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ORIGINAL RESEARCH

Radiofrequency Catheter Ablation for Pediatric Atrioventricular Nodal Reentrant Tachycardia: Impact of Age on Procedural Methods and Durable Success

Edward T. O'Leary, MD; Jamie Harris, MSN, APRN, CPNP; Kimberlee Gauvreau, ScD; Courtney Gentry, BSN; Audrey Dionne, MD; Dominic J. Abrams, MD; Mark E. Alexander, MD; Vassilios J. Bezzerides, MD, PhD; Elizabeth S. DeWitt, MD; John K. Triedman, MD; Edward P. Walsh, MD; Douglas Y. Mah, MD

BACKGROUND: Catheter-based slow-pathway modification (SPM) is the treatment of choice for symptomatic atrioventricular nodal reentrant tachycardia (AVNRT). We sought to investigate the interactions between patient age and procedural outcomes in pediatric patients undergoing catheter-based SPM for AVNRT.

METHODS AND RESULTS: A retrospective cohort study was performed, including consecutive patients undergoing acutely successful SPM for AVNRT from 2008 to 2017. Those with congenital heart disease, cardiomyopathy, and accessory pathways were excluded. Patients were stratified by age quartile at time of SPM. The primary outcome was AVNRT recurrence. A total of 512 patients underwent successful SPM for AVNRT. Age quartile 1 had 129 patients with a median age and weight of 8.9 years and 30.6 kg, respectively. Radiofrequency energy was used in 98% of cases. Follow-up was available in 447 (87%) patients with a median duration of 0.8 years (interquartile range, 0.2–2.5 years). AVNRT recurred in 22 patients. Multivariable Cox proportional hazard modeling identified atypical AVNRT (hazard ratio [HR], 5.83; 95% CI, 2.01–16.96; *P*=0.001), dual atrioventricular nodal only (HR, 4.09; 95% CI, 1.39–12.02; *P*=0.011), total radiofrequency lesions (HR, 1.06 per lesion; 95% CI, 1.01–1.12; *P*=0.032), and the use of a long sheath (HR, 3.52; 95% CI, 1.23–10.03; *P*=0.010) as predictors of AVNRT recurrence; quartile 1 patients were not at higher risk of recurrence (HR, 0.45; 95% CI, 0.10–1.97; *P*=0.29). Complete heart block requiring permanent pacing occurred in one quartile 2 patient at 14.9 years of age.

CONCLUSIONS: Pediatric AVNRT can be treated with radiofrequency-SPM with high procedural efficacy and minimal risk of complications, including heart block. Atypical AVNRT and dual atrioventricular nodal physiology without inducible tachycardia remain challenging substrates.

Key Words: atrioventricular nodal reentrant tachycardia ■ catheter ablation ■ pediatric ■ supraventricular tachycardia

Catheter-based slow pathway modification (SPM) using radiofrequency or cryothermal energy is the treatment of choice for symptomatic children and adults with atrioventricular nodal reentrant tachycardia (AVNRT) who are intolerant or refractory to antiarrhythmic drug therapy.[1–4] Procedural efficacy outcomes using either radiofrequency or cryothermal energy in children and adolescents are excellent, with reported short-term success rates of 98% to 100%.[5,6] The question of whether radiofrequency or cryothermal ablation (CRYO) is the optimal energy source has been debated and retrospectively investigated,

Correspondence to: Douglas Y. Mah, MD, Arrhythmia Service, Department of Cardiology, Boston Children's Hospital, 300 Longwood Ave, Boston, MA 02115. E-mail: douglas.mah@cardio.chboston.org

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CLINICAL PERSPECTIVE

What Is New?

- Catheter ablation is an accepted treatment for atrioventricular nodal reentrant tachycardia in children, although concerns about the safety of radiofrequency ablative energy in smaller hearts remain.
- We demonstrate that radiofrequency catheter ablation of atrioventricular nodal reentrant tachycardia can be performed with high efficacy and safety, even in the smallest of patients.

What Are the Clinical Implications?

- Our data emphasize the ongoing need to improve outcomes in patients with atypical forms of atrioventricular nodal reentrant tachycardia and those with isolated dual atrioventricular nodal physiology without inducible atrioventricular nodal reentrant tachycardia.

Nonstandard Abbreviations and Acronyms

AVB	atrioventricular block
AVNRT	atrioventricular nodal reentrant tachycardia
CRYO	cryothermal ablation
CS	coronary sinus
DAVN	dual atrioventricular nodal
EAM	electroanatomic mapping
EPS	electrophysiologic study
Q1	quartile 1
Q2	quartile 2
Q4	quartile 4
SPM	slow pathway modification
SVT	supraventricular tachycardia

with radiofrequency having more durable long-term efficacy at the expense of a ≈1% risk of atrioventricular block (AVB) requiring permanent pacemaker implantation. CRYO reduces this risk of AVB albeit with increased risk of AVNRT recurrence.[7,8] It is unclear if long-term outcomes are negatively impacted by using a radiofrequency-based strategy in the youngest of patients with AVNRT, where operators still must use adult-sized catheters despite the anatomically smaller triangle of Koch. Our aim was thus to explore the interaction between patient age and procedural safety and efficacy outcomes during radiofrequency-SPM to determine whether similar ablation strategies should be performed across all age groups.

METHODS

The data that support the findings of this study are available from the corresponding author on reasonable request.

Patients

Study approval was obtained from the Boston Children's Hospital Committee on Clinical Investigation and Institutional Review Board. A retrospective cohort study was performed, including consecutive patients who underwent SPM for AVNRT in our electrophysiology laboratory from 2008 to 2017. Patients were identified through a search of our division's case log database, with demographic and clinical data extracted from the electronic medical record. Patients with congenital heart disease and cardiomyopathy were excluded from the study. Those who underwent simultaneous ablation of one or multiple accessory pathways were excluded from the analysis. Patients with acutely unsuccessful ablations for AVNRT were excluded from study analysis, as recurrence was the primary outcome of interest.

Procedure

All procedures were performed under general anesthesia with elective endotracheal intubation. Baseline programmed electrical stimulation testing was performed to elucidate supraventricular tachycardia (SVT) mechanism with catheters placed in the high right atrium, coronary sinus (CS), right ventricle, and at the His bundle. Definitions of dual atrioventricular nodal (DAVN) physiology, typical AVNRT, and atypical AVNRT were chosen, as previously published.[9,10] DAVN physiology was defined as the presence of any of the following: (1) discrete A2H2 jump >50 ms for a given 10-ms decrease in the A1A2 interval; (2) A2H2 prolongation >300 ms independent of a prior A2H2 jump; (3) typical slow-fast atrioventricular nodal echo beat; and (4) sustained slow pathway conduction seen during rapid atrial pacing, defined as a stimulation-to-QRS interval greater than the paced cycle length. SVT was characterized as typical AVNRT if possessing all of the following: (1) His-atrial <70 ms; (2) atrio-His/His-atrial ratio >1; and (3) His-refractory ventricular premature beats failed to advance or delay atrial timing. Atypical AVNRT was defined by a His-atrial >70 ms with delayed retrograde atrial activation timing and failure of His-refractory ventricular premature beats to affect atrial timing. For statistical analysis purposes, atypical AVNRT included both fast-slow and slow-slow variants.

When the diagnosis of AVNRT was confirmed, the expected location of the rightward inferior slow pathway (SP) extension in the triangle of Koch, between the posteroseptal tricuspid valve annulus and the mouth of the CS, was mapped typically in sinus rhythm. An electroanatomic mapping (EAM) system (CARTO; Biosense Webster, Diamond Bar, CA) became available to our laboratory in 2008 and was used thereafter almost exclusively. Nonirrigated radiofrequency ablation was targeted at atrioventricular groove sites with a dominant ventricular electrogram and ideally with a "bump-and-spike" atrial electrogram signifying a near-field SP potential. Mapping and ablation were performed initially using the ablation catheter delivered through a standard short venous sheath. In cases where this method provided insufficient catheter stability or reach, long introducer sheaths were used. Test radiofrequency applications at target sites were continued for up to 20 seconds in search of an accelerated junctional rhythm as feedback for effective SPM. If junctional acceleration was observed, atrial overdrive pacing was commenced to monitor fast pathway integrity, and applications were continued for up to 60 seconds. Applications were immediately terminated on observing either rapid junctional acceleration (cycle length <400 ms) or AH prolongation on the His bundle recording channel during atrial pacing. System impedance, as measured from the ablation catheter, was monitored for evidence of effective tissue heating (10–15 Ω decrease), inadvertent catheter slippage into the CS, and coagulum formation (steam pop). Additional consolidation lesions at the site of success were often performed at the discretion of the operator.

Mapping was performed progressively higher in the triangle of Koch if no junctional acceleration was observed during initial test applications, with the superior border of the lower one third of the triangle defined as the roof of the CS. Coronary sinus angiography was frequently performed when ablation encroached on the CS roof. Mapping and ablation were performed in the mouth and proximal CS in cases where AVNRT was thought to use a leftward inferior SP extension. Transseptal access was occasionally performed to investigate and ablate left atrial SP extensions. The decision to switch from radiofrequency to CRYO was at the discretion of the operator, but typically was not done unless above the CS roof.

SPM was considered acutely successful if: (1) AVNRT was no longer inducible in those patients who were inducible during baseline testing; or (2) evidence of SPM was achieved in those without inducible AVNRT (ie, elimination of atrioventricular nodal echo beats, A2H2 jumps, or sustained slow pathway conduction). In those who had inducible AVNRT at baseline and were noninducible following SPM, the presence of residual SP conduction and/or single atrioventricular nodal echo beats were acceptable end points. Radiofrequency success was defined as: (1) demonstration of successful SPM following a radiofrequency application, with or without CRYO consolidation; or (2) radiofrequency consolidation at the site of a successful CRYO-SPM. Cryothermal success was defined as a successful CRYO-SPM without further radiofrequency consolidations at the site of success.

Patients primarily followed up at our institution were seen approximately at 1 month and 1 year following ablation. Routine ambulatory monitoring was not performed in asymptomatic patients. Patients from outside local or regional centers had follow-up at the discretion of their primary cardiologist.

Statistical Analysis

The primary outcome variable was AVNRT recurrence, defined as documented supraventricular tachycardia on a 12-lead ECG or ambulatory monitor, and/or reinducible AVNRT during repeated electrophysiologic study (EPS). The study cohort was stratified by age quartiles, and the youngest quartile (quartile 1 [Q1]) was compared with the older quartiles (quartile 2 [Q2]–quartile 4 [Q4]) to explore the primary study aim. Additional predictor variables included AVNRT subtype (typical AVNRT, atypical AVNRT, or isolated DAVN without inducible AVNRT). Additional covariates of interest included weight at EPS, lesion success type (radiofrequency versus CRYO), radiofrequency and CRYO time, ablation above the CS roof, intraprocedural use of a long sheath, and residual SP conduction following SPM. Fluoroscopic and total procedural times were recorded.

Continuous variables are summarized using medians with either range or interquartile range (IQR), unless otherwise explicitly stated. Categorical variables are summarized using frequencies and percentages. Because interest focused on a comparison of the youngest patients with those who were older, age was dichotomized at the 25th percentile. Additional analyses explored age as a continuous variable, and parameterized using a restricted cubic spline to allow for a nonlinear relationship with recurrent AVNRT. Comparisons of patient and procedural characteristics for the lowest quartile of age versus the other 3 quartiles combined were performed using the Wilcoxon rank sum test and Fisher exact test. Comparisons across the 3 AVNRT subtypes were performed using Kruskal-Wallis and Fisher exact tests. For patients with follow-up after initial ablation, freedom from recurrent AVNRT was estimated using the Kaplan-Meier method. Cox proportional hazards regression was used to investigate relationships between patient and procedural characteristics and time to recurrent AVNRT; patients who did not experience the outcome event were censored at the time of last follow-up. The proportional hazards assumption was evaluated using scaled Shoenfield residuals. Hazard ratios (HRs) were estimated with 95% CIs. A multivariable model was constructed, excluding patient age. Variables significant at the 0.20 level in unadjusted analysis were considered for inclusion in the multivariable model; $P<0.05$ was required for retention in the final model. To examine the effect of age on time to AVNRT recurrence, adjusted for other factors associated with the outcome, lowest age quartile was then entered into the model. Models were also fitted by entering continuous age and age as a restricted cubic spline. Interactions between lowest age quartile and other risk factors were explored.

RESULTS

Patients

Interrogation of our case log database identified 517 patients who had undergone SPM for AVNRT at our institution during the defined study period. Five patients had acutely unsuccessful SPM for AVNRT and were excluded. Thus, a total of 512 patients with structurally normal hearts underwent acutely successful SPM over the 10-year study period and were included for analysis. The median age and weight of the entire study cohort was 15.0 years (IQR, 12.3–16.7 years) and 55.9 kg (IQR, 43.6–66.0 kg), respectively. Median ages and distributions among the age quartiles are displayed in Figure 1, along with the corresponding weight quartiles for reference. Patient demographic data comparing Q1 with Q2 to Q4 are shown in Table 1. The median age in Q1 was 8.9 years (range, 2.2–12.3 years); and in Q2 to Q4, it was 15.9 years (range, 12.3–29.5 years). Patients in Q1 had significantly lower median weights than those in Q2 to Q4 (30.6 versus 60.1 kg; $P<0.001$). Female sex predominated in the Q2 to Q4 cohort (61% versus 48%; $P=0.01$). All Q1 patients were undergoing their first ablation procedure compared with 96% of Q2 to Q4 patients ($P=0.009$).

Index Procedural Findings and Outcomes

Procedural data comparing Q1 with Q2 to Q4 are shown in Table 1. The frequencies of each AVNRT subtype were similar among both cohorts, with typical AVNRT being most observed. The younger Q1 cohort had a faster AVNRT tachycardia cycle length during EPS than the older Q2 to Q4 cohort (281 versus 305 ms; $P<0.001$). A long sheath was used less often in Q1 than Q2 to Q4 (31% versus 50%; $P<0.001$), although ablation above the CS roof was performed with similar frequency (21% in Q1 versus 23% in Q2 to Q4; $P=0.72$). Transseptal access and radiofrequency ablation targeting left SP extensions along the left posteroseptal or posterior mitral valve annulus were performed in 7 patients (1 patient in Q1 and 6 patients in Q2 to Q4).

Radiofrequency ablation was performed in 98% of Q1 and 99% of Q2 to Q4 ($P=0.42$). Total radiofrequency time was shorter in Q1 (212 seconds) versus

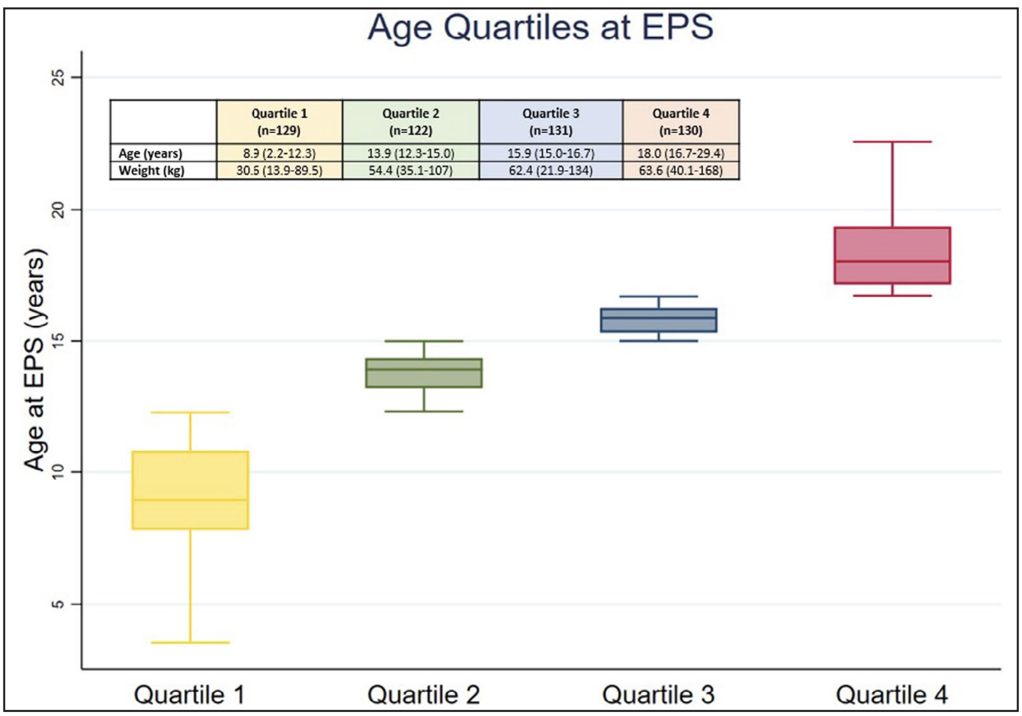

Figure 1. Box plots of age quartiles.
Table above shows medians (range) of each age and weight quartile. A quartile 4 age outlier of 29.4 kg was removed from the box plot. EPS indicates electrophysiologic study.

Table 1. Demographics and Procedural Data by Age Quartile

Variable	Age quartile 1 (n=129)	Age quartiles 2–4 (n=383)	*P* value
Age, y	8.9 (7.8–10.8)	15.9 (14.4–17.2)	…
Weight, kg	30.6 (26.1–40.2)	60.1 (53–70)	<0.001
Female sex	62 (48)	235 (61)	0.010
Pre-EPS documented SVT	129 (100)	366 (96)	0.009
Pre-EPS AAD	117 (91)	329 (86)	0.22
First ablation	129 (100)	366 (96)	0.009
EAM used	95 (74)	298 (78)	0.33
AVNRT subtype			0.12
Typical	110 (85)	302 (79)	
Atypical	5 (4)	36 (9)	
DAVN only	14 (11)	45 (12)	
Any inducible AVNRT	115 (89)	337 (88)	0.87
Tachycardia cycle length, ms	281 (260–316)	305 (270–360)	<0.001
Radiofrequency used	126 (98)	378 (99)	0.42
Test radiofrequency lesions	4 (1–7)	4 (2–7)	0.26
Consolidation radiofrequency lesions	3 (2–5)	3 (2–5)	0.01
Total radiofrequency lesions	7 (4–11)	8 (5–13)	0.05
Total radiofrequency time, s	212 (131.5–355)	269 (176–395)	0.005
Time per radiofrequency lesion, s	31.9 (25.6–40.6)	33 (27–41.3)	0.28
Cryoablation used	14 (11)	30 (8)	0.28
Test CRYO lesions	1 (1–4)	1 (0–4)	0.31
Consolidation CRYO lesions	2 (2–4)	4 (2–6)	0.14
Total CRYO lesions	5 (3–9)	6 (3–10)	0.66
Total CRYO time, s	836 (588–956)	800 (651–1430)	0.65
Time per CRYO lesion, s	117.6 (90–227.8)	154.7 (111.6–216)	0.76
Radiofrequency success (vs CRYO success)	120 (93)	358 (93)	0.84
Long sheath used	40 (31)	192 (50)	<0.001
Ablation above MOCS	27 (21)	88 (23)	0.72
Residual SP conduction	34 (26)	120 (31)	0.32
Fluoroscopy time, min	3 (0.6–11.7)	3 (1–11.1)	0.52
Fluoroscopy dose, mGy	17 (2–83)	30.5 (5–214)	<0.001
Procedural time, min	124 (103–148)	134 (112–159)	0.004

Values are number (percentage) and median (interquartile range). AAD indicates antiarrhythmic drug; AVNRT, atrioventricular nodal reentrant tachycardia; CRYO, cryothermal ablation; DAVN, dual atrioventricular nodal; EAM, electroanatomic mapping; EPS, electrophysiologic study; MOCS, mouth of coronary sinus; SP, slow pathway; and SVT, supraventricular tachycardia.

Q2 to Q4 (269 seconds; *P*=0.005). A small but statistically significant reduction in the use of radiofrequency consolidation lesions was seen in Q1 versus Q2 to Q4 (Table S1). There were no significant differences in test radiofrequency lesions, total radiofrequency lesions, and time per radiofrequency lesions between groups. CRYO was used infrequently in both groups (11% in Q1 versus 8% in Q2 to Q4; *P*=0.28). No significant differences were observed between Q1 and Q2 to Q4 in CRYO lesion number or CRYO time. Short-term radiofrequency success was achieved in 93% of both cohorts, with short-term CRYO success seen in the remaining 7% of each group. Residual SP conduction (meeting the definition of short-term success) was observed equally between Q1 and Q2 to Q4 patients (26% versus 31%; *P*=0.32).

No difference in EAM use (74% versus 78%; *P*=0.33) or median fluoroscopy time (3 versus 3 minutes; *P*=0.52) was observed between Q1 and Q2 to Q4 cohorts, respectively. The younger Q1 cohort received a lower median fluoroscopy dose (17 versus 30.5 mGy; *P*<0.001) and had a shorter median procedural time (124 versus 134 minutes; *P*=0.004) compared with Q2 to Q4 patients. Median fluoroscopy dose was highest in atypical AVNRT (84.5 mGy) compared with DAVN (50 mGy) and typical AVNRT (22 mGy; *P*=0.002). A trend toward increased median fluoroscopy time was similarly observed in atypical

Table 2. Demographics and Procedural Data by AVNRT Subtype

Variable	Typical AVNRT (n=412)	Atypical AVNRT (n=41)	DAVN (n=59)	*P* value
Age, y	15 (12–16.7)	15.7 (14.4–17.1)	14.2 (12.4–16.8)	0.14
Quartile 1	110 (27)	5 (12)	14 (24)	0.12
Weight, kg	55.3 (43–65.2)	65 (54.4–71.3)	55 (39.9–62.6)	0.006
Female sex	240 (58)	26 (63)	31 (53)	0.55
Pre-EPS documented SVT	399 (97)	40 (98)	56 (95)	0.65
Pre-EPS AAD	363 (88)	33 (80)	50 (85)	0.24
First ablation	401 (97)	38 (93)	56 (95)	0.12
EAM used	316 (77)	29 (71)	48 (81)	0.46
Tachycardia cycle length, ms	300 (270–350)	310 (270–373)	…	0.36
Radiofrequency used	407 (99)	40 (98)	57 (97)	0.24
Test radiofrequency lesions	4 (2–8)	4 (2–7)	3 (2–6)	0.33
Consolidation radiofrequency lesions	3 (2–5)	3 (2–5)	3 (2–5)	0.86
Total radiofrequency lesions	8 (5–13)	8.5 (5–13.5)	7 (4–12)	0.38
Total radiofrequency time, s	255 (163.5–386.5)	263 (172.5–411)	210 (132–389)	0.73
Time per radiofrequency lesion, s	32.8 (26.8–41.1)	31.8 (25.7–39.8)	33 (26.1–42.5)	0.70
Cryoablation used	31 (7.5)	6 (15)	7 (12)	0.17
Test CRYO lesions	1 (0–4)	1 (1–2)	1 (0–4)	0.69
Consolidation CRYO lesions	4 (3–6)	2 (1–6)	2 (1–3)	0.24
Total CRYO lesions	6 (4–10)	5.5 (3–13)	4 (2–6)	0.17
Total CRYO time, s	960 (658–1533)	708.5 (298–1048)	651 (479–781)	0.06
Time per CRYO lesion, s	142.3 (108.7–227.8)	127.3 (29.8–244.3)	162.8 (111.6–239.5)	0.82
Radiofrequency success (vs CRYO success)	387 (94)	38 (93)	53 (90)	0.39
Long sheath used	191 (46)	20 (49)	21 (36)	0.27
Ablation above MOCS	94 (23)	6 (15)	15 (25)	0.41
Residual SP conduction	130 (32)	7 (17)	17 (29)	0.15
Fluoroscopy time, min	2.8 (0.9–10.9)	6 (1.8–18.1)	5.3 (0.8–10.8)	0.09
Fluoroscopy dose, mGy	22 (4–148)	84.5 (17.5–332)	50 (11–117)	0.002
Procedural time, min	127 (107–152)	159 (135–195)	138 (120–164)	<0.001

Values are number (percentage) and median (interquartile range). AAD indicates antiarrhythmic drug; AVNRT, atrioventricular nodal reentrant tachycardia; CRYO, cryothermal ablation; DAVN, dual atrioventricular nodal; EAM, electroanatomic mapping; EPS, electrophysiologic study; MOCS, mouth of coronary sinus; SP, slow pathway; and SVT, supraventricular tachycardia.

AVNRT (6 minutes) and DAVN (5.3 minutes) versus typical AVNRT (2.8 minutes; *P*=0.09). Similarly, atypical AVNRT (159 minutes) had longer median procedural times than DAVN (138 minutes) and typical AVNRT (127 minutes; *P*<0.001).

Procedural data stratified by AVNRT subtype are shown in Table 2. Patients with atypical AVNRT cases had significantly increased body weight, higher fluoroscopy doses, and longer procedural times compared with those with typical AVNRT and DAVN. No significant variation was identified with respect to use of EAM, radiofrequency, and CRYO lesion number, radiofrequency and CRYO time, radiofrequency versus CRYO success, ablation above the CS roof, use of a long sheath, or residual SP conduction after ablation. Of the patients with atypical AVNRT, those in Q1 (median, 1; IQR, 1–2) received less radiofrequency consolidation lesions than those in Q2 to Q4 (median, 3; IQR, 2–6; *P*=0.03; Figure 2). There were otherwise no differences observed in test, consolidation, and total radiofrequency lesion number between Q1 and Q2 to Q4 within each AVNRT subtype.

No femoral arteriovenous fistulae or access-related injury requiring blood transfusion was observed; available clinical records were insufficient to comment on simple hematoma frequency. A single case of high-grade AVB necessitating permanent pacemaker implantation occurred in a 14-year-old male patient (categorized into Q2 to Q4) with typical AVNRT. Radiofrequency ablation was used after CRYO was unsuccessful at the level of the CS roof, with complete heart block developing during a radiofrequency consolidation lesion. Atrioventricular conduction did not recover despite dexamethasone administration, and a permanent pacemaker was implanted 1 week later.

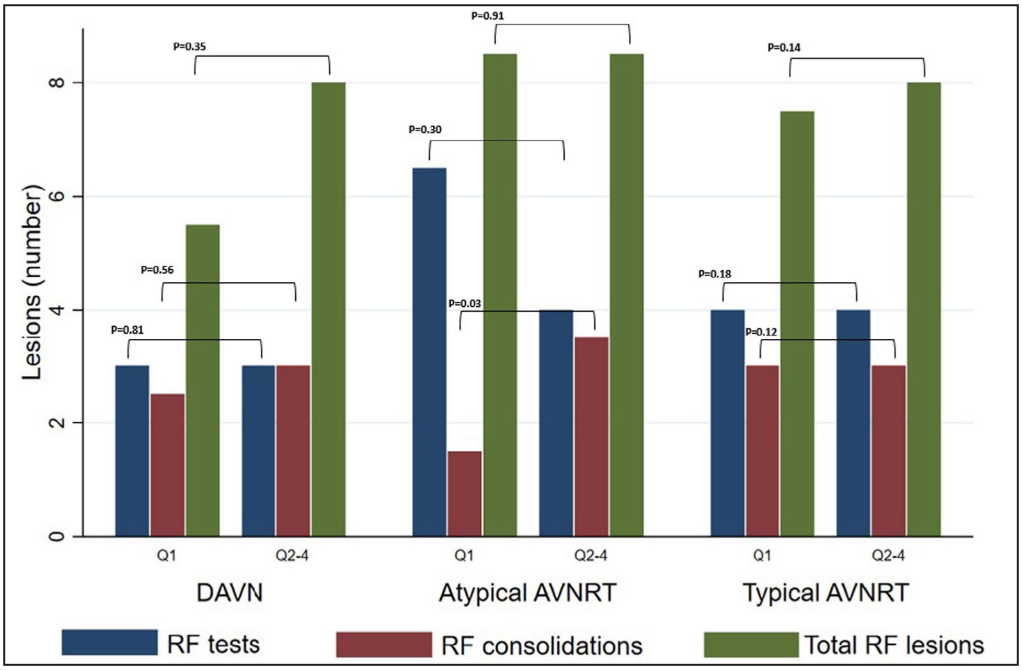

Figure 2. Bar graphs of test, consolidation, and total radiofrequency (RF) lesion number, stratified by atrioventricular nodal reentrant tachycardia (AVNRT) subtype and age quartile 1 (Q1) vs quartiles 2 to 4 (Q2–4).
DAVN indicates dual atrioventricular nodal.

Outcomes at Follow-Up

Follow-up data were available for 447 patients (87% of the original cohort) with a median follow-up time of 0.8 years (IQR, 0.2–2.5 years) and no significant difference in follow-up between Q1 (median, 0.5 years; IQR, 0.2–1.8 years) and Q2 to Q4 (median, 0.8 years; IQR, 0.2–2.5 years; P=0.39). No patients experienced late-onset AVB over the follow-up period. A total of 22 (5%) patients with available follow-up had recurrent AVNRT. Patients with recurrent AVNRT had a median follow-up time of 0.6 years (IQR, 0.3–0.9 years) compared with 0.8 years (IQR, 0.2–2.5 years) in those without recurrence (P=0.45). Univariable associations with AVNRT recurrence are shown in Table 3 (left panel). Only atypical AVNRT (HR, 5.83; 95% CI, 2.01–16.96; P=0.001), DAVN (HR, 4.09; 95% CI, 1.39–12.02; P=0.011), increasing total radiofrequency lesions (HR, 1.06 per lesion; 95% CI, 1.01–1.12; P=0.032), and long sheath use (HR, 3.52; 95% CI, 1.23–10.03; P=0.019) retained statistical significance in the final multivariable model (Table 3, right panel). Kaplan-Meier survival curves are shown in Figure 3. The retention of age quartile to the final multivariable model (to address the study's primary objective) did not alter these associations, and age remained insignificantly associated with AVNRT recurrence (HR, 0.45; 95% CI, 0.10–1.97; P=0.29).

Continuous age and age parameterized using a restricted cubic spline were not significantly associated with AVNRT recurrence. Interactions between risk factors and patient age were not statistically significant. A sensitivity analysis excluding the 8 patients who did not receive any radiofrequency ablation was performed and did not alter the above findings from the multivariable analysis.

DISCUSSION

In this single-center retrospective cohort study of >500 patients undergoing acutely successful SPM for AVNRT, we demonstrated that a radiofrequency-based SPM strategy in the modern EAM era is a safe and effective approach irrespective of age. To our knowledge, this represents the largest published pediatric AVNRT ablation cohort. The key findings of this study include the following: (1) younger age was not associated with a higher risk of AVNRT recurrence at follow-up; (2) procedural methods with respect to radiofrequency use and ablation above the CS roof were similar across ages; (3) atypical AVNRT and DAVN represent higher-risk substrates for recurrence, use more fluoroscopy, and consume more laboratory resources with longer procedural times; and (4) only a single case (0.2%) of intraprocedural AVB requiring permanent pacing was observed with no late-onset AVB observed and no cases of AVB in the younger cohort.

In the present study, Q1 patients with a median age and weight of 8.9 years and 30.6 kg, respectively, were directly compared with Q2 to Q4 patients who were

Table 3. Cox Proportional Hazards Model for Associations With Time to Recurrent AVNRT

Variable	Univariable analysis			Multivariable analysis		
	Hazard ratio	95% CI	*P* value	Hazard ratio	95% CI	*P* value
Age (↑1 y)	1.06	0.94–1.18	0.34			
Quartile 1	0.31	0.07–1.34	0.12	0.45	0.10–1.97	0.29
Weight (↑5 kg)	1.03	0.93−–1.15	0.52			
Female sex	1.37	0.56–3.37	0.49			
Pre-EPS documented SVT	0.67	0.09–4.96	0.69			
Pre-EPS AAD	1.84	0.43–7.91	0.42			
EAM used	3.82	0.89–16.50	0.072			
AVNRT subtype						
Typical	1.00	…	…	1.00	…	…
Atypical	4.56	1.60–12.94	0.004	5.83	2.01–16.96	0.001
DAVN only	2.69	0.95–7.65	0.063	4.09	1.39–12.02	0.011
Any inducible AVNRT	0.49	0.18–1.32	0.16			
Tachycardia cycle length (↑10 ms)	0.94	0.86–1.04	0.22			
Radiofrequency used						
Test radiofrequency lesions (↑1)	1.08	1.02–1.15	0.006			
Consolidation radiofrequency lesions (↑1)	1.07	0.96–1.21	0.23			
Total radiofrequency lesions (↑1)	1.07	1.02–1.12	0.006	1.06	1.01–1.12	0.032
Total radiofrequency time (↑100 s)	1.20	1.01–1.42	0.042			
Time per radiofrequency lesion (↑10 s)	0.73	0.49–1.10	0.13			
Cryoablation used						
Test CRYO lesions (↑1)	1.13	0.87–1.47	0.35			
Consolidation CRYO lesions (↑1)	0.97	0.69–1.35	0.84			
Total CRYO lesions (↑1)	1.05	0.87–1.27	0.58			
Total CRYO time (↑100 s)	1.04	0.83–1.29	0.75			
Time per CRYO lesion (↑10 s)	0.99	0.85–1.15	0.90			
Initial radiofrequency success (vs CRYO success)	0.84	0.20–3.61	0.82			
Long sheath used	3.97	1.46–10.77	0.007	3.52	1.23–10.03	0.019
Ablation above MOCS	0.80	0.27–2.36	0.69			
Residual SP conduction	1.12	0.47–2.67	0.80			
Fluoroscopy time (↑1 min)	0.94	0.88–1.01	0.09			
Fluoroscopy dose (↑10 mGy)	0.99	0.96–1.01	0.28			
Procedural time (↑30 min)	1.42	1.15–1.77	0.001			

AAD indicates antiarrhythmic drug; AVNRT, atrioventricular nodal reentrant tachycardia; CRYO, cryothermal ablation; DAVN, dual atrioventricular nodal; EAM, electroanatomic mapping; EPS, electrophysiologic study; MOCS, mouth of coronary sinus; SP, slow pathway; and SVT, supraventricular tachycardia.

essentially adult sized (median age, 15.9 years; median weight, 60.1 kg). Overall, short-term success and recurrence rates were no different between Q1 and Q2 to Q4, and the frequency of AVB was minimal throughout all quartiles. This was despite notable procedural differences in the youngest quartile of patients. Total procedural time was shorter in Q1 patients, despite similarities in the number and total time of radiofrequency and CRYO lesions. A small but statistically significant decrease in the number of radiofrequency consolidation lesions was seen in Q1 patients, likely attributable to the smaller size of the patient and reluctance to place additional ablative energy near the atrioventricular node. The association between long sheath use with AVNRT recurrence, although intriguing, should be interpreted with caution and should not be generalized to operators using long sheaths from other vendors. Our group practice is to use a long sheath only when catheter maneuverability and/or stability is suboptimal through a standard short sheath, thereby selecting for more challenging anatomy and substrates. Upsizing to a long sheath in smaller patients theoretically increases the risk of vascular injury, although we did not observe such complications. Similarly, the multivariable

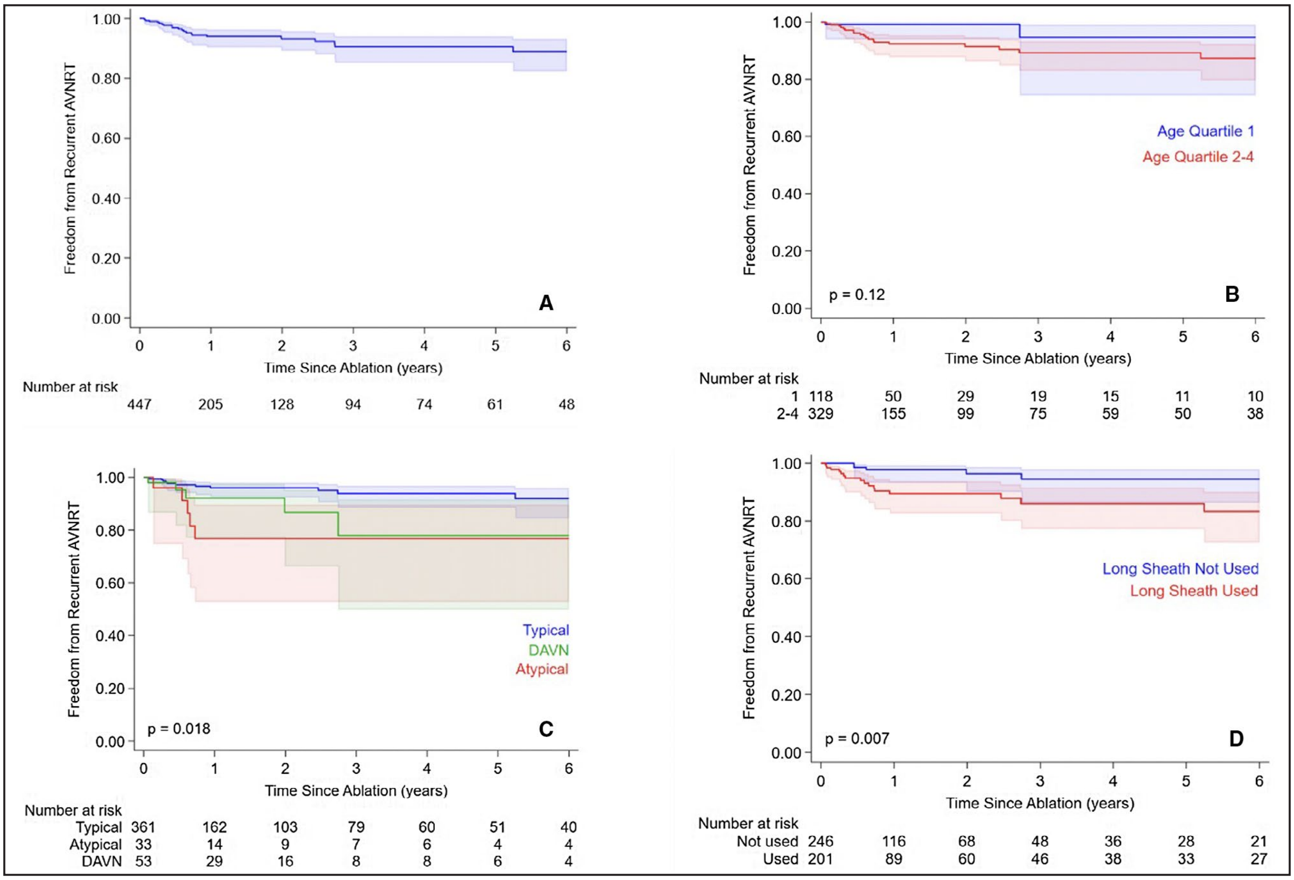

Figure 3. Kaplan-Meier survival curves with 95th percentile CI bands showing freedom from atrioventricular nodal reentrant tachycardia (AVNRT) recurrence: for the total study cohort (A); by age quartile 1 vs age quartiles 2 to 4 (B); by AVNRT subtype (C); and by long sheath use (D).
DAVN indicates dual atrioventricular nodal.

association between the increased number of total radiofrequency lesions and AVNRT recurrence is confounded by more challenging substrates (perhaps even with incorrect SVT diagnoses) where more ablation lesions in the usual right inferior SP territory failed to modify the true SVT substrate.

Radiofrequency energy was used in 98% of the younger Q1 cohort, with 93% resulting in radiofrequency success, representing a near identical strategy with equivalent outcomes to that used in the older Q2 to Q4 cohort. CRYO was used with similar frequency in both cohorts, and the observation that CRYO was used in 11% of Q1 cases but was only responsible for 7% of successful SPM implies that radiofrequency ablation was performed after demonstrating safety with CRYO at a specific location; this is anecdotally consistent with the authors' experience. No difference was observed in the frequency of ablation above the CS roof between the 2 cohorts, occurring in 21% of Q1 and 23% in Q2 to Q4. Our current strategy is to create a detailed EAM shell of the septal tricuspid valve annulus and proximal CS, using impedance data to further delineate the CS ostium. We have a low threshold to perform CS angiography to delineate level of the CS roof and orientation of the atrial septum as ablation is performed progressively higher in the triangle of Koch.

Others have reported on the safety of radiofrequency-SPM for AVNRT in the pediatric population, albeit with important caveats. Siebels et al described 412 patients with a mean age of 12.9 years undergoing exclusive radiofrequency-SPM for AVNRT.[11] AVNRT recurrence occurred in 13.5% at a median follow-up of 47 months with only SVT noninducibility (ie, DAVN only) identified as a risk factor for recurrence. Their experience differed from the present study in that they performed most of their procedures under fluoroscopic guidance, with EAM only used in patients with congenital heart disease, who made up 6% of their population. Backhoff et al published a retrospective cohort of 241 patients with a median age of 12.5 years, although with substantial less radiofrequency use (70%).[12] Recurrent AVNRT was found in 9% of the study cohort at a median follow-up of 5.9 years. No patient or procedural variables were found to have significant associations with AVNRT recurrence using Cox regression analysis, perhaps because of the smaller study cohort and the relative rarity of the outcome. No cases of AVB requiring permanent pacing occurred in the above cited studies. It is unclear whether the higher recurrence rates seen in these studies were attributable to the inclusion of patients with congenital heart disease, less aggressive radiofrequency ablation, or simply observing patients for longer periods of follow-up. Extended patient follow-up within our present study is warranted and may address this question, as others have demonstrated the potential for late AVNRT recurrence following successful ablation.[13–15]

Our demonstration that atypical AVNRT cases had longer procedural times and more radiation exposure supports the notion of increased case complexity within this subtype. Siebels et al did not identify atypical AVNRT as a risk factor for recurrence, and Backhoff et al did not differentiate among AVNRT subtypes.[11,12] In a multicenter adult study performed by Katritsis et al, atypical AVNRT was responsible for 5.4% of all AVNRT cases.[9] The recurrence rate at 3 months following ablation was 5.6% in atypical AVNRT versus 1.8% in a matched typical AVNRT cohort. Interestingly, successful SPM was achieved from the right septum in 97% of cases, implying that ablation within the proximal CS or along the left septum was not necessary for success. Potential causes of our higher observed recurrences in this population include more conservative ablation in anatomically smaller triangles of Koch and incomplete SP mapping. Perhaps more systematic mapping and identification of the antegrade and retrograde limbs of the reentrant circuit, as opposed to empiric ablation of the right inferior SP extension, would be of value.[16] Given the risks of atrioventricular nodal and coronary arterial injury when ablating within the proximal CS in children, more focused investigation is needed to determine the optimal ablation approach to atypical AVNRT, particularly with respect to the leftward inferior SP extension.

The lack of inducible SVT in patients with DAVN physiology precludes accurate characterization of tachycardia mechanism and serves as a suboptimal procedural end point; it is unsurprising that this subpopulation would have a higher recurrence risk. The evidence supporting empiric SPM in pediatric patients with DAVN physiology but without inducible AVNRT is limited to small case series.[17] Siebels et al similarly found empiric SPM to be associated with recurrence.[11] One contributing factor behind these subpar results lies in the poor sensitivity and specificity of DAVN physiologic criteria in predicting inducible AVNRT during EPS in pediatric patients. Blurton et al demonstrated that both the presence of an A2H2 jump ≥50 ms (sensitivity, 42%; specificity, 69%) and sustained slow pathway conduction (sensitivity, 60%; specificity, 82%) have, at best, modest diagnostic accuracy in predicting inducibility.[10] Alternatively, the feasibility of voltage gradient mapping has been demonstrated in children and adults with AVNRT.[18,19] This technique, along with the availability multielectrode high-density mapping catheters with higher voltage resolution, may prove to be of value in complex cases.

Several important limitations of this study should be noted. The retrospective, single tertiary care center design limits its generalizability to other populations. However, 459 (97%) of our cases were first-time ablations, implying that these were not necessarily complex patients referred from outside centers. Follow-up was not available for 13% of the total cohort, which may contribute to a selection bias. Our median follow-up duration was substantially shorter than the referenced studies above, and our recurrence rates may become higher with ongoing follow-up. The low event rate of the primary outcome may have underpowered the study to detect significant variable associations, particularly with respect to the large observed effect size (HR, 0.45) that younger age quartile had on AVNRT recurrence. Diagnostic EPS protocols and mapping and ablation techniques were not standardized among the practicing electrophysiologists. Our bias toward using radiofrequency over CRYO limits the conclusions that can be drawn from this work about the comparative safety and efficacy of these 2 energy modalities.

CONCLUSIONS

In a high-volume center, pediatric AVNRT can be managed with a radiofrequency-based SPM strategy with high procedural efficacy and minimal risk of complications, including heart block. Atypical AVNRT and isolated DAVN physiology remain challenging substrates. Improved mapping and ablation strategies are required for atypical AVNRT. More specific electrophysiologic surrogates for clinical AVNRT and novel end points are needed to improve outcomes in patients with DAVN without inducible AVNRT.

ARTICLE INFORMATION

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Affiliations

Department of Cardiology, Boston Children's Hospital, Boston, MA; and Harvard Medical School, Boston, MA.

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Disclosures

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Supplemental Material

Table S1

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SUPPLEMENTAL MATERIAL

Table S1. The median (interquartile range) number of radiofrequency consolidation lesions was 3 (2-5) in age quartile 1 and 3 (2-5) in age quartile 2-4.

	Age Quartile 1 (n=125)	Age Quartile 2-4 (n=377)
>= 4	42%	49%
>=5	26%	35%
>=6	20%	24%
>=7	13%	16%
>=8	9%	12%

There was a p value = 0.010 when using Wilcoxon rank sum test to compare the distributions between these two groups despite the identical median and interquartile range values. The percent patients surpassing cutoff radiofrequency consolidation lesion values of ≥4 and continuing up to ≥8 was higher in age quartile 2-4 than age quartile 1.