Catheter ablation via the left atrium for atrioventricular nodal reentrant tachycardia: A narrative review

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BACKGROUND Since 1996, it has been recognized that catheter ablation for atrioventricular nodal reentrant tachycardia (AVNRT) may require an approach through the left atrium.

OBJECTIVE The purposes are to present a case report and to provide a comprehensive narrative review on this topic.

METHODS A literature review of all articles that provided detailed information on patients who underwent catheter ablation via the left atrium for AVNRT was performed. The primary search queried PubMed using Medical Subject Headings (MeSH) terms "atrioventricular nodal reentrant tachycardia" and "left." The secondary search was performed by manual review of reference lists and Google Scholar citations of manuscripts retrieved by the primary search. The review was limited to the English language.

RESULTS The searches yielded 30 articles that described 79 patients. A case report was added. Therefore, the final review consisted of 80 patients. The prevalence of left atrial ablation for patients with AVNRT undergoing catheter ablation at tertiary care centers was approximately 1%. Failed right atrial ablation, with or without coronary sinus ablation, was the most common indication for left atrial ablation. Pooled data from 3 cohort studies estimated the acute success rate for radiofrequency ablation of the slow pathway at the septal or inferoparaseptal segments of the mitral valve annulus after failed right-sided ablation to be 90%. There were no reports of atrioventricular block requiring permanent pacemaker implantation.

CONCLUSION Catheter ablation of the slow pathway via the left atrium is an important technique for AVNRT cases that are refractory to conventional ablation.

KEYWORDS Atrioventricular nodal reentrant tachycardia; Case report; Catheter ablation; Left atrium; Narrative review

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Introduction

Catheter ablation is the treatment of choice for curative care of atrioventricular nodal reentrant tachycardia (AVNRT).[1–3] It is one of the greatest triumphs of the early invasive clinical cardiac electrophysiology era.[4] Current indications include intractable symptoms refractory to medical management, patient preference, and high-risk occupations. AVNRT can rarely incite malignant ventricular arrhythmias and catheter ablation is likely the preferred treatment in most of these patients, irrespective of the presence or absence of structural heart disease.[5,6]

In 1973, Denes and colleagues[7] first reported dual atrioventricular (AV) nodal physiology as a requirement for AVNRT. Subsequent anatomic delineations of the fast and slow pathways were elucidated by Sung and colleagues[8] in 1981. Introduction of radiofrequency energy to catheter ablation techniques led to high success rates and low complication rates in the early 1990s.[2] Today, catheter ablation of the slow pathway with radiofrequency energy has a >95% long-term arrhythmia-free survival rate at experienced centers.[9] Cryoenergy is a commonly used alternative, particularly in children, given a potentially higher safety profile for AV block requiring permanent pacemaker placement.[10–12]

Rarely, treatment of AVNRT may necessitate catheter ablation within the left atrium.[2,3] In a contemporary study from 8 tertiary care centers, this was required in 11 of 1084 (1.0%) patients.[9] The purpose of this narrative review is to provide a comprehensive overview of catheter ablation via the left atrium for AVNRT. A case report is presented.

Case report

A 27-year-old Amish woman of white race with no other medical conditions was referred as an outpatient to be considered for electrophysiology study with possible catheter ablation. She had been experiencing palpitations, shortness of breath, and occasional lightheadedness for the past 3 years. Initially, her symptoms could be stopped using the Valsalva maneuver. She subsequently had 2 visits to the emergency room and was prescribed metoprolol succinate 25 mg daily.

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KEY FINDINGS

- The prevalence of the need for catheter ablation via the left atrium for atrioventricular nodal reentrant tachycardia (AVNRT) is approximately 1%.

- Failure of conventional right-sided slow pathway ablation is the most common indication for left atrial ablation. Resetting responses to late atrial extrastimuli is a technique described by investigators at the University of Oklahoma Health Sciences Center that has promise for estimating when left atrial ablation may be required, but it requires prospective study.

- Reports of successful left atrial slow pathway ablation most targeted the inferoparaseptal and septal segments of the mitral valve atrioventricular (AV) junction. Features of local electrogram characteristics at successful sites include AV electrogram amplitude ratio < 1, multicomponent atrial electrogram, and slow pathway potentials.

- The acute success rate for radiofrequency catheter ablation via the left atrium for AVNRT, after failure of conventional right-sided ablation, is approximately 90%.

- Successful targeting of the slow pathway from the left ventricular side of the mitral valve AV junction has been reported after failure of ablation from the left atrial side.

Owing to lack of response, she was changed to propranolol 20 mg twice daily. An echocardiogram was normal. Her symptoms continued to increase to approximately 10 episodes per week with each episode lasting an average of 1 hour. She had occasionally measured her heart rate to be greater than 200 beats per minute. She had a third visit to the emergency room, where she was documented to have supraventricular tachycardia (SVT) at a rate of approximately 180 beats per minute. After termination with intravenous adenosine, an electrocardiogram in sinus rhythm was normal and without ventricular pre-excitation. Her physical examination was normal. Owing to failure of outpatient medications, she elected to undergo electrophysiology study with possible catheter ablation.

Three sheaths were inserted into the right femoral vein. Conscious sedation was primarily achieved with a weight-based continuous infusion of propofol. Catheters were placed in the coronary sinus, His bundle region, and right ventricle. A 4-mm-tip nonirrigated NAVISTAR® radiofrequency ablation catheter (Biosense Webster, Diamond Bar, CA) was used in the right ventricle. Atrial pacing from the proximal coronary sinus electrode demonstrated a shift from fast to slow pathways at a pacing cycle length (CL) of 550 ms. The AV block CL was 430 ms. Programmed atrial stimulation with single extrastimuli using a drive CL of 600 ms

from the proximal coronary sinus electrode revealed 2 jumps (increase of ≥ 50 ms in the A_2H_2 interval associated with a corresponding decrease of 10 ms in the A_1A_2 interval) that suggested 3 anterograde AV nodal pathways (Figure 1A). AV nodal echo beats were observed with both first and second slow pathways. Para-Hisian pacing maneuver elicited a nodal response. There was no retrograde jump.

Isoproterenol was started at 1 μg/min. The sinus rhythm CL decreased from 984 ms to 570 ms. Programmed atrial stimulation with single extrastimuli using a drive CL of 500 ms from the proximal coronary sinus demonstrated a jump (A_2H_2 interval increase from 91 ms to 210 ms) with double AV nodal echo beats when the A_1A_2 interval was decreased from 290 ms to 280 ms (Figure 1B). SVT was induced with A_1A_2 intervals of 270 ms and 260 ms (Figure 1B and Figure 2A).

Typical AVNRT with a CL of 362 ms was suggested based on concentric atrial activation, AH 324 ms, HA 38 ms, VA_{His} 0 ms, and AH/HA ratio > 1. A short HA interval was present and the earliest atrial electrogram preceded the ventricular electrogram during SVT. Ventricular overdrive pacing maneuver demonstrated a V-A-H-A-V response, or a pseudo V-A-A-V response (Figure 2B), consistent with typical AVNRT. The postpacing interval minus tachycardia CL (517 ms – 335 ms) was 182 ms (Figure 2B).

Radiofrequency catheter ablation of the right inferoparaseptal and septal regions was performed in a temperature-controlled mode with a target temperature of 55°C at powers of 30–50 W for up to 60 seconds per lesion (Figure 3A and 3B). Numerous lesions elicited junctional beats. Two lesions were delivered at the roof of the coronary sinus with lower power, including at the earliest retrograde atrial activation site during SVT. In total, 57 lesions were delivered for a cumulative radiofrequency time of 31 minutes and 47 seconds, yet AVNRT could still be easily induced.

A fourth sheath was inserted into the left femoral vein and a phased-array intracardiac echocardiography catheter was introduced. Transseptal puncture was performed with an SL-1 sheath and 8000 U of intravenous sodium heparin was administered as a bolus. The left inferoparaseptal region of the mitral valve AV junction was interrogated. The second ablation lesion delivered in this area resulted in junctional beats, after which AVNRT could not be induced. The radiofrequency time for this lesion was 60 seconds. The successful site had a multicomponent atrial electrogram with an average AV electrogram amplitude ratio of 0.4 and was opposite the second coronary sinus electrode pair (Figure 3C and 3D).

Programmed atrial stimulation on isoproterenol and after washout failed to induce AVNRT and demonstrated complete elimination of the first and second slow pathways (Figure 4). An electrotonic effect was present after elimination of both slow pathways, when compared to the baseline state, as there was a decrease in the fast pathway effective refractory period from 460 ms to 260 ms that was accompanied by an increase in the maximum fast pathway AH interval
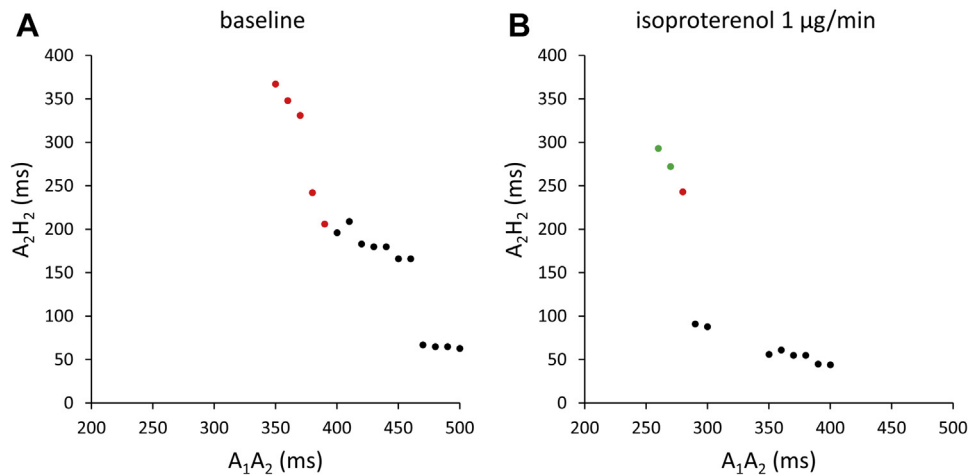
Figure 1   Atrioventricular nodal conduction curves. Stimulation sequences associated with echo beats are indicated with red dots and those associated with initiation of sustained supraventricular tachycardia are indicated with green dots. **A:** At case start, programmed atrial stimulation with single extrastimuli using a drive cycle length (CL) of 600 ms demonstrated 2 jumps. **B:** During infusion of isoproterenol 1 μg/min, only the jump using the second slow pathway persisted with programmed atrial stimulation using a drive CL of 500 ms.

from 67 ms to 188 ms. The AV block CL after isoproterenol washout was 300 ms. The total procedure time was 5 hours and 35 minutes with a total fluoroscopy time of 8.6 minutes. The length of the procedure was primarily attributable to comprehensive retesting after each ablation lesion that produced junctional beats.

The patient noted complete resolution of her clinical symptoms at an outpatient appointment 2 months after her ablation. The electrocardiogram demonstrated sinus rhythm with a PR interval of 122 ms. She was also free of symptoms at a telephone visit 6 months after her ablation.

To the best of my knowledge, this is the first report of a patient with triple anterograde AV node physiology and AVNRT that required catheter ablation via the left atrium. Both slow pathways were able to produce echo beats in the baseline state. However, isoproterenol administration led to disappearance of the first jump and initiation of AVNRT using the second slow pathway. Thus, procedural success required ablation of the second slow pathway that utilized the left inferior input of the AV node. Studies have reported the prevalence of multiple anterograde AV nodal pathways in patients with AVNRT who have undergone electrophysiology study to be between 5.2% and 39.7%.[13–16] It is possible that a second right-sided attempt, after time allowance for resolution of ablation edema, would have been successful. Some left inferior inputs may be successfully ablated by deep right septal lesions. However, left atrial ablation facilitated success in 1 procedure. This case adds to the body of literature on challenging AVNRT cases.

Methods
The case report presented in this manuscript adhered to the CARE (CAse REport) guidelines.[17] Written informed consent was obtained from the patient.

The narrative review was conducted using the IMRAD (Introduction, Methods, Results, and Discussion) format that was modified to accommodate the case report.[18,19]

A primary search of the literature for all relevant articles listed in PubMed was conducted without limitation for the year of publication on November 3, 2020. Medical Subject Headings (MeSH) terms "atrioventricular nodal reentrant tachycardia" and "left" were used. Results were restricted to those in the English language and in humans. Articles were identified and included if they described clinical situations in which patients who underwent electrophysiology study were diagnosed with AVNRT and catheter ablation was attempted in the left atrium. Only articles with detailed case information were selected. Studies of AVNRT that described patients who underwent left atrial ablation but did not include detailed case information were excluded. A secondary search consisted of a manual review of reference lists and Google Scholar citations of the retrieved articles.

AVRNT was designated as typical, atypical, or indeterminate based on the Katritsis and Josephson classification system.[20] A separate electrophysiology study with catheter ablation attempt before the procedure where left atrial ablation was performed was listed as "prior electrophysiology study." For "indication for left atrial procedure," the reason listed was that reported for the procedure where left atrial ablation was performed. "Right-sided ablation" refers to ablation lesions delivered in the right atrium, with or without ablation in the proximal coronary sinus. Anatomic sites for left atrial ablation were converted, when necessary, to correspond with the 1999 consensus statement on living anatomy of the AV junctions from the Working Group of Arrhythmias of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (Figure 5).[21] The prevalence of the need for catheter ablation via the left atrium for AVNRT was estimated using studies that also
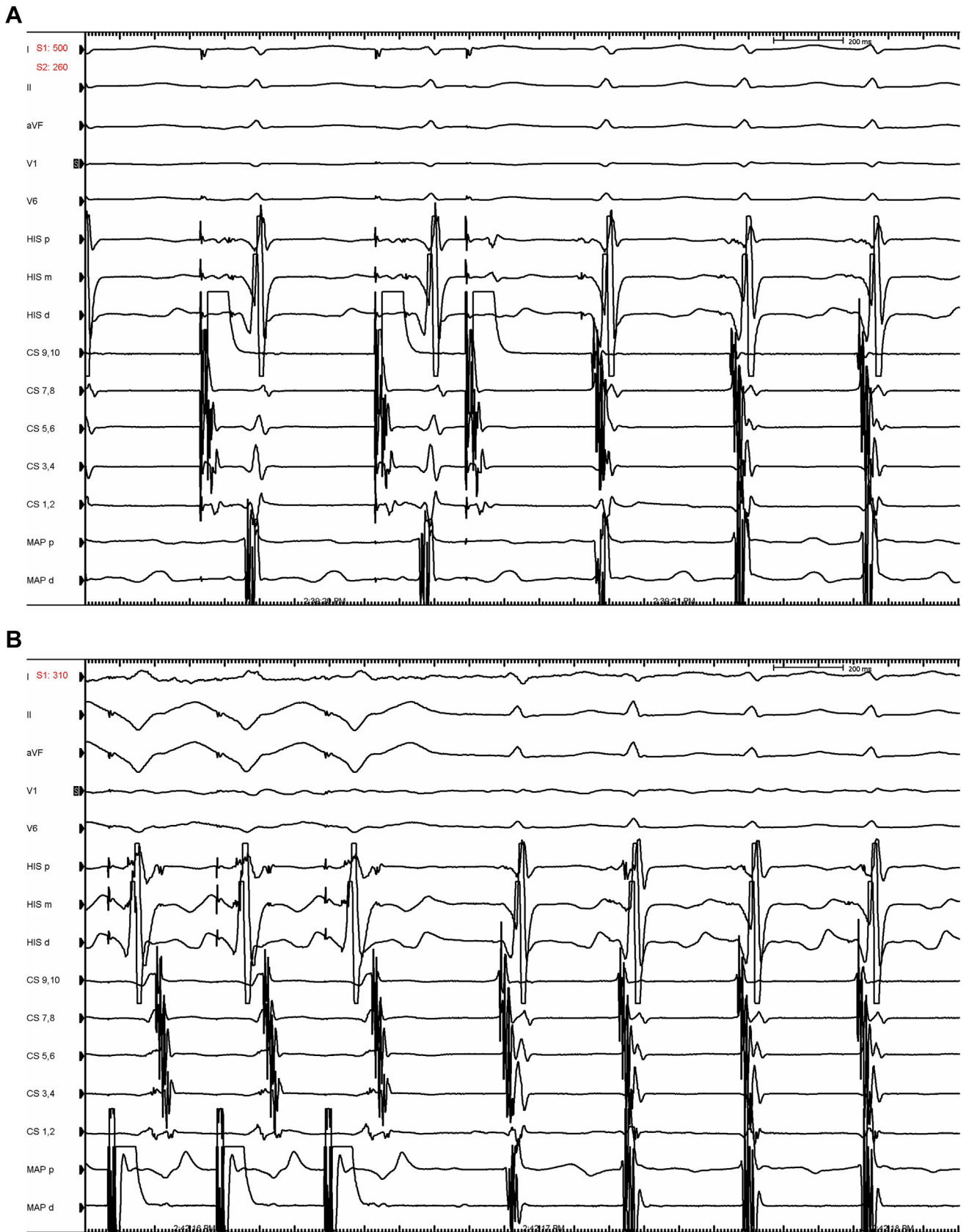
Figure 2 **A:** Induction of supraventricular tachycardia on isoproterenol 1 μg/min using a drive cycle length (CL) of 500 ms and a single atrial extrastimulus with a coupling interval of 260 ms from the proximal coronary sinus electrode. **B:** Ventricular overdrive pacing maneuver at a CL of 310 ms.
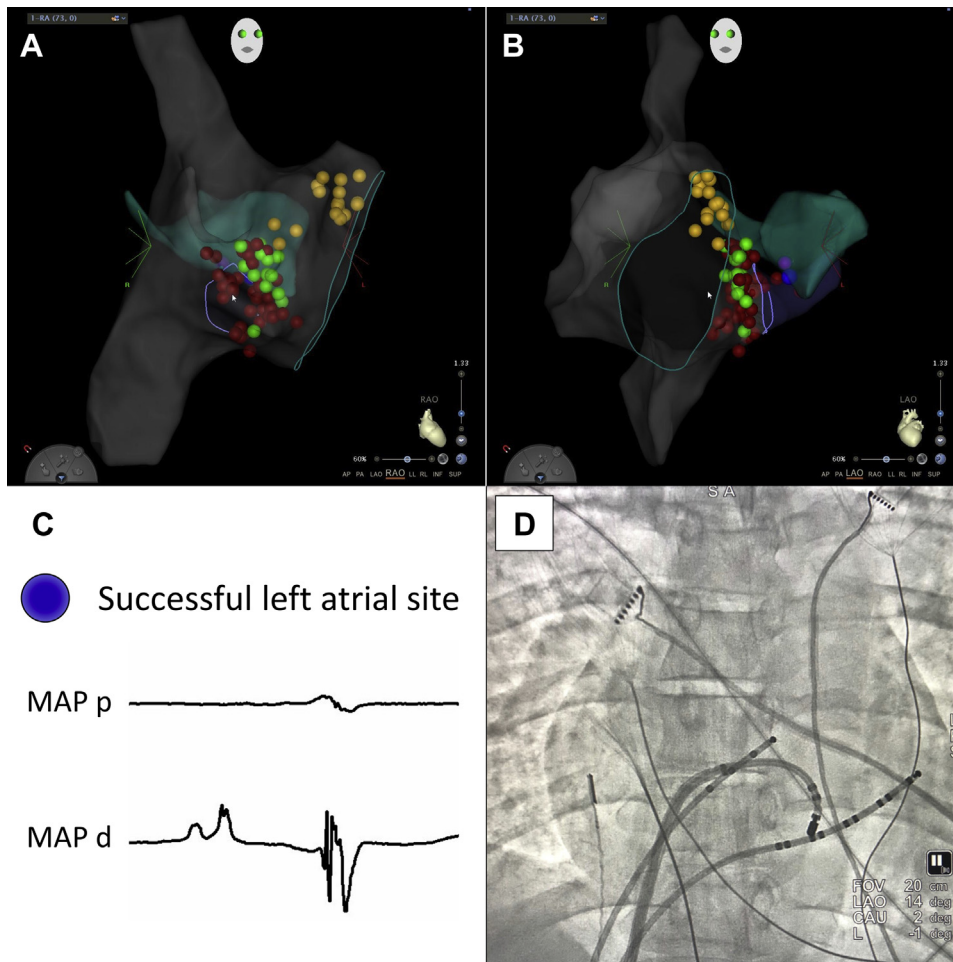
Figure 3   **A:** Electroanatomic map in the right anterior oblique projection. **B:** Electroanatomic map in the left anterior oblique projection. Cardiac chambers are color-coded to indicate the right atrium (*gray*), the proximal coronary sinus (*lavender*), and a portion of the left atrium (*teal*). Dots are color-coded to indicate His bundle electrograms (*yellow*), right atrial or coronary sinus ablation lesions not associated with junctional beats (*red*), right atrial ablation lesions associated with junctional beats (*green*), a left atrial ablation lesion not associated with junctional beats (*purple*), and a left atrial ablation lesion associated with junctional beat (*blue*). **C:** Electrograms at the successful site. **D:** Left anterior oblique 14° fluoroscopy image with the ablation catheter at the successful site.

reported the total number of patients undergoing catheter ablation for AVNRT.

Results
Study results
The flow diagram of the literature search, which yielded 30 articles, is presented in Figure 6.[22–51] There were 3 cohort studies,[26,46,51] 3 cases series,[24,29,47] and 24 case reports. These articles described 79 patient experiences. The final review, which included the case report from this manuscript, therefore consisted of 80 patients. One article,[52] identified during the secondary search, included 4 patients that were included in a subsequently published article.[46] While this article was not included in the final review, it was useful to estimate the prevalence of catheter ablation via the left atrium in patients with typical AVNRT. There were 2 abstracts that were excluded.[53,54] The abstract published by Tondo and colleagues[53] in 1996 was notable for being the first description of left atrial ablation for AVNRT.

Basic and detailed electrophysiology study characteristics are presented in Table 1 and Table 2, respectively. There were 9 articles, all case reports of single patients, that described patients with congenital heart disease. These ranged from simple congenital heart disease, such as a patent foramen ovale, to complex congenital heart disease.[23,25,30,32,35,38,42,44,45]

Prevalence estimates
For prevalence calculations of the need for a left atrial approach in patients undergoing catheter ablation for AVNRT, articles were divided into those that reported any AVNRT and only typical AVNRT. There were 7 articles, counting both papers with overlapping patients, that presented the number of patients from which the left atrial ablation patients were derived.[24,26,37,46,47,51,52] The study by Stavrakis and colleagues[47] was excluded, as it only reported patients with left atrial ablation at the posteroinferior mitral valve AV junction segment and not the number of patients
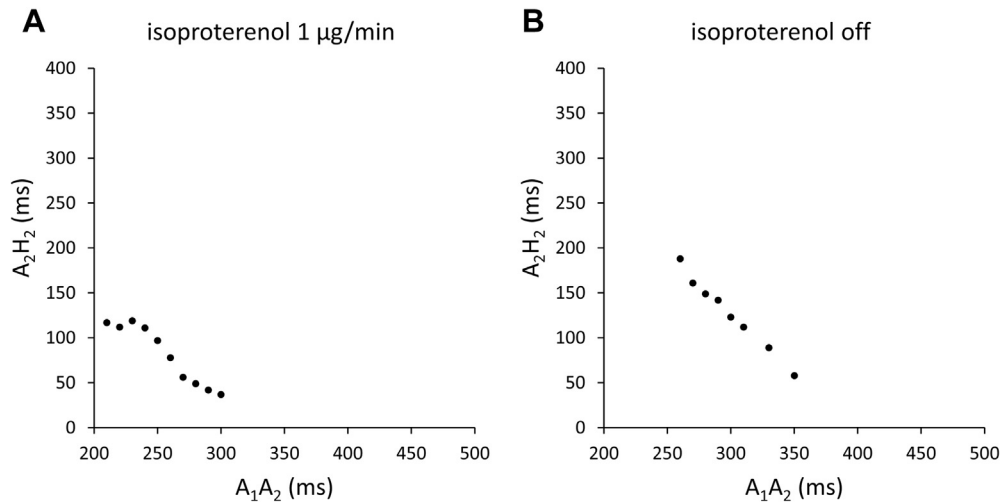
A   isoproterenol 1 µg/min

B   isoproterenol off

Figure 4   Postablation atrioventricular nodal conduction curves. **A:** Programmed atrial stimulation with a drive cycle length (CL) of 400 ms and single extrastimuli from the proximal coronary sinus. **B:** At case end, 7 minutes after cessation of isoproterenol, programmed atrial stimulation with a drive CL of 600 ms and single extrastimuli from the proximal coronary sinus.

with left atrial ablation at any mitral valve AV junction segment.

There were 3 articles that reported the number of patients undergoing catheter ablation via the left atrium from populations that included any AVNRT: 1 of 313 (0.3%) from Alhumaid and colleagues,[37] 15 of 1342 (1.1%) from Katritsis and colleagues,[46] and 5 of 154 (3.2%) from Narayanan and associates.[51] There were 3 articles that reported the number of patients undergoing catheter ablation via the left atrium from populations that included only typical AVNRT: 3 of 420 (0.7%) from Sorbera and colleagues,[24] 9 of 587 (1.5%) from Kilic and colleagues,[26] and 4 of 221 (1.8%) from Katritsis and colleagues.[52] Therefore, the estimated prevalence of the need for catheter ablation via the left atrium was 1.2% (21 of 1809) for any AVNRT and 1.3% (16 of 1228) for only typical AVNRT.

Cohort studies

Kilic and colleagues[26] reported a retrospective cohort with 9 of 587 patients who required left atrial ablation for typical AVNRT at Gulhane Military Medical Academy in Turkey. When compared to the 578 patients who underwent conventional right-sided slow pathway ablation, the left atrial ablation group had longer tachycardia CLs (366 ± 44 ms vs 320 ± 29 ms; p<0.001) and longer AH intervals during tachycardia (267 ± 43 ms vs. 215 ± 28 ms; $P < .001$). All other clinical and electrophysiology characteristics were similar between groups. Acute success was not achieved in 1 patient who had ablation in the septal segment of the mitral valve AV junction despite application of 10 lesions. This was the only cohort study or case series that used an exclusively retrograde aortic approach. The average fluoroscopy time was 35.9 ± 7.7 minutes. There were no recurrences, with a
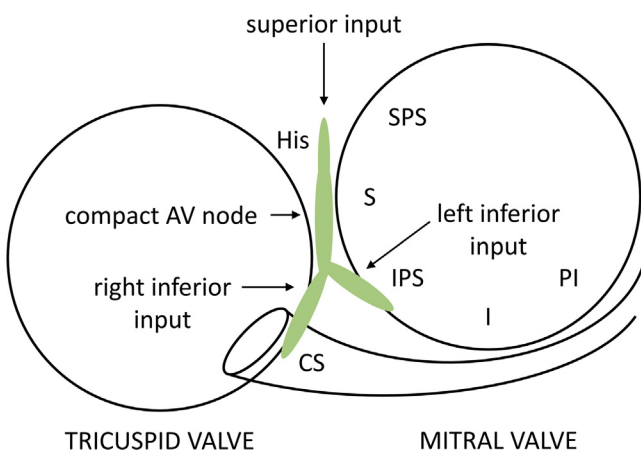

Figure 5   Relevant atrioventricular junction segments using the anatomically correct nomenclature.[21] AV = atrioventricular; CS = coronary sinus; I = inferior; IPS = inferoposteroseptal; PI = posteroinferior; S = septal; SPS = superoparaseptal.
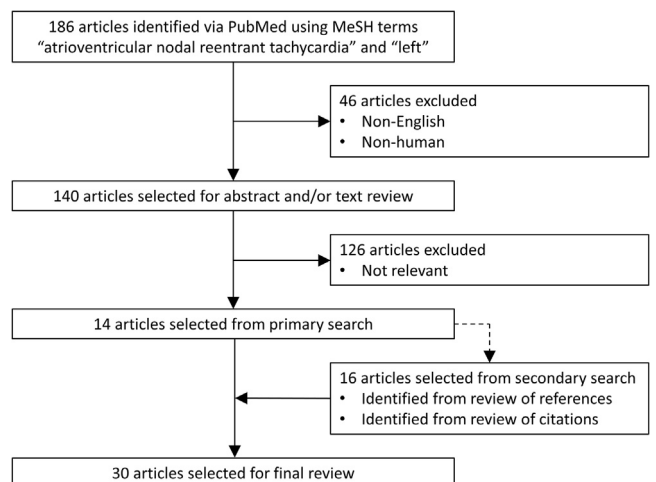

Figure 6   Literature flow diagram. MeSH = Medical Subject Headings.

Table 1 Basic characteristics of patients reported to have undergone catheter ablation via the left atrium for atrioventricular nodal reentrant tachycardia

Article	First author	Cases	Year	Country	Notable features	Prior EPS	Type Typical	Type Atypical	Indication for left atrial procedure
1	Jaïs[22]	1	1999	France	First full publication	1	1		Failed right-sided ablation
2	Altemose[23]	1	2000	USA	PFO	1	1		Failed right-sided ablation
3	Sorbera[24]	3	2000	USA		1	3		Failed right-sided ablation
4	Khairy[25]	1	2004	USA	Tricuspid atresia and ASD		1		De novo
5	Kilic[26]	9	2005	Turkey			9		Failed right-sided ablation
6	Kobza[27]	1	2005	Germany	Fast pathway ablation	1	1		Failed right-sided ablation
7	Wieczorek[28]	1	2005	Germany			1		Failed right-sided ablation
8	Jorat[29]	2	2007	Iran			1	1	Failed right-sided ablation
9	Katritsis[30]	1	2008	Greece	Dextrocardia and situs inversus		1		Failed right-sided ablation
10	Ito[31]	1	2009	Japan				1	Failed right-sided ablation
11	Heist[32]	1	2010	USA	Dextrocardia and situs inversus, PFO			1	Earliest A during AVNRT
12	Higuchi[33]	1	2010	Japan	Dilated cardiomyopathy		1		Failed right-sided ablation
13	Katritsis[34]	1	2010	Greece			1		Failed right-sided ablation
14	Stoyanov[35]	1	2010	Bulgaria	Corrected partial AV canal defect	1	1		Inability to record right His
15	Yamabe[36]	1	2010	Japan	Multiple retrograde pathways			1	Earliest A during AVNRT
16	Alhumaid[37]	1	2012	USA	Fast pathway ablation		1		Failed right-sided ablation
17	Arana-Rueda[38]	1	2012	Spain	Tricuspid atresia		1		De novo
18	Arguedas-Jimenez[39]	1	2014	Spain		1	1		Failed right-sided ablation
19	Ip[40]	1	2014	USA	Total left-sided circuit, AN bystander		1		Failed right-sided ablation
20	Gonzalez[41]	1	2015	Spain	Pediatric (age 13 years)		1		Failed right-sided ablation
21	Morales[42]	1	2015	USA	Unroofed coronary sinus			1	Failed right-sided ablation
22	Green[43]	1	2016	USA	Success in LV	1	1		Failed right-sided ablation
23	Hluchy[44]	1	2017	Germany	Corrected D-TGA		1		Failed right-sided ablation
24	Chokr[45]	1	2018	Brazil	Persistent left SVC; success in LV		1		Failed right-sided ablation
25	Katritsis[46]	26	2018	Greece, USA	First prospective series	15	22	4	15 failed right-sided ablation; 11 de novo
26	Stavrakis[47]	10	2018	USA		7	10		Failed right-sided ablation
27	Świętoniowska-Mścisz[48]	1	2018	Poland	Zero fluoroscopy	1	1		Failed right-sided ablation
28	Nakashima[49]	1	2019	Japan				1	Failed right-sided ablation
29	Kalinsek[50]	1	2020	Slovenia	Zero fluoroscopy	1	1		Failed right-sided ablation
30	Narayanan[51]	5	2021	India			5		Failed right-sided ablation
31	Wang	1	2021	USA	Multiple anterograde pathways		1		Failed right-sided ablation

Data are presented as number of patients.

AN = atrionodal; AV = atrioventricular; AVNRT = atrioventricular nodal reentrant tachycardia; ASD = atrial septal defect; D-TGA = dextro-transposition of the great arteries; EPS = electrophysiology study; LV = left ventricle; NR = not reported; PFO = patent foramen ovale; SVC = superior vena cava; UK = United Kingdom; USA = United States of America.

mean follow-up time of 37 ± 13 months in the left atrial ablation group.

Katritsis and colleagues[46] presented both retrospective and prospective data in 26 patients who underwent catheter ablation via the left atrium for typical or atypical AVNRT at centers in Greece (Athens Euroclinic) and the United States (Brigham and Women's Hospital and the University of Michigan Health System). The retrospective cohort consisted of 15

Table 2 Detailed electrophysiology study characteristics of patients reported to have undergone catheter ablation via the left atrium for atrioventricular nodal reentrant tachycardia

Article	First author	Cases	Approach			Energy	Ablation target characteristics	JR	Site of successful ablation						Failure or recurrence
			TS	RA	EAM				SPS	S	IPS	I	PI	LV	
1	Jaïs[22]	1		1		RF	AVR 0.125	1			1				
2	Altemose[23]	1	1†			RF	SP potential	1			1				
3	Sorbera[24]	3	3			RF	AVR ≤ 0.5, SP potential	3		3					
4	Khairy[25]	1	1†		1	RF		1		1					
5	Kilic[26]	9		9		RF	AVR < 0.5	9		2	6				1
6	Kobza[27]	1	1			RF	AVR < 0.5	1		1					
7	Wieczorek[28]	1		1		RF	Multicomponent AEGM	1		1					
8	Jorat[29]	2	1	1		RF	AVR < 0.5, SP potential	1			2				
9	Katritsis[30]	1		1		RF		1			1				
10	Ito[31]	1		1	1	RF	Earliest AEGM during RVP	1		1					
11	Heist[32]	1	1†		1	Cryo	Earliest AEGM in AVNRT			1					
12	Higuchi[33]	1	1		1	RF	SP potential	1			1				
13	Katritsis[34]	1	1			RF					1				
14	Stoyanov[35]	1	1			RF	AVR > 0.5	1			1				
15	Yamabe[36]	1	1			RF	Earliest AEGM in AVNRT			1	1				
16	Alhumaid[37]	1		1		RF	Small His electrogram		1						
17	Arana-Rueda[38]	1	1		1	RF		1		1					
18	Arguedas-Jimenez[39]	1		1		RF	Multicomponent AEGM	1			1				
19	Ip[40]	1	1			RF		1			1				
20	Gonzalez[41]	1	1			RF	AVR 1.0, multicomponent AEGM	1			1				
21	Morales[42]	1			1	RF	Earliest AEGM in AVNRT				1				
22	Green[43]	1	1			RF	AVR < 1	1						1	1
23	Hluchy[44]	1		1	1	RF		1			1				
24	Chokr[45]	1	1			RF	AVR 0.125	1						1	1
25	Katritsis[46]	26	NR	NR		RF	AVR < 1	26			26				1
26	Stavrakis[47]	10	10			RF	Resetting response	9					10		
27	Świętoniowskia-Mścisz[48]	1		1	1	RF	AVR 0.2	1			1				
28	Nakashima[49]	1	1			RF	Earliest AEGM in AVNRT					1			
29	Kalinsek[50]	1	1		1	Cryo	Mechanical termination of AVNRT				1				
30	Narayanan[51]	5	5			RF	AVR < 1	2			5				2
31	Wang	1	1		1	RF	AVR 0.4, multicomponent AEGM	1			1				

Data are presented as number of patients.

AEGM = atrial electrogram; AVNRT = atrioventricular nodal reentrant tachycardia; AVR = atrioventricular ratio; EAM = electroanatomic mapping; I = inferior; IPS = inferoparaseptal; JR = junctional rhythm; LV = left ventricular; NR = not reported; RA = retrograde aortic; RF = radiofrequency; RVP = right ventricular pacing; S = septal; SP = slow pathway; SPS = superoparaseptal; TS = transseptal.
†Transseptal access performed through existing atrial septal defect or patent foramen ovale.

of 1342 patients who underwent left atrial ablation after failure of right-sided ablation (R+L group). The prospective cohort consisted of 11 patients enrolled at Athens Euroclinic who underwent de novo left atrial ablation only (L group) as proof of concept for this strategy. This was the only prospective series of all the articles retrieved in the literature review. There were no significant differences in electrophysiology characteristics between the R+L and L groups. The R+L group had more average fluoroscopy time compared to the L group (30.5 minutes vs 20.0 minutes; $P = .061$). Acute success was achieved in all patients. There was 1 late recurrence in the R+L group and none in the L group. The postablation follow-up period was described as "at least 3 months."

Narayanan and colleagues[51] described a retrospective cohort of 5 of 154 patients who underwent left atrial ablation for any AVNRT at Medicover Hospitals in India. When patients with left atrial ablation were compared to those that only had right-sided ablation, radiofrequency times were significantly longer (50.8 ± 16.9 minutes vs 9.9 ± 8.5 minutes; $P = .005$), as were procedure times (166.0 ± 35.0 minutes vs 79.6 ± 35.9 minutes; $P = .004$). Between groups, there were no statistically significant differences during AVNRT for AH intervals, HV intervals, and CLs. Of the 5 patients who had left atrial ablation, there were 2 acute failures. Over a mean follow-up of 12.2 ± 4.0 months, there was 1 recurrence of symptomatic AVNRT in a patient who had acute failure despite left atrial ablation.

Indication for left atrial ablation

In patients without structural heart disease, there were only 2 articles where the indication for left atrial ablation was for a reason other than failure of conventional right-sided ablation. The patient reported by Yamabe and colleagues[36] was first diagnosed with AV reentrant tachycardia using a concealed left-sided accessory pathway. Catheter ablation was performed by a transseptal approach, after which 4 atypical AVNRTs were induced. The first 2 were ablated from the septal and inferoparaseptal regions of the AV junction within the left atrium based on the earliest retrograde atrial activation site during AVNRT. As stated above, Katritsis and colleagues[46] performed a prospective study where the left atrium was targeted as the first site for catheter ablation.

Stavrakis and colleagues[47] reported a case series of 10 patients who underwent left atrial ablation at the posteroinferior aspect of the mitral valve AV junction (described as the inferolateral mitral annulus in the original paper) of 843 (1.2%) total patients with typical AVNRT at the University of Oklahoma Health Sciences Center in the United States. All 10 patients had failed right-sided ablation. They noted that 4 (40%) had HA intervals < 30 ms during AVNRT and 3 (30%) were initiated with "double fire" (1:2 AV conduction via anterograde fast and slow pathways). Patients were retrospectively identified and left atrial ablation targets were based on resetting responses to late atrial extrastimuli technique. Atrial extrastimuli were introduced at multiple sites near the posteroinferior mitral valve AV junction,

beginning near the end of the QRS complex and after the onset of retrograde atrial activation. Coupling intervals were decreased by 5 or 10 ms. The atrial end of the anterograde slow pathway was considered to be where the latest atrial extrastimulus advanced the next His bundle potential by ≥ 10 ms and reset the tachycardia. Acute success was achieved in all patients with a single ablation lesion delivered on the posteroinferior segment in 7 of 10 patients and the maximum lesions required for any patient was only 4. There were no recurrences in the 9 patients who had follow-up information at 1 year.

Catheter ablation

The slow pathway was the initial target within the left atrium for all patients. Radiofrequency energy delivered by nonirrigated catheters was the predominant method. Most described techniques performed during sinus rhythm that were guided by a combination of anatomy and electrograms in the septal and inferoparaseptal segments of the mitral valve AV junction.

A best estimation of acute success and long-term freedom from recurrence for patients who underwent catheter ablation of the slow pathway via the left atrium after failure in the right atrium, with or without coronary sinus ablation, used the 3 cohort studies.[26,46,51] Of the 29 patients included, there were 3 acute failures for an overall acute success rate of 89.7%. Of the 26 remaining patients who achieved acute success, there was 1 recurrence for an overall long-term freedom from recurrence rate of 96.2%.

Fast pathway ablation in the left atrium was reported twice. Kobza and colleagues[27] described "Application of [radiofrequency] current at the left atrial septum inferior to the His bundle unexpectedly resulted in fast pathway ablation." This was associated with an increase in the AH interval from 90 ms to 160 ms. At this ablation site, localized to the septal segment of the left atrial AV junction, there was an AV electrogram amplitude ratio of <0.5 and a His bundle electrogram was not recorded. Nevertheless, fluoroscopy images demonstrated that the tip of the ablation catheter, introduced via a transseptal route, was virtually directly opposite the right-sided His bundle catheter tip.

Alhumaid and colleagues[37] reported a case where catheter ablation of the slow pathway failed in the right atrium with radiofrequency energy and cryoenergy. Left atrial slow pathway ablation using radiofrequency energy via a retrograde aortic route also failed. Therefore, the left-sided fast pathway was intentionally targeted. The catheter tip was positioned at the superoparaseptal segment of the mitral valve AV junction where a small His bundle electrogram was recorded. Radiofrequency ablation was successful and associated with an increase in the PR interval from 150 ms to 180 ms. The total procedure time was 280 minutes with 103 minutes of fluoroscopy. Postprocedure, cardiac tamponade was diagnosed and successfully treated with placement of a pericardial drain. The patient was eventually discharged.

This was the only acute or long-term procedural complication reported in all 80 patients included in this review.

Two cases were reported where slow pathway ablation was successful at the left ventricular side of the inferoparaseptal segment of the mitral valve AV junction after both right-sided and left atrial ablation failed.[43,45] In both cases, the signal at the successful site recorded small, far-field atrial signals and large ventricular signals.

Two articles described the use of irrigated radiofrequency catheters.[43,47] Power-controlled delivery of 30–35 W was used in the left atrium at posteroinferior segments of the mitral annulus by Stavrakis and colleagues.[47] Green and colleagues[43] used 50 W at the inferoparaseptal segment of the left ventricle. Lesions were delivered with a temperature limit of 42°C.

There were 2 reports of cryoenergy for catheter ablation of the slow pathway via the left atrium.[32,50] Both used 4-mm-tip cryoablation catheters. Cryoenergy was delivered during tachycardia, leading to slowing and termination.

Discussion

This narrative review is the first comprehensive overview of the worldwide experience on catheter ablation via the left atrium for AVNRT since it was first described in 1996 by Tondo and colleagues.[53] There are several major observations. First, the need for left atrial ablation was approximately 1% of patients with AVNRT who underwent catheter ablation at tertiary care centers. Second, there is limited insight into when left atrial ablation may be required. Third, despite the lack of a universally accepted technique, the acute success rate was approximately 90%.

Patients in industrialized countries with AVNRT who seek curative care have a treatment option, catheter ablation, that is associated with an approximately 95% success rate and an exceedingly low risk for serious complications. The most concerning complication, complete AV block requiring implantation of a permanent pacemaker, occurs at a rate of <1%. These results are even more astounding considering that AVNRT accounted for 20% of the indications for AV junction ablation and permanent pacemaker placement in a multicenter registry published in 1988.[55]

Despite generally excellent outcomes, the quest for refinement is ongoing. Catheter ablation via the left atrium is an important consideration. In a contemporary, multicenter study from tertiary care referral centers, only 1 patient required a pacemaker for AV block out of 1084 (0.1%) patients who underwent catheter ablation for AVNRT.[9] In contrast, the rate for periprocedural pacemaker implantation in the Swedish catheter ablation registry was 32 of 6977 (0.46%) patients.[56] Some of the difference between these rates may be willingness to proceed with left atrial ablation, as 11 patients underwent left atrial ablation in the first study while left atrial ablation was not reported in the second study.

Young patients with debilitating symptoms are an important subgroup within the AVNRT population. Life-long medications may be burdensome or ineffective. Yet, catheter ablation–associated complete AV block leading to permanent pacemaker implantation is tremendously life-altering. AVNRT recurrence after slow pathway ablation has been associated with younger age, possibly indicating more reluctance from operators to be aggressive.[9]

There are no consistently identifiable factors during electrophysiology study to indicate that a left atrial approach may be needed. Otomo and colleagues[57] reported eccentric coronary sinus atrial activation in 5% of patients with AVNRT. Eccentric activation may be attributable to involvement of the left inferior input. These situations may be effectively treated by ablation within the coronary sinus. Lower powers, between 25 W and 40 W, have been used with 4-mm-tip nonirrigated radiofrequency ablation catheters.[3,57] Some operators have described no further need for left atrial ablation after adopting ablation within the coronary sinus using externally irrigated radiofrequency catheters to deliver energy between 10 W and 20 W.[3]

A 3-part stepwise anatomic approach to right-sided slow pathway ablation has been described by Gonzalez and colleagues.[3] The first site, targeting the right inferior input of the AV node, is "between [the coronary sinus] ostium and tricuspid annulus at the level of [the coronary sinus] ostium." The second site, targeting the left inferior input of the AV node, is the proximal (up to 20 mm inside) coronary sinus musculature at the roof. The third site is within the triangle of Koch, superior to the coronary sinus ostium. The risk of AV block is higher at this site given the potential to damage the superior input of the AV node, or fast pathway.[58,59] Given this, a left atrial approach may be considered if acute endpoints for ablation success are unable to be reached after ablation within the inferior aspect of the triangle of Koch. It has, in fact, been stated that ablation in the superior aspect of the triangle of Koch "has no indication in the modern treatment of AVNRT."[58]

Catheter ablation for AVNRT is performed with high success rates in patients with congenital heart disease. However, outcomes vary depending on complexity. In a multicenter retrospective study, patients with complex congenital heart disease, when compared to patients with simple congenital heart disease, had lower rates of acute success (82% vs 97%; $P = .04$) and long-term success (86% vs 100%; $P = .004$) while having higher rates of AV block (14% vs 0%; $P = .004$) and the need for chronic pacing (10% vs 0%; $P = .008$).[60] Acute success was defined as noninducibility and long-term success was defined as absence of symptoms of tachycardia at least 1 year after the last ablation procedure. Given reports of successful outcomes for patients with congenital heart disease in the articles retrieved for this manuscript, left atrial ablation may be a method by which to achieve higher acute success rates in patients with complex congenital heart disease.

Technical considerations for catheter ablation

There is no consensus on the optimal approach for catheter ablation of the slow pathway via the left atrium.

Conventional ablation for AVNRT consists of 2 approaches guided primarily by anatomy or electrograms.[3] In practice, these approaches are often combined.[9] Pooling the experience of the reviewed articles, a general technique can be proposed.

The anatomic areas of the mitral valve AV junction that have been the most successful targets are the inferoparaseptal and septal segments, which may be reached through both transseptal and retrograde aortic approaches. The objective is to target the atrial end of the left inferior extension of the AV node (Figure 5).[3,59] In sinus rhythm, local electrogram characteristics that are attractive ablation targets include AV electrogram amplitude ratio < 1, multicomponent atrial electrograms, and slow pathway potentials. In AVNRT, the earliest retrograde atrial activation has been used to estimate the effective site.

Resetting responses to late atrial extrastimuli during AVNRT is a promising technique to determine if a left atrial approach should be considered and where to deliver ablation lesions.[47] The sensitivity and specificity are unknown, as the study was retrospective and all patients had successful ablation sites at the posteroinferior segment of the mitral valve AV junction. Use of this technique to rule out involvement of the left-sided AV node extension has been suggested in a case report,[61] but this technique requires prospective evaluation with a larger sample size. It is also unclear whether this maneuver is useful for AVNRT involving other segments of the mitral valve AV junction.

For safety purposes, incremental atrial pacing can distinguish slow pathway potentials from left-sided His potentials, as shortening of the potential-to-ventricular electrogram interval with decreasing atrial CLs is suggestive of a slow pathway potential.[24] As proposed by Katritsis and colleagues,[46,52] an electrophysiology catheter may also be placed at the left-sided His position via the retrograde aortic route. At successful sites, the atrial electrogram on the ablation catheter is closer to that recorded on the coronary sinus catheter when compared to the left-sided His bundle catheter. However, femoral arterial cannulation is associated with potential complications that include bleeding requiring transfusion, retroperitoneal hemorrhage, pseudoaneurysm, arteriovenous fistula, arterial dissection, thrombosis or embolism leading to limb ischemia, and hematoma.[62]

Marking left-sided His bundle electrograms with an electroanatomic mapping system may also decrease the possibility of AV block. Other potential advantages of electroanatomic mapping include the ability to mark ablation lesions and decreasing fluoroscopy exposure. For patients with suspected AVNRT, the use of electroanatomic mapping systems is variable. A retrospective study that examined practices at The Johns Hopkins Hospital demonstrated an increase in the use of electroanatomic mapping systems from 0% in the 2005–2006 academic year to 36.2% in the 2014–2015 academic year in patients who underwent catheter ablation for AVNRT.[63] Maury and colleagues[64] in France stated, "[3-dimensional] mapping systems are probably useless and not cost-effective for the vast majority of atrioventricular

node re-entrant tachycardia." For patients with AVNRT who have failed conventional ablation in the right atrium and coronary sinus using primarily fluoroscopic guidance, the option of proceeding to the left atrium must be balanced with the option of stopping the procedure and returning in the future with an electroanatomic mapping system.

For patients who undergo attempted left atrial slow pathway ablation after failed right-sided ablation, there is still a 10% acute failure rate. Two reports of successful slow pathway ablation in the left ventricle are worth noting.[43,45] A 5-part stepwise anatomic approach may be proposed: (1) between the coronary sinus ostium and tricuspid annulus at the level of the coronary sinus ostium, (2) the roof of the proximal coronary sinus musculature, (3) the inferior aspect of the triangle of Koch, (4) the left atrial side of the inferoparaseptal or septal segments of the mitral valve AV junction, and (5) the left ventricular side of the inferoparaseptal segment of the mitral valve AV junction.

Radiofrequency energy is typically delivered using a 4-mm-tip nonirrigated catheter. Settings vary by individuals and centers but are similar to those for right-sided ablation.[3,46] Target temperatures are 55°C to 60°C with starting power around 20 W. If no adverse signs are seen, such as AH prolongation or junctional beats with absence of ventriculoatrial conduction, power may be increased to 50 W. If junctional rhythm is not seen within 30 seconds, radiofrequency energy is stopped. If junctional rhythm with 1:1 ventriculoatrial conduction is elicited, then radiofrequency energy is continued for 10–60 seconds or until cessation of junctional rhythm. Some operators continue for 15–30 seconds after the cessation of junctional rhythm.[47]

Catheter ablation via the left atrium for AVNRT is analogous to left-sided atrial tachycardia and accessory pathway ablation with respect to risk for intraprocedural and postprocedural thromboembolic events.[65] Therefore, intravenous sodium heparin is recommended as a bolus of 5000–15,000 U (or 90–200 U/kg) immediately after arterial access, then followed by a continuous infusion at 1000 U/hour during the procedure. The recommended activated clotting time is >300 seconds. Postprocedural oral anticoagulation or antiplatelet agents are not recommended unless otherwise indicated. Long sheaths should be continuously flushed. Silent cerebral infarcts, despite intraprocedural anticoagulation, have been described following catheter ablation of left-sided accessory pathways using nonirrigated radiofrequency catheters.[66]

In general, irrigated radiofrequency catheters are neither needed nor recommended for routine slow pathway ablation, so there is little published information on safe and effective settings. Nevertheless, open-irrigated radiofrequency catheters with contact force are associated with less thrombus and fewer steam pops.[67] Theoretically, these may be safer for left atrial slow pathway ablation.

Bertini and colleagues[68] reported the use of a 4-mm-tip open-irrigated, flexible tip radiofrequency catheter (Therapy™ Cool Flex™, Abbott Laboratories, Chicago, IL) for slow pathway ablation in patients with AVNRT. Settings

included powers of 20–30 W with a maximum temperature of 43°C. Acute success was achieved in all 80 patients and there was 1 patient with recurrence. There were no cases of AV block with or without pacemaker implantation. The authors stated that this was "the first study focusing on AVNRT-only open-irrigated catheter ablation in an adult cohort."

A 3.5-mm-tip open-irrigated radiofrequency ablation catheter with real-time tissue-tip contact force (TactiCath™; Abbott Laboratories, Chicago, IL) has also been used for AVNRT. Kerst and colleagues[69] reported 9 adult patients and 5 pediatric patients with AVNRT who were treated with this catheter. Contact force was limited to below 20 g during ablation. Settings consisted of a flow rate of 17 mL/min, a cutoff temperature of 43°C, and a maximum power of 30 W for up to 45–60 seconds. Acute success was achieved in all patients and there were no episodes of AV block.

Contino and colleagues[70] described a patient with typical AVNRT who failed slow pathway ablation on the right inferoparaseptal segment with a 4-mm-tip nonirrigated radiofrequency catheter. They were able to achieve acute success using the TactiCath catheter on the same site. Two lesions were delivered using power-controlled mode with average forces of 14 and 7 g, powers between 20 W and 25 W, and for 60 seconds. Impedance drops for the 2 lesions were 21 and 35 ohms.

Cryoablation for AVNRT currently prefers the use of 6-mm-tip cryocatheters (FREEZOR EXTRA™; Medtronic, Dublin, Ireland), given lower recurrence rates when compared to 4-mm-tip cryocatheters.[3,10,11] Cryomapping, by cooling the tip to -30°C for 20 seconds, may be performed to assess the potential target sites. During cryomapping, noninducibility of AVNRT suggests a potentially successful site while the potential for AV block may be monitored by continual assessment of PQ intervals. Cryoablation is performed with a 4-minute freeze and a target temperature of -80°C. After thawing, a second 4-minute "bonus" freeze may be delivered. Cryoablation is much less thrombogenic when compared to standard radiofrequency ablation.[71]

Ultimately, the selection of catheter is at the discretion of the operator given the lack of comparative data. The bulk of experience with left atrial slow pathway ablation has been with the 4-mm-tip nonirrigated radiofrequency ablation catheter. However, there are certainly reasons to consider irrigated radiofrequency catheters or cryocatheters.

Dual AV nodal nonreentrant tachycardia
Dual AV nodal nonreentrant tachycardia is an uncommon arrhythmia where sinus beats transmit to the ventricles in a 1:2 fashion via anterograde fast and slow pathways.[72] Catheter ablation of the slow pathway is the treatment of choice. It is performed with generally the same technique as for AVNRT. Failed right atrial ablation for dual AV nodal nonreentrant tachycardia has been reported and a left atrial approach may theoretically achieve success in such refractory cases.[73]

Limitations
All review papers, particularly those that retrieve a high percentage of case reports, are subject to reporting bias. In addition, there was no consistency of reporting data among investigators. Prevalence estimates may suffer from reporting bias, as data were derived from high-volume referral centers.

Conclusion
Catheter ablation via the left atrium is an important option for curative care of AVNRT. Systematic study of features that may indicate the need for a left atrial approach and may suggest optimal ablation targets within the left atrium are needed. Failure of ablation in the right atrium, coronary sinus, and left atrium may necessitate ablation within the left ventricle.

Disclosures
The author declared no conflict of interest.

Patient Consent
Written informed consent was obtained from the patient.

Ethics Statement
The case report presented in this manuscript adhered to the CARE (CAse REport) guidelines.

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