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Follow-Up of Radiofrequency Catheter Ablation in Children: Results in 100 Consecutive Patients

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Objectives. **The purpose of this study was to determine the outcome of a group of closely followed-up pediatric patients who had undergone radiofrequency ablation for cardiac arrhythmias.**

Background. **Although radiofrequency ablation in children has been shown to be effective and safe in the short term, results of longer term follow-up of these children must be considered when determining the place of radiofrequency ablation in the management of pediatric arrhythmias.**

Methods. **One hundred children aged 2 months to 17 years underwent a total of 119 radiofrequency ablation procedures for cure of tachycardia. Follow-up clinical data, electrocardiograms and 24-h Holter monitors were obtained and analyzed.**

Results. **All patients were alive, and none were lost to follow-up after a mean follow-up of 21.5 months (range 6 to 50). Success at last follow-up included accessory pathways in 66 (89%) of 74 patients, atrioventricular (AV) node reentry in 15 (88%) of 17, intraatrial reentry in 2 (67%) of 3, atrial flutter in 3 (100%) of 3, atrial ectopic tachycardia in 2 (67%) of 3, junctional ectopic tachycardia in 1 (100%) of 1 and ventricular tachycardia in 2 (100%) of 2 (overall success, 90 [90%] of 100). All recurrences were observed within 6 months of ablation. Major and minor complications (7%) included chest burn (one patient), foot microembolus (two patients), hematoma without pulse loss (four patients), femoral arteriovenous fistula requiring repair (one patient) and transient Mobitz I AV block (one patient). Immediate success, recurrence and complication rates were similar in the ≥12-year old versus the <12-year old group. Echocardiograms, available in 109 (92%) of 119 patients, showed possible procedure-related abnormalities in 2 (mitral regurgitation in 1, tricuspid regurgitation in 1, both mild), with no aortic insufficiency after 30 left-sided ablations performed by the retrograde approach. Follow-up Holter monitors, available in 77 (77%) of 100 patients, showed possible procedure-related abnormalities in 5 (frequent atrial ectopic tachycardia in 2, atrial flutter in 1, accelerated ventricular rhythm in 2). There were no early or late deaths.**

Conclusions. **In children, the risks of radiofrequency ablation are low at follow-up evaluation. Longer-term follow-up of children undergoing radiofrequency ablation will be necessary to determine whether coronary abnormalities or serious new arrhythmias will develop.**

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Radiofrequency catheter ablation is a nonsurgical technique for the cure of cardiac arrhythmias. Since its introduction into adult and pediatric cardiology practice 4 years ago, the use of the technique has spread widely. It has now replaced open heart surgery in the care of many patients with drug-refractory arrhythmias. In addition, children and adults who would not otherwise be candidates for surgical intervention are now undergoing radiofrequency ablation at many centers. The initial results of ablation in children have been excellent, with a low rate of complications (1–8). The long-term safety of the technique has not been established, however. Still unresolved are questions of whether radiofrequency lesions might eventually lead to new arrhythmias due to the myocardial scar, to coronary abnormalities due to the proximity of these vessels to the site of lesion or to an increased incidence of radiation-induced malignancy. Children may have a different or higher risk for these theoretic problems because of continued growth and cardiac development, as well as potentially longer life span and therefore time available for the occurrence of problems. Reports of the use of radiofrequency ablation to date have focused on immediate results, with only limited inclusion of follow-up information. Despite the fact that these issues remain unresolved, radiofrequency ablation has become the treatment of choice at many centers. Before the technique becomes the standard of care, it is critically important that the outcomes of these patients are examined carefully.

It is nearly 4 years since the first radiofrequency ablation in a pediatric patient was performed at our center in 1989 (1). The purpose of this report is to present the safety and

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efficacy of the technique in a consecutive series of pediatric patients who have been carefully followed up clinically for up to 4 years.

Methods

Patients. All pediatric patients undergoing radiofrequency catheter ablation at our center for any diagnosis were included in the follow-up study. Because the aim of the study was to assess the effect of the procedure in patients who are still growing and developing, only patients aged ≤17 years at the time of the initial procedure were included.

Radiofrequency ablation techniques. The protocol was approved by the Committee on Human Research, and written informed patient consent was obtained for the procedure. Several patients in the series have been previously reported as part of inclusive series of all patients undergoing catheter ablation at our institution (1,2,9–11), the methods have been previously described. These methods are briefly described here.

For the last 2 years of the series, patients began receiving oral aspirin 3 days before the procedure. Premedication was administered using oral pentobarbital (5 mg/kg body weight) and either morphine (0.05 mg/kg) or methadone (0.1 mg/kg). Additional intravenous sedation was administered when necessary with either pentobarbital (2 mg/kg) or morphine (0.05 mg/kg). An initial electrophysiologic study was performed for definition of arrhythmia mechanism and intracardiac mapping. Anticoagulation (in all left-sided cases) was achieved using 100 μg/kg of intravenous heparin, and activated clotting times were measured, with additional doses of heparin given to maintain the activated clotting time at >240 s. Radiofrequency lesions were created, as previously reported (2,9), using a 7F or 6F steerable quadripolar electrode catheter with a large (4 mm) distal electrode (Mansfield Scientific, Inc. or EP Technologies). Radiofrequency current was supplied using a radiofrequency lesion generator (model RFG3B, Radionics Corp.), and up to 32 W of continuous, unmodulated current at 500 kHz was delivered between the distal pole of the ablation catheter and a large surface area skin electrode. If a sudden increase in telemetered voltage and decrease in current occurred, indicating an increase in impedance, application of energy was immediately discontinued, the catheter was removed, and the distal electrode was cleaned before reintroduction. Otherwise, energy was delivered for up to 100 s at each site. Often, short "test" applications were given, observing for changes such as loss of pre-excitation or tachycardia termination, before a longer application. One additional application was directed to successful sites. Heparinization was not reversed with protamine at the conclusion of the procedure, and no postprocedure anticoagulation was administered.

Total fluoroscopic time for both the diagnostic and therapeutic portions of the procedure was logged. Total procedure time was recorded, from the start of the electrophysiologic study (after insertion of catheters) until catheters were removed. The occurrence of both major and minor early and late complications of the procedure was noted.

Accessory pathways. Energy was delivered to either the atrial or ventricular side of the atrioventricular (AV) ring. In four patients, mapping of the right AV ring was facilitated using an intracoronary mapping wire (Spectramed), as previously described (2,12). Left freewall pathways were approached either anterograde, through a patent foramen ovale or after a transseptal puncture, or retrograde, under the mitral leaflet or after flexing the catheter back into the left atrium.

Atrioventricular node modification. In patients with AV node reentrant tachycardia, modification was performed by the anterior ("fast pathway") approach in the first 5 patients, as previously described (13), or the posterior ("slow pathway") approach in the next 13 patients (12).

Junctional ectopic tachycardia. In one patient with congenital junctional ectopic tachycardia, ablation of the junctional focus and the AV node were performed, as previously described (1).

Atrial ectopic tachycardia and idiopathic ventricular tachycardia. Automatic foci were located using a combination of mapping to identify the site of earliest ventricular activation and pacing from candidate sites to reproduce both surface electrocardiographic (ECG) configuration and intracardiac electrogram activation sequence. These sites were used as the targets for application or radiofrequency energy.

Atrial flutter and intraatrial reentrant tachycardia. As previously described (11), sites of early atrial activation during tachycardia were sought that exhibited electrogram fractionation. Sites that duplicated the tachycardia P wave configuration and axis during pacing from these sites were sought for energy application. In the most recent patients, sites from which overdrive pacing resulted in entrainment without surface fusion and long stimulus to P wave latency (i.e., concealed entrainment) were also sought. In patients with atrial flutter, these sites were in the low right atrium between the inferior vena cava and tricuspid valve. In patients with intraatrial reentrant tachycardia after congenital heart disease surgery, these sites were always closely related to a surgically created obstacle, such as an atriotomy site.

Success/failure. The *procedural success rate* was determined for each arrhythmia substrate for which radiofrequency ablation was attempted. A procedure was defined as successful if, at the end of the procedure, there was no evidence of the particular substrate or accessory pathway by electrophysiologic testing. The *long-term success rate* was determined for each patient at last follow-up contact. Long-term success ("cure") was recorded if, at the last follow-up contact, there was no evidence of recurrence of the arrhythmia diagnosis for which ablation was attempted. This included a lack of both ECG evidence (e.g., return of pre-excitation) and clinical evidence (return of symptoms). In patients with multiple diagnoses (e.g., AV node reentry and Wolff-Parkinson-White syndrome), long-term success was

determined if possible for each diagnosis. For patients with multiple pathways, long-term success was recorded only if there was no evidence of any recurrent accessory pathway conduction or supraventricular tachycardia at last follow-up.

Follow-up procedures. The postablation follow-up protocol consisted of the following: ECG, 24 h ambulatory ECG (Holter monitor) and echocardiogram on the day after the procedure; history and physical examination, ECG and Holter monitor 2 months later and at yearly intervals thereafter; and any other tests indicated by findings on these studies. In many cases, these follow-up visits and studies were performed locally by referring physicians. Follow-up electrophysiologic studies were not routinely recommended in asymptomatic patients.

Attempts at direct contact of all patients and their parents were made as part of this study. The status of the patient was ascertained with respect to symptoms referable to the cardiovascular system and, in particular, symptoms that might indicate recurrence of the original arrhythmia substrate, occurrence of a new arrhythmia or occurrence of a late complication. In those patients with symptoms suggesting new or recurrent arrhythmias, documentation was sought at follow-up visits by ECG, 24-h ambulatory ECG monitoring or transtelephonic event monitoring.

All referring physicians or primary care physicians, or both, were also contacted for information on all local follow-up visits. Copies of ECGs, Holter monitors, echocardiograms and any other studies were obtained from referring physicians for analysis at our center.

Statistical methods. The group of patients aged <12 years was compared with the group aged ≥12 years with respect to presenting diagnosis, initial success rate or ablation and complication rate, and the results were analyzed by the chi-square test. The time intervals from ablation to recurrence for the entire group and for the group with accessory pathways were analyzed using life table methods, as described by Colton (14), and standard errors at each interval were calculated by the method of Greenwood (14), using the recommended follow-up intervals for the life table intervals and excluding from analysis those patients with procedure failure. The cumulative probability of remaining free of recurrence for the patients with initially successful ablation was graphed along with the standard errors at each interval. The recurrence risks at each interval were compared for the group <12 years of age versus the group ≥12 years old by the method of Greenwood (14).

Results

Patients. One hundred patients (median age 12.87 years, range 2 months to 17.8, median weight 46.4 kg, range 5.8 to 108) underwent 119 radiofrequency catheter ablation procedures between August 28, 1989 and March 9, 1993 (Fig. 1). Eighty-two patients underwent a single procedure, 17 underwent two procedures, and 1 underwent three procedures. Multiple procedures were performed either for multiple

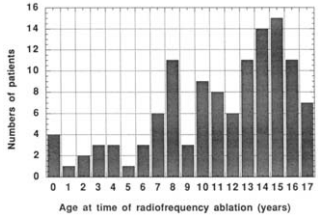

Figure 1. Patient ages at time of initial radiofrequency catheter ablation procedure.

substrates or for repeat ablation of recurrent substrates. In 98 patients, a single substrate was approached by ablation; in one patient, two substrates were approached (accessory pathway and AV node reentry), and in one patient, three substrates were approached (accessory pathway, AV node reentry and atrial flutter). The primary indication for the procedure was a life-threatening arrhythmia in 17 patients, failure of antiarrhythmic medication in 42, adverse effects of antiarrhythmic medication in 7, planned cardiac surgery in 2 and patient choice in 32. Patients with failed therapy with antiarrhythmic medications had taken a mean of 2.52 medications (range 2 to 5). Thirteen patients also had congenital heart disease.

Radiofrequency ablation procedures. Overall, an initially successful ablation was achieved for 93% of arrhythmia substrates (Table 1). Most initial failures occurred in attempts at ablation of right-sided accessory pathways located on the free wall. Mean fluoroscopic duration was 54.2 min (range 13.3 to 240), and mean total procedure time was 203.2 min (range 54 to 422).

The subset of patients aged <12 years was similar to that aged ≥12 years, both with respect to the diagnoses for which ablation was performed and the initial success rates of the procedure (Table 2).

Forty-six procedures included ablation in the left atrium or ventricle, all with systemic heparinization. Two of these were ablation of left atrial ectopic tachycardia (via a patent foramen ovale), 3 were ablation of left ventricular sites of ventricular tachycardia (retrograde), and 41 were ablation of left free wall accessory pathways. The latter were via a patent foramen ovale in 8, via transseptal puncture in 10 and retrograde in 27. All ablations performed after transseptal puncture or via a patent foramen ovale were performed on the atrial side of the mitral annulus. In 5 of the 27 procedures performed by a retrograde approach to the mitral annulus, ablation lesions were directed to the atrial side of the annulus, and in 22 they were directed to the ventricular side. Four of the 46 procedures included two approaches because of failure of the first approach.

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Table 1. Procedural Success Rates for Specific Arrhythmia Substrates*

Diagnosis/Pathway Location	Initial Success (no. of successful/ total procedures)	Symptomatic Recurrence (no. of recurred/ total initial successes)
Accessory pathways†	79/88 (90%)	9/79 (11%)
Right free wall	22/29 (76%)	6/22 (27%)
Posteroseptal‡	9/9 (100%)	0/9 (0%)
Anteroseptal‡	5/6 (83%)	2/5 (40%)
Intermediate septal‡	3/3 (100%)	0/3 (0%)
Left free wall	40/41 (98%)	1/40 (3%)
Atrioventricular node reentry	18/18 (100%)	3/18 (17%)
Atrial ectopic tachycardia	4/4 (100%)	1/4 (25%)
Atrial flutter	3/3 (100%)	0/3 (0%)
Intraatrial reentry	5/5 (100%)	2/5 (40%)
Junctional ectopic tachycardia	2/2 (100%)	1/2 (50%)
Ventricular tachycardia	3/3 (100%)	1/3 (33%)
All procedures	114/123 (93%)	17/114 (15%)

*One hundred twenty-three substrates were approached during 119 ablation sessions in 100 patients. †Twenty-five accessory pathways were concealed; 63 were manifest. ‡The posteroseptal and intermediate septal groups include four and three pathways, respectively, that were slowly conducting and decrementai in patients with the permanent form of junctional reciprocating tachycardia.

Complications. Complications occurred as a result of nine procedures (7.6%) (Table 3). One major complication occurred: A patient developed a bruit over the femoral entry site where two venous sheaths and one arterial cannula had been inserted. He had an angiographically proved arteriovenous fistula that was repaired surgically without difficulty or pulse loss. Minor complications occurred in eight procedures: There were four significant hematomas without sequelae, three at femoral sites and one at a jugular venous site. Two patients developed a painful right foot, consistent with the diagnosis of microembolization, that resolved within several days. In both, left lateral accessory pathways had been approached via the femoral artery on that side, and procedure times were quite prolonged in both (5 h 10 min and 6 h, respectively) after introduction of catheters. A patient with the permanent form of junctional reciprocating tachycardia underwent successful ablation of an intermediate septal accessory pathway with Wenckebach conduction in sinus rhythm immediately after the ablation. It was completely reversible with atropine and with isoproterenol infusion and resolved several days later without return of tachycardia. Finally, one patient developed chest redness at the site where the grounding patch had been placed, and this was considered a mild chest burn.

Table 2. Comparison of Procedural Success Rates for Specific Arrhythmia Substrates by Age

Diagnosis/Pathway Location	Initial Success (no. of successful/total procedures)	
	Age <12 yr	Age ≥12 yr
Accessory pathways	37/41 (90%)	42/47 (89%)
Right free wall	12/16	10/13
Posteroseptal	4/4	5/5
Anteroseptal	2/2	3/4
Intermediate septal	3/3	0/0
Left free wall	16/16	24/25
Atrioventricular node reentry	6/6	12/12
Atrial ectopic tachycardia	2/2	2/2
Atrial flutter	1/1	2/2
Intraatrial reentry	4/4	1/1
Junctional ectopic tachycardia	2/2	0/0
Ventricular tachycardia	0/0	3/3
All procedures	52/56 (93%)	62/67 (93%)

Table 3. Immediate Complications Observed After 119 Ablation Procedures

Complications Observed	No. of Patients
Hematoma (femoral)	3
Hematoma (internal jugular)	1
Arteriovenous fistula (femoral)	1
Foot pain consistent with microembolization	2
Mild chest burn at site of ground patch	1
Transient Mobitz I 2nd-degree atrioventricular block	1

The incidence of complications in the group aged <12 years (4 [7.3%] of 55) was similar to the incidence in the group aged ≥12 years (5 [7.8%] of 64).

Echocardiography. A two-dimensional echocardiogram was obtained within 24 h of the ablation procedure after 109 (92%) of 119 procedures, and in all patients who had undergone left-sided ablation procedures. Findings were unchanged in the 13 patients with coexisting congenital heart defects. Echocardiographic abnormalities that were possibly due to damage to valve leaflets as a result of the ablation procedure were seen in two patients. The first was a 7-year old child who had a left posterior paraseptal pathway ablated by the retrograde route with the ablation catheter positioned under the mitral leaflet. The echocardiogram showed trivial mitral regurgitation that was quite eccentric and apparently arising from the site of the ablation. A repeat echocardiogram 1 month later showed persistence of the regurgitant jet, but the degree of regurgitation was still trivial. Routine dental procedure antibiotic prophylaxis against bacterial endocarditis was recommended in the future, however. The second patient was an 8-year old child who had a transiently successful ablation of a right anterior pathway, with introduction of the catheter into the ventricle and positioning of the tip under the tricuspid valve leaflet. The echocardiogram showed trivial tricuspid regurgitation with a somewhat eccentric jet anteriorly. This had disappeared on a repeat study 1 month later. No aortic insufficiency was observed echocardiographically after any of the 30 procedures in which the aortic valve was crossed with an ablation catheter.

Electrocardiography. A 12- or 15-lead ECG was obtained after 119 (100%) of 119 procedures, and these studies showed no serious abnormalities. No signs of coronary ischemia, such as abnormal Q waves or ST segment change, were noted. Three patients had developed right bundle branch block after ablation of anteroseptal accessory pathways. One patient had Mobitz I conduction. Five patients had first-degree AV block after AV node modification by the anterior approach, as expected. Patients with manifest pre-excitation with either failed ablation or immediate recurrence showed pre-excitation. Two patients had prolonged QT intervals after ablation of manifest accessory pathways. Subsequently, ECGs were obtained in 100 of 100 of patients at follow-up visits with referring physicians. In some cases, recurrences were diagnosed on the basis of these tracings (Table 1). Both patients with QT interval prolongation noted immediately postablation had persistent QT prolongation on follow-up ECGs. Both patients had had symptoms consistent with the long QT syndrome (e.g., syncope or aborted sudden death) and are being treated with beta-adrenergic blocking medications. No signs of coronary ischemia, such as abnormal Q waves or ST segment change, were noted in any patient.

Twenty-four hour ambulatory electrocardiography. A 24-h Holter monitor was obtained within 48 h after 110 (92%) of 119 procedures. One of these had an episode of supraventricular tachycardia captured on the recording. Otherwise, no significant supraventricular or ventricular ectopy was recorded, and there was no abnormal bradycardia.

Subsequently, 24-h Holter monitors were obtained in 77 patients (77%) at follow-up visits with referring physicians. Patients who had not had Holter monitoring were contacted, and none had developed new symptoms, such as chest pain, syncope, palpitations or tachycardia. The mean interval from last ablation procedure to last Holter monitor was 7.2 months (range 0.5 to 34.6). In two patients, there were frequent premature atrial contractions that had not been seen on the preablation or immediate postablation Holter monitor. Both patients had undergone AV node modification by the posterior approach. In two patients, significant ventricular ectopy was recorded. The first patient had undergone two ablation sessions for AV node modification by the posterior approach at age 14 years, with application of energy in the mouth of the coronary sinus on the second attempt. The recording showed several short episodes of nonsustained ventricular rhythm at a rate of 150 beats/min in the early morning hours. There were no other abnormalities, and he continues to be asymptomatic. The second patient was 2 months of age at the time of ablation for the permanent form of junctional reciprocating tachycardia. He presented at 5 weeks of age with severe left ventricular dysfunction and an echocardiographically determined percent fractional shortening of 5%. The administration of flecainide and of sotolol in this patient had been associated with the development of ventricular tachycardia. Radiofrequency ablation involved delivery of four lesions to the posterior septal region at 5 to 16 W. After successful ablation, electrophysiologic study showed frequent premature ventricular contractions during isoproterenol infusion. Both telemetry and a Holter monitor 1 week after the ablation showed frequent uniform premature ventricular contractions as well as several episodes of nonsustained ventricular accelerated rhythm at a rate of 180 beats/min. The sinus rate at these times was slightly slower. He was treated with amiodarone for 3 months, and a follow-up recording 3 months later showed no significant ventricular ectopy and no tachycardia. Amiodarone was successfully withdrawn.

One patient developed frequent paroxysmal atrial flutter seen on a follow-up Holter monitor, as well as clinically, after two successful ablation sessions for two right-sided accessory pathways associated with Ebstein's anomaly. It was unclear whether atrial flutter had occurred spontaneously prior to ablation. Immediately after the second ablation, he underwent uncomplicated surgical closure of an atrial septal defect.

Clinical follow-up and risk of recurrence. The mean interval from the initial ablation procedure to this study was 21.5 months (range 6 to 50 months). All patients were seen at least once in follow-up by their referring physician after the procedure. Subsequently, four patients were lost to follow-up. All had been asymptomatic, without signs of recurrence at that last follow-up evaluation. At the time of the last clinical contact, 90 of all patients (90%) were completely asymptomatic, with no signs of recurrence of tachycardia (Table 4). Five patients underwent transtelephonic event monitoring to evaluate symptoms of "palpitations." In four, only sinus rhythm or sinus tachycardia was diagnosed. In one, recurrent tachycardia was diagnosed, prompting repeat ablation. There were no deaths and no reports of syncope or chest pain in the group. No malignancies were reported during the follow-up interval.

Life table analysis for patients who had initially successful ablation showed that the chance of remaining free of arrhythmia was 86.3% at 6 months, with no further increase in risk after 6 months (Fig. 2). This analysis excluded patients who had unsuccessful procedures, and procedures in patients who had two accessory pathways approached at a single session were entered only once. Most recurrences were observed in the 1st 2 days after ablation, and nearly all were evident by 2 months (Fig. 2). When patients with ablation of accessory pathways were analyzed separately, the chance of remaining free of recurrence was slightly higher (89.5%) (p = NS), but the time course of recurrence was similar in that all recurrences were evident by 6 months (Fig. 3). Among patients with accessory pathways, the highest risk of recurrence was observed in the group with right free wall pathways (27%) (Table 1). When patients <12 years of age were compared with patients ≥ 12 years of age, the chance of remaining free of recurrence was nearly identical (86.4% vs. 86.2%) (Fig. 4).

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Table 4. Clinical Status of Patients at Last Follow-Up

Diagnosis*	"Cured"/Total	"Cured" or Improved/Total	Not Improved/Total
Accessory pathway-mediated tachycardia	66/74 (89%)	67/74 (90%)	7/74 (10%)
Right free wall	14/18 (78%)	15/18 (83%)	5/18 (28%)
Posteroseptal	9/9 (100%)	9/9 (100%)	0 (0%)
Anteroseptal	3/5 (60%)	3/5 (60%)	2/5 (40%)
Intermediate septal	3/3 (100%)	3/3 (100%)	0/3 (0%)
Left free wall	39/39 (100%)	39/39 (100%)	0/39 (100%)
Atrioventricular node reentry	15/17 (88%)	15/17 (88%)	2/17 (12%)
Atrial ectopic tachycardia	2/3 (67%)	3/3 (100%)	0 (0%)
Atrial flutter	3/3 (100%)	3/3 (100%)	0 (0%)
Intraatrial reentry	2/3 (67%)	3/3 (100%)	0 (0%)
Junctional ectopic tachycardia	1/1 (100%)	1/1 (100%)	0 (0%)
Ventricular tachycardia	2/2 (100%)	2/2 (100%)	0 (0%)
All patients*	90/100 (90%)	91/100 (91%)	9/100 (9%)

*One patient was symptomatic after two arrhythmia mechanisms (accessory pathway and atrioventricular [AV] node reentry), and one was symptomatic after three mechanisms (accessory pathway, AV node reentry and atrial flutter).

Discussion

Follow-up data from adult series. To date, reports of the use of radiofrequency catheter ablation have emphasized initial results and complications and have included limited follow-up data. Jackman et al. (15,16) reported mean follow-up intervals of 8.0 and 15.3 months in adult patients undergoing ablation of accessory pathways and AV node reentrant tachycardia, respectively, and Calkins et al. (17) reported a mean follow-up interval of 10 months in patients after accessory pathway ablation. Recently, Greene et al. (18) reported follow-up of 1 to 59 months in 310 patients after radiofrequency ablation for supraventricular tachyarrhythmias. No late development of arrhythmia was noted, except in one patient who developed polymorphous ventricular tachycardia after AV junction ablation (18).

The long-term outcome of patients who have undergone direct current ablation is somewhat better studied. The Percutaneous Cardiac Mapping and Ablation Registry reported a 1.8% incidence of sudden death after direct current ablation of the AV junction up to 13 months after the procedure (19) and a 13% incidence of sudden death after ablation of ventricular tachycardia (20). In the latter group, most deaths were probably due to recurrence of the original arrhythmia. However, two patients had a new morphology of ventricular tachycardia documented after ablation, and the investigators could not exclude proarrhythmia due to the ablation. Perry et al. (21) reported one child who died after a documented ventricular fibrillation arrest 6 years after successful AV junction ablation using direct current. This child had ventricular tachycardia after the ablation, and examination of the heart at autopsy showed clear ventricular scars in two locations.

Figure 2. Life table analysis of entire group after initially successful ablation. Probability of remaining free of recurrence is plotted on the Y axis (±SE). **Numbers** superimposed on graph indicate number of patients available at start of the interval. d = days; m = months.

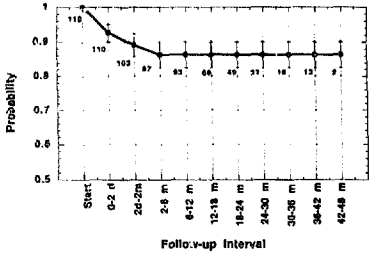
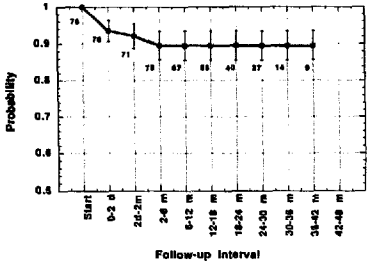


Figure 3. Life table analysis of the group with accessory pathways after initially successful ablation. Probability of remaining free of recurrence is plotted on the Y axis (±SE). **Numbers** superimposed on graph indicate number of patients available at start of the interval. d = days; m = months.



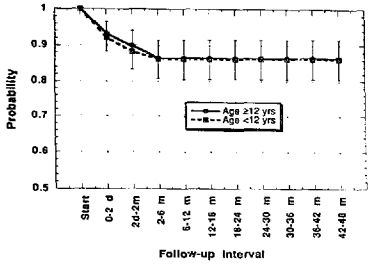


Figure 4. Life table analysis of patients ≥12 versus <12 years old after initially successful ablation. Probability of remaining free of recurrence is plotted on the Y axis (±SE). d = days; m = months.

Follow-up data from pediatric series. Follow-up data in children undergoing radiofrequency ablation procedures have been less extensively reported than in adults. It may not be reasonable to assume that the long-term consequences of the procedure will be similar to those being reported in adults for several reasons: Pediatric patients referred for catheter ablation procedures have a higher incidence of congenital heart disease than adult patients (13% of our series). After the ablation, children grow and develop, including the coronary circulation and the sympathetic nervous system. Finally, the immature myocardium may be more vulnerable to thermal injury than mature (adult) myocardium, as several recent animal experiments have suggested (22,23). These considerations raise the speculation that ablation in young patients may put the coronary arteries at risk or may be potentially more proarrhythmic than in older patients, and this concern suggests that that pediatric patients undergoing radiofrequency ablation deserve long-term clinical follow-up.

Our group (2) previously reported follow-up intervals of 1 to 16 months, and Dick et al. (3) reported intervals of 4 to 12 months. More recently, Saul et al. (6) reported results of accessory pathway ablation in 56 patients aged <18 years, with a median follow-up interval of 7 months (range 1 to 23). One patient, a 1-month old infant, died suddenly 2 weeks after a successful ablation. Because of the lack of an alternative explanation, the presumed cause was proarrhythmia related to the ablation procedure (6). Other late-appearing complications were not noted in this group. However, that study did not include postablation echocardiograms in most patients, and 24-h ECG monitoring was only performed when appropriate.

Implications of recurrence and long-term cure data. It should be noted that Tables 1 and 2 deal with procedures in the denominator, whereas Table 4 deals with patients in the denominator. One might ask, for patients with accessory pathways, if 90% were successful and 10% recurred, why the long-term cure rate is 89% and not 80%. The reason is that a significant number of patients had multiple procedures, either for recurrence or for initial failure with a subsequent attempt that was successful. Some of the 10% who had initially unsuccessful procedures subsequently were successfully ablated and are counted in the 89% with long-term cure, and some of the patients who had a recurrence had successful repeat ablation and also are counted in the 89% long-term cure group. The patients in the "not improved" group are those who had a recurrence and did not have repeat ablation, those with failed repeat ablation and those with failed initial ablation. The clinician, when counseling a patient with an accessory pathway who is a potential candidate for ablation, on the basis of Tables 1 and 4, can say that the chance of initial success is ~90%, that the chance of recurrence is ~10% and that the chance that they will experience long-term relief of symptoms is ~90%, provided that they are willing to participate in the complete program, which includes close clinical follow-up and repeat ablation if appropriate. Furthermore, if they are followed up to >6 months and have no clinical evidence of recurrence, their likelihood of remaining asymptomatic is excellent. However, if there is evidence of a right free wall accessory pathway by ECG, one would quote a somewhat lower likelihood of success and a somewhat higher risk of recurrence on the basis of these data. Finally, these data suggest that procedural success rates, procedural risks and the risk of recurrence in patients aged <12 years are as favorable as in the older age group. Therefore, these data do not suggest that delaying elective ablation procedure solely on the basis of age is justified.

Electrocardiogram and Holter findings. In our series, we identified no serious new arrhythmias after ablation. The minor arrhythmias that were observed unlikely to be related to the ablation procedure. For example, the patient who developed atrial flutter had tricuspid regurgitation because of Ebstein's anomaly of the tricuspid valve, a dilated right atrium and an atrial septal defect for which he underwent surgical closure. In the two patients with frequent premature atrial contractions, the axis of the P waves of the premature atrial beats was superior, raising the possibility that they were slow AV node echo beats related to the original substrate for AV node reentry. Finally, the 2-month old infant with the permanent form of junctional reciprocating tachycardia clearly had ventricular ectopy before the ablation, and the extremely poor ventricular function certainly was a risk factor for ventricular arrhythmia. The decision to treat with amiodarone for a limited period, however, was influenced by the experience of Saul, et al. (6), who reported a sudden death in an infant after radiofrequency catheter ablation (6).

Findings on echocardiography. The results of echocardiography after radiofrequency catheter ablation suggest that it is possible to injure the cardiac valves in children by catheter manipulation or delivery of energy. Minich et al. (24) have reported a significant incidence of aortic insuffi-

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ciency after ablation of left-sided accessory pathways by the retrograde route and have recommended that such pathways be approached by the anterograde route, utilizing transseptal puncture if necessary (24). However, Lesh et al. (25) reported one episode of transient coronary air embolism in an adult patient undergoing ablation of a left-sided pathway using transseptal puncture. The episode was associated with the exchanging of catheters through the Mullins sheath positioned in the left atrium and was clearly due to the introduction of air into the long sheath during the exchange. A recent study by Lesh et al (26) suggests, however, that the overall success rate of the transseptal approach is similar to the retrograde approach, but the procedure is done more rapidly when performed by the transseptal approach. Although we have observed no aortic insufficiency in any of our pediatric patients who underwent radiofrequency ablation by the retrograde route, we remain quite concerned about the possible complications of both the retrograde and the transseptal routes. The lowest risk approach may well be to introduce the catheter via a patent foramen ovale because this avoids the use of long venous sheaths as well as crossing the aortic valve. A patent foramen ovale is much more likely to be present in younger patients (27) and, if present, provides one rationale for recommending radiofrequency ablation at earlier ages.

Risks of radiation exposure. Calkins et al. (28) estimated the increased risk of fatal malignancy due to an average of 1 h of fluoroscopy exposure in their laboratory at 0.1%, assuming an average patient age of 35 years. The average duration of fluoroscopic exposure in our series was similar to that of Calkins et al (28). The risk of this exposure in children, however, would be somewhat greater, because of their somewhat longer life expectancy. In addition, the calculations of Calkins et al. were based on measurements made in their laboratory with adult patients. The estimated absorbed doses in different laboratories in smaller body sizes would most likely be different.

Importance of follow-up studies in cost-benefit analyses. The use of radiofrequency catheter ablation in the management of patients with symptomatic tachyarrhythmias has become widespread in both adult and pediatric age groups (29). The rapid adoption of this technique is certainly due to the excellent success rate of the technique in such patients, as well as to the remarkably low initial complication rate observed by most physicians performing these procedures. Recently, investigators have compared the cost-effectiveness of radiofrequency ablation techniques to the principal alternatives previously available in such patients, namely surgical ablation and long-term antiarrhythmic therapy (9,30–32). In adult patients who would otherwise be considered candidates for surgical ablation, the cost of radiofrequency ablation is dramatically lower than the cost of surgical ablation (9,30). Furthermore, even when patients were considered who would otherwise be offered antiarrhythmic medication, the costs of radiofrequency ablation were still significantly lower than the costs of medical management (31,32). The latter prediction should apply to children with Wolff-Parkinson-White syndrome, and the cost advantage of catheter ablation should be at least as large considering the longer expected life span during which children may incur medical costs. These analyses rely on assumptions that the creation of cardiac lesions using radiofrequency energy will have little or no long-term adverse consequences. If this assumption is incorrect, and long-term cardiac problems develop as a result of these procedures, then the conclusions that radiofrequency ablation is cost-effective could be incorrect. Therefore, before the use of radiofrequency ablation becomes the standard of care for the management of pediatric patients with tachyarrhythmias, it is critically important that careful follow-up studies of patients undergoing these procedures be performed. This report provides some initial data to support these analyses and conclusions, but even longer term follow-up of these patients will certainly be necessary.

Study limitations. The findings of this study are limited in the following areas: 1) Although the follow-up interval in our study is longer than in previously reported pediatric series, this study cannot exclude a risk of very late development of complications, and continued follow-up will be necessary. 2) Patients in this series did not undergo either follow-up coronary angiography or routine follow-up electrophysiologic study unless there was evidence of recurrence or an additional substrate for tachycardia. It is debatable whether the additional risk involved in such procedures is warranted in asymptomatic patients without signs of coronary abnormalities or new arrhythmias on noninvasive studies, and Saul et al. (6) have reported normal coronary angiograms in 14 pediatric patients after catheter ablation. Future studies will address these questions by less invasive techniques, such as exercise testing and cardiac scintigraphy. 3) The group of patients aged <2 years at the time of ablation represents a small subset in which short- and long-term risks may well be different that in the larger pediatric population. Multicenter studies will most likely be necessary to accurately assess these risks. 4) The true risk of malignancy may be difficult or impossible to determine because it is an event that may require ≥20 years to detect, and the sample size necessary to determine an increased risk is likely to be very large.

Conclusions. We found that the short- and intermediate-term risk of complications after radiofrequency ablation in pediatric patients is quite low. Our findings in a carefully followed-up group are very encouraging. Studies to evaluate the long-term risk of radiofrequency catheter ablation in pediatric patients will be critically important when assessing the place of these innovative techniques in the overall management of children with cardiac arrhythmias.

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