25.5
Anteroseptal	1–13	5.0	11 (85)	59.9±4.1	0.58±0.08	29.9±5.9	90.0±7.9	34.7±18.7
Posteroseptal	1–25	4.0	39 (95)	56.2±3.8	0.58±0.07	32.2±5.1	98.5±10.8	39.8±20.7
Right free wall	1–42	5.0	11 (73)	55.7±3.8	0.55±0.07	30.5±4.8	104.9±12.9	44.2±22.8
All locations	1–59	3.0	159 (91)	54.0±8.4	0.56±0.08	30.9±5.3	99.1±16.8	40.7±23.7

*AP denotes accessory pathway. Plus–minus values are means ±SD.

only preexcited QRS complexes and did not have normal atrioventricular nodal conduction at electrophysiologic study before ablation. Complete atrioventricular block followed the application of radiofrequency current to the posteroseptal tricuspid annulus near the posterior margin of the coronary-sinus ostium. This site is remote from the normal location of the atrioventricular node. Hemopericardium and cardiac tamponade occurred in one patient after the application of radiofrequency energy in a small venous branch of the proximal coronary sinus. The intrapericardial blood was drained percutaneously, and the patient did not require surgery. Four other patients received radiofrequency current in a venous branch of the coronary sinus; pericarditis without effusion developed in one. There were no complications related to the application of radiofrequency current along the mitral or tricuspid annulus. Complications related to cannulation of the right femoral artery occurred in two patients: one patient had a small pseudoaneurysm of the right femoral artery, which was repaired under local anesthesia, and the other patient had a large femoral hematoma and required blood transfusion.

Discussion

Although radiofrequency current produces smaller lesions than high-energy direct-current shocks,[25] studies in animals have demonstrated that lesions potentially effective for accessory-pathway ablation can be produced when the ablation electrode is positioned firmly against the mitral or tricuspid annulus.[26,29] In the present study, designed to test this hypothesis, radiofrequency current eliminated ventricular preexcitation and atrioventricular reentrant tachycardia in 164 of 166 patients (99 percent). This was accomplished with a single procedure in 148 patients and with two in 16. A late follow-up electrophysiologic study was performed in 75 of the 164 patients (46 percent) and confirmed the absence of accessory-pathway conduction in all.

The principal reason for testing radiofrequency current was its potential to minimize the morbidity associated with ablation procedures. Even with experienced teams, the mortality resulting from surgical ablation of accessory pathways may be as high as 5 percent,[2] and the frequency of reoperation for complications such as bleeding or recurrence of accessory-pathway conduction may be as high as 4 percent.[3,40] Although catheter ablation with high-energy direct-current shocks is better tolerated than surgery, it still carries an appreciable risk of cardiac perforation, injury to coronary arteries, and new ventricular arrhythmias.[13-24] In the present study there was no mortality, and complications occurred in only six patients (3.6 percent). Application of radiofrequency current to the endocardial surface of the mitral or tricuspid annulus did not result in cardiac perforation or injury to the valve or the coronary artery during a mean follow-up period of eight months, although the potential for long-term adverse effects of this procedure is unknown. Pericarditis or cardiac tamponade occurred in two of five patients with posteroseptal accessory pathways in whom radiofrequency current was delivered through a small venous branch of the coronary sinus. This suggests that ablation from these vessels should be undertaken with caution, and alternative therapy, including surgery, should be considered for patients with posteroseptal pathways that cannot be ablated from either the mitral or tricuspid annulus.

The results of this study demonstrate that catheter delivery of radiofrequency current guided by direct recordings of accessory-pathway activation is highly effective in ablating accessory pathways, with no mortality and lower morbidity than surgical ablation or catheter ablation with high-energy shocks.

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