CONTEMPORARY REVIEW

Catheter ablation in children and adolescents

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Abstract

Adult and pediatric interventional electrophysiology practices have been diverging for the past 10 years, and so we review current pediatric ablation practice. Radiofrequency ablation (RFA) is safe and efficacious as documented by recent prospective, multi-center pediatric studies. Computer assisted mapping systems used for complex arrhythmias in adult patients have been successfully deployed in selected pediatric substrates. With increased computational power, decreased catheter size, and increased maneuverability, we expect increased use in the pediatric population. Finally, cryoablation has demonstrated efficacy and safety in locations traditionally associated with increased risk when using RFA, particularly around the AV node. As larger, multi-institutional studies are undertaken, the benefits of this technology in pediatric patients will be better defined.

Keywords: Ablation; Cryoablation; Children

Introduction

In the years following the introduction of transcatheter ablative techniques involving radiofrequency (RF) energy in the late 1980s, most adult laboratories have seen a shift in the incidence of patients with arrhythmias presenting for ablation. Patients with Wolff-Parkinson-White (WPW) syndrome and concealed accessory pathways (APs) once were common but now are seen less commonly in adult practices, perhaps because most adult patients with these problems have already been treated by ablation technology. In contrast, pediatric laboratories have not seen this shift. The majority of such patients first present in their teen years, school-age years, or infancy, so they usually still are cared for by pediatric services. In distinction, the current interest in atrial fibrillation in adult invasive electrophysiology programs does not extend to pediatric laboratories because of the very low incidence of this arrhythmia in children and the clear risks inherent to ablation of this substrate. Consequently, adult and pediatric interventional electrophysiology practices have been diverging for the past 10 years, and a review of current pediatric ablation practice is in order.

Because most of the tools for ablation were not designed with the pediatric patient in mind, pediatric electrophysiologists commonly are in the position of modifying their techniques. The smaller size of the pediatric patient certainly is a consideration, as are the anatomic variations encountered in patients with congenital heart disease. Over the past 5 years, the development of multi-institutional ablation registries has allowed, and will continue to allow, improved critical evaluations of techniques in the pediatric population. Mapping systems have been used successfully for ablating substrates in complex congenital heart disease. Finally, new ablation technologies that may offer safer, efficacious ablation in the region of the normal conduction system have been adapted for pediatric use.

RF catheter ablation

Technologic advances in energy sources and the development of smaller catheters have made RF energy application the primary method for ablation of tachycardia substrates in pediatric laboratories. As experience with this technique in pediatric patients has grown, efficacy has improved and complications have decreased.1 Kugler et al1 reviewed the outcomes of patients in the Pediatric Radiofrequency Catheter Ablation Registry who underwent ablation from 1991 to 1995 and from 1996 to 1999 (Table 1). In these two time periods, the failure rate decreased by 50%, the fluoroscopy time decreased by 20%, and the complication rate decreased by 25%.

The safety and efficacy of this technique have been further addressed in systematic fashion by the establishment of the Prospective Assessment after Pediatric Cardiac Ab-
lation (PAPCA) database. This multi-institutional project was implemented as an activity of the Pediatric Electrophysiology Society. Participating centers report all pediatric patients undergoing RF ablation. Reported data include noninvasive studies, imaging studies, and invasive electrophysiologic studies (EPS). Patients who underwent RF ablation for atrioventricular nodal reentrant tachycardia (AVNRT) or AP-mediated tachycardia were prospectively evaluated. A total of 481 patients aged 0 to 16 years were in the prospective cohort. Cohort-eligible registry participants \( (n = 504) \) and not cohort-eligible registry patients \( (n = 1,776) \) were used for comparisons. Overall success rates were high at 95.7%. Patients with a left-sided free-wall pathway had the highest success rate of 97.8%. There were no deaths, and the complication rate was low at approximately 4% for EPS and ablation. The most common complication encountered with EPS was hematoma at the catheter entry site. With ablation, the most common complication was AV nodal block. This was limited to ablation of AVNRT (2.1%) and septal pathways (3.0%). Importantly, there was no difference in complication rate in patients with left-sided APs who had an ablation performed using a transseptal approach vs a retrograde approach.

Avoiding AV nodal block with ablation procedures in patients with smaller cardiac dimensions is technically challenging. A single-institution study of septal AP ablation in pediatric patients demonstrated an incidence of AV block similar to that reported in the PAPCA data. A total of 145 procedures were performed in 127 pediatric patients. The acute success rate was >90% in all pathway locations except for the mouth of the coronary sinus, where the success rate was 88%. Permanent AV block occurred in 4 (3%) of 136 patients who underwent ablation. In these four patients, the pathway was located near the AV node and His bundle in the anteroseptal \( (n = 2) \) or midseptal \( (n = 2) \) position. Of significance, recurrence of pathway function was highest in patients with pathways at these same locations: anteroseptal (14%) and midseptal (12%).

In addition to pathway proximity to the normal conduction system, another variable that could have an effect on the safety and efficacy of RF ablation is the number of APs present in the patient. Weng et al reviewed their institutional experience with ablation of multiple APs in pediatric patients with WPW syndrome. Of 317 consecutive patients with WPW syndrome who underwent EPS and RF ablation, 9% had multiple pathways. Most patients had two pathways \( (n = 22) \) and one patient had four pathways. There were 64 pathways in total. Four of the pathways were fascicular ventricular fibers that did not require treatment. Of the remaining 60 pathways, 55 were successfully ablated and five failed ablation. Patients with multiple pathways had a higher incidence of antidromic tachycardia and shorter AP effective refractory periods compared with patients with WPW syndrome and a single AP. However, in these two groups, the success rates (92% vs 93%) and complication rates (1.7% vs 2.1%) were comparable.

### Table 1

<table>
<thead>
<tr>
<th>Success Rates for Tachycardia Mechanism/Pathway</th>
<th>Early Era</th>
<th>Late Era</th>
<th>Early Era vs Late Era</th>
<th>P Value (Early vs Late)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left free wall</td>
<td>1,397/1,491 (94%)</td>
<td>78/86 (91%)</td>
<td>1,319/1,405 (94%)</td>
<td>0.001</td>
</tr>
<tr>
<td>Right free wall</td>
<td>564/663 (85%)</td>
<td>37/44 (84%)</td>
<td>527/619 (85%)</td>
<td>0.001</td>
</tr>
<tr>
<td>Anterior septal</td>
<td>349/419 (83%)</td>
<td>39/43 (91%)</td>
<td>310/376 (90%)</td>
<td>0.26</td>
</tr>
<tr>
<td>Posterior septal</td>
<td>300/374 (80%)</td>
<td>21/24 (92%)</td>
<td>279/350 (81%)</td>
<td>0.38</td>
</tr>
<tr>
<td>All accessory pathways</td>
<td>2,810/3,147 (89%)</td>
<td>215/239 (90%)</td>
<td>2,595/2,908 (90%)</td>
<td>0.20</td>
</tr>
<tr>
<td>AV nodal reentry</td>
<td>795/838 (95%)</td>
<td>17/18 (94%)</td>
<td>778/820 (95%)</td>
<td>0.43</td>
</tr>
<tr>
<td>Atrial ectopic tachycardia</td>
<td>185/208 (89%)</td>
<td>22/24 (92%)</td>
<td>163/184 (89%)</td>
<td>0.47</td>
</tr>
<tr>
<td>Total</td>
<td>3,790/4,193 (90%)</td>
<td>254/281 (90%)</td>
<td>3,536/3,912 (90%)</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Other complications of RF ablation occur much less frequently but have been reported. Safety is a primary concern during catheterization, especially in children. Techniques to minimize radiation exposure, to better identify anatomic markers in structurally abnormal hearts, and to minimize the known risks of RF ablation have been investigated. In young patients with septal tachycardias in whom the normal conduction system is at risk, techniques including intubation and apnea during RF application, coronary sinus pacing to observe AV conduction, power output titration with temperature control, not ablating during tachycardia, and mapping the location of the optimal His-bundle signal have been advocated. Of 217 septal substrates ablated, normal AV conduction was seen in all patients. Success and recurrence rates were comparable to those reported in the PAPCA studies. Although an understanding of the relative importance of such measures is difficult, the authors note that catheter tip stability is paramount to safe, efficacious ablation of septal substrates.

Patients with congenital heart disease are commonly encountered in the practice of pediatric electrophysiology. The usual anatomic landmarks used to perform ablations may be altered or absent. In patients with congenital heart disease who have undergone an unsuccessful ablation of right-sided APs, a microcatheter was introduced in the right coronary artery to provide better localization of the AV groove. In this group of patients, APs were successfully ablated without complications.

With the establishment of RF ablation as a safe and effective method for treatment of symptomatic patients with tachycardia, attention has turned to patients who are asymptomatic but are known to have substrates for potentially life-threatening arrhythmias. One such group is patients with asymptomatic WPW syndrome. The suspected mode of death in these patients is conduction of a rapid atrial arrhythmia down an AP to the ventricle, thereby inducing ventricular fibrillation. Ablation of the AP(s) ameliorates this risk of sudden cardiac death. The criteria for sudden death risk stratification used for adults with WPW syndrome may not be applicable to children, making the decision to perform invasive testing and ablation less clear. To clarify the current practice of pediatric electrophysiologists with respect to this issue, Campbell et al surveyed pediatric electrophysiologists who had submitted data to the Pediatric Radiofrequency Ablation Registry. In the group who responded, 37 of 43 had more than 5 years of experience performing RF ablation, and 30 of 43 had performed more than 200 ablations. Of the 43 responding pediatric electrophysiologists, 36 used invasive testing to risk stratify patients with WPW syndrome and used the results to select patients for RF ablation.

### Advanced mapping systems

The production of relatively inexpensive computer systems that have a large storage capacity and the ability to process signals rapidly coupled with a small physical size have allowed the development of mapping systems that allow electrophysiologists to reliably localize intracardiac catheter positions with decreased use of fluoroscopy. In children, who have a life expectancy of 60 to 80 years after ablation, the possibility of decreasing exposure to ionizing radiation is particularly appealing. One such system is the CARTO system (Biosense Webster, Diamond Bar, CA, USA). The system uses a magnet mounted under the catheterization table coupled with a proprietary catheter placed in the intracardiac chamber of interest. While the patient is in a stable rhythm, the catheter is manipulated under fluoroscopy while the endocardial surface is mapped. The magnet under the table locates the catheter tip in three-dimensional space when an endocardial signal is measured, and the system stores the spatial and electrical information. The computer then constructs a virtual three-dimensional electroanatomic map of the chamber. The catheter tip location within the mapped space is displayed on the computer screen, allowing catheter manipulation without fluoroscopy. The displayed map can be rapidly switched among a voltage map, a wavefront propagation map, and an isochronal activation map.

In pediatric patients, the CARTO system has been used to ablate tachycardia substrates in those who have undergone surgical repair of congenital heart disease. A common rhythm encountered in patients with repaired congenital heart disease is intra-atrial reentrant tachycardia (IART). The actual tachycardia circuit depends on the specific postoperative anatomy of the right atrium. Ablation of these circuits can be accomplished by creating a complete line of block between two boundary lines of the circuit, such as valve annuli, crista terminalis, or scar lines. Electroanatomic mapping has been used to delineate conductive tissue within these circuits and the circuit boundaries in order to effectively ablate the tachycardia substrate.
ure is a particularly challenging arrhythmia for management with ablation. In these patients, tissue that is involved in the circuit may be on either side of the baffle, requiring access to both the systemic and pulmonary venous atria to ablate the circuit. Reviewing their experience with combined electroanatomic and entrainment mapping of IART circuits in postoperative Mustard patients, Zrenner et al noted that 10 of 13 circuits involved the tissue between the inferior vena cava–right atrial junction and the tricuspid annulus. As a result of the surgical construction of the baffle, tissue in the circuit was present on both sides of the baffle in more than half of their patients. Their overall success rate of 86% was facilitated by improved ability to customize the ablation afforded by electroanatomic mapping in conjunction with entrainment mapping of the tachycardia.

The ability to manipulate the catheter in a smaller cardiac chamber can limit the usefulness of the CARTO system in pediatric patients. Because the system requires multiple sample points to create the endocardial map, the addition or subtraction of a single point can significantly change the map created. In addition, obtaining points can be time consuming. Strategies to conserve time and create an accurate endocardial map have been used successfully in the setting of ectopic atrial foci. de Groot et al evaluated the use of unipolar vs bipolar signal recordings with the CARTO system. In order to delineate scar tissue, and hence the boundaries for IART circuits, bipolar recordings were necessary; unipolar recordings did not allow sufficient definition of the areas of scar. Despite these issues, Drago et al performed successful ablations of right free-wall pathways in children using the CARTO system excluding the use of fluoroscopy.

The EnSite system (Endocardial Solutions, St. Paul, MN, USA) is a noncontact mapping system that uses a 64-electrode array mounted on a balloon catheter with a 9Fr shaft. The system can be deployed in a cardiac chamber and simultaneous recording of intracavitary electrograms performed. The chamber is delineated with a roving catheter that emits a locator signal. By devising and solving inverse solutions to Laplace’s equation, 3,000 virtual electrograms that emits a locator signal. By devising and solving inverse solutions to Laplace’s equation, 3,000 virtual electrograms can be calculated. They then are displayed on a computer-generated image of the endocardium produced from the information from the locator catheter.

Using this system, Paul et al were able to ablate a right ventricular outflow tract tachycardia in an 8-year-old, 40-kg girl. This case illustrates some advantages and disadvantages of use of the EnSite system in pediatric patients. An advantage of the EnSite system is that it allows the mapping of focal tachycardias, such as ventricular tachycardias, which may not be hemodynamically tolerated, especially while the patient under anesthesia. However, to actually perform the ablation, the balloon must be partially deflated to allow placement of the ablation catheter. As with many tools and techniques adapted for pediatric use, the size of the equipment relative to the size of the patient is of prime concern and may become a limiting factor. Although this ablation was successful, the system may not have been as useful in a smaller patient. In addition, the balloon catheter has a 9Fr shaft, which is easily placed in an adult but is not so easily placed in the smaller venous system of a child with other catheters in place.

IART has been ablated using the EnSite system. In patients who developed IART after surgery for congenital heart disease, Paul et al were able to characterize circuits and anatomic landmarks such as atriotomy scars and valve annuli in patients who had undergone a Fontan operation for single-ventricle repair or atrial switch procedure for repair of transposition of the great arteries. They were able to target an area for RF ablation in 13 of 14 patients. In one patient who had a Fontan, a closed-loop circuit was not identified in the systemic venous atrium and was presumed to be in the left atrium. In 12 patients, linear lesions terminated the tachycardia. The complete line of block between two anatomic boundaries was well delineated with the EnSite system. Kriebel et al further studied 13 of their patients who had undergone an atrial switch procedure for transposition of the great arteries. The EnSite system was used in five of these patients; conventional mapping was used in the other eight patients. In all five patients mapped with the EnSite system, the tachycardia was successfully ablated. In the eight patients who have undergone conventional mapping, 12 of 13 circuits were successfully ablated. As in the first study, a complete line of block was easily demonstrated. Fluoroscopy time in the EnSite group was similar to that in the conventional group (19 ± 9.6 min vs 22 ± 13.2 min). Although the difference did not reach statistical significance, the procedural time was 1.5 hours longer in the EnSite group than in the conventional group (252 ± 93.8 min vs 171 ± 52.2 min).

Cryoablation

A system that allows the performance of endocardial ablation using subfreezing temperatures has been developed by CryoCath (CryoCath Technologies Inc., Montreal, Canada). Instead of using RF energy to cause tissue destruction by heating, cryoablation uses circulating nitrous oxide through the catheter tip to cool the tissue in contact with the tip. The system can be used in a cryomapping mode whereby the tip is cooled to −30° to −35°C. At that temperature, the conduction properties of the contacted tissue are reversibly altered (Figure 1). If an undesirable effect is seen, such as prolonged AV conduction indicating potential damage to the normal conducting system, it can be reversed by stopping the refrigerant flow and allowing the catheter tip to warm (Figure 2). If no undesirable effect is seen at mapping temperatures, the temperature can be decreased to ablation temperatures of −75°C, producing a permanent ablation lesion.

The safety margin afforded by reversibility of the lesion at higher temperatures has been demonstrated. In children under-

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going ablation of tachycardia substrates high in the conduction system, transient AV block was seen in 8 of 31 patients. The block immediately reversed with restoration of normal AV conduction upon discontinuation of energy application.32 Gaita et al33 reported their experience with cryoablation of permanent junctional reciprocating tachycardia, with the AP in the posterior to mid septum. Using only cryoablation, they successfully treated all four of their patients. They also safely ablated in the middle cardiac vein and coronary sinus orifice, two locations that are associated with higher RF complication rates. These authors highlighted another potentially useful feature of cryoablation. Patients experience much less discomfort with application of cryoablation compared with RF energy, which may allow significantly less anesthesia use in selected patients.

In addition to the safety margin afforded as a result of the reversibility of cryolesions, further safety may be afforded by another feature of cryoablation. Once mapping temperatures

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**Figure 1**  Patient with Wolff-Parkinson-White syndrome and an anteroseptal accessory pathway. With application of cryoablation energy, initially loss of preexcitation with preservation of normal atrioventricular conduction is seen. Abl d = ablation catheter, distal electrode pair; Abl p = ablation catheter, proximal electrode pair; CS = coronary sinus; RVa = right ventricular apex; STIM = pacing stimulus channel.

**Figure 2**  Same patient as shown in Figure 1. With continued application of cryoablation energy, 2:1 atrioventricular conduction of sinus rhythm suddenly develops. Energy delivery is immediately terminated. By the end of the tracing, 1:1 conduction returns. Abl d = ablation catheter, distal electrode pair; Abl p = ablation catheter; CS = coronary sinus; RVa = right ventricular apex; STIM = pacing stimulus channel.
have been reached, the catheter tip becomes adherent to the endocardium, producing an extremely stable catheter position. The combination of these features has allowed the safe ablation of tachycardia substrates located in the region of the normal conduction system. The report of the experience with cryoablation in Charleston, South Carolina, noted that two of the patients who were successfully ablated had a potential recorded at the ablation site. Additional reports of safe ablation of substrates located near the AV junction have been published. Twenty-six pediatric patients (14 with AVNRT, 10 WPW syndrome, and 2 reentrant supraventricular tachycardia due to a concealed AP) were ablated without adverse events attributable to cryoablation.

The safety and efficacy of cryoablation were evaluated in the largest published pediatric series to date from an international registry and included 64 patients from 14 participating centers. Thirty patients were diagnosed with AVNRT, 31 patients had AVRT, 3 had ventricular tachycardia, and 2 had atrial tachycardia. Two patients had more than one arrhythmia substrate. Acute success was achieved in 69% of these patients, with the highest success rates (83%) in patients diagnosed with AVNRT. No adverse events were reported. RF was used successfully in all four patients with AVNRT and in one patient with an anterosepetal AP in whom cryotherapy failed. However, following acute cryoablation failure, RF also failed in 57% of patients with other septal APs, in one patient with VT, and two patients with atrial ectopic tachycardia, indicating that reasons for ablation failure in some of these substrates may not be attributable to cryoablation.

At a single institution, 62% of pediatric patients with structurally normal hearts who had acute success with RF ablation of supraventricular tachycardia remained free of tachycardia with a follow-up of at least 10 years. The long-term success of cryoablation and the predictors of success remain unknown. In a study of cryoablation for AVNRT at four institutions, Kirsh et al. found an acute success rate of 93% without any permanent AV block. Over a 6-month average follow-up, 6 (9%) of the 64 patients who had an initially successful ablation had recurrence of tachycardia. No predictor of recurrence, other than lesion applications <4 minutes, could be elucidated. As expected with any new procedure, there was a relationship between procedural volume and acute success rate.

In our program, nearly 100 pediatric patients have undergone cryoablation over a 18-month period. Of this group, most had AVNRT. All but two had an initially successful cryoablation. There have been no complications, specifically, no permanent AV block. Approximately 5% have experienced a clinical recurrence. In our experience, AVNRT can be ablated with cryoablation with results similar to RF ablation in terms of acute success, with essentially no risk of permanent AV block. Although in general the success with AVRT has not been as high as with AVNRT, cryoablation has allowed us to address tachycardia substrates in locations associated with increased risk with use of RF ablation.

**Conclusion**

RF ablation has been established as safe and efficacious for pediatric patients through both single-institution and prospective, multicenter reports. The development of computer-assisted mapping systems for treatment of complex arrhythmias in adult patients has been successfully used in selected pediatric patients. As refinements in these technologies, such as increased computational power, decreased catheter size, and increased maneuverability, are made, increased use in the pediatric population likely will result. Finally, cryoablation has demonstrated efficacy and safety in locations traditionally associated with increased risk with use of RF ablation, particularly around the AV node. As larger, multi-institutional studies are undertaken, the benefits of this technology in pediatric patients will be better defined.

**References**


