Catheter Modification of the Atrioventricular Junction With Radiofrequency Energy for Control of Atrioventricular Nodal Reentry Tachycardia

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Background. The utility of transcatheter application of radiofrequency energy to eliminate atrioventricular nodal reentrant tachycardia (AVNRT) was investigated.

Methods and Results. Thirty-nine patients (mean age, 53±20 years; range, 14–86 years) with medically refractory AVNRT underwent perinodal ablation with radiofrequency energy. A custom-designed 6Fr catheter with a large (3-mm-long) distal electrode and interelectrode pacing of 2 mm was used in the majority of cases. The catheter used for ablation was initially positioned across the tricuspid anulus to obtain the largest His bundle electrogram, then withdrawn to obtain the largest atrial:ventricular electrogram ratio, with a small His bundle electrogram (≤100 µV). Each application of radiofrequency energy (350–550 kHz, 16.2±5.2 W) was stopped after 60 seconds or if PR prolongation or an impedance rise was noted. The endpoints of the procedure were persistent modification of atrioventricular nodal conduction (either first-degree atrioventricular block or impairment of ventriculoatrial conduction) and noninducibility of AVNRT before and during isoproterenol administration. Radiofrequency energy was applied a mean of 6.8±3.5 times per session. After a mean follow-up of 8±3.0 months, 32 of the 39 patients (82%) have been free of AVNRT, and did not have high grade AV block. Three patients (8%) developed complete atrioventricular block and had pacemakers implanted. Two patients had unsuccessful initial procedures, and two patients had initially successful ablations but had recurrences of tachycardia 4–6 weeks later. Elimination of AVNRT appeared to be due to effects on the retrograde fast pathway in most patients.

Conclusions. Radiofrequency ablation of the perinodal right atrium appears to be safe and effective for treatment of typical AVNRT. (Circulation 1991;83:827–835)

Atrioventricular (AV) nodal reentry is the most common cause of paroxysmal supraventricular tachycardia.1–5 This arrhythmia was the primary indication for ablation of the AV junction in 20% of patients described in a multicenter registry.6 Ablation of the AV junction is palliative in that patients are left with complete AV block and a lifelong dependence on permanent pacing.7 Surgical techniques have been recently developed to abolish AV nodal reentrant tachycardia (AVNRT) while maintaining AV conduction.8–11 Both cryoablation and electrophysiologically guided dissection of perinodal tissues have been shown to be effective in eliminating AVNRT and to produce a low incidence of inadvertent complete AV block. The disad-

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vantages of these operative procedures include the expenses, risk, and morbidity of open heart surgery.

Catheter-delivered direct current defibrillator discharges applied to the low septal right atrium have been used to treat AVNRT with preservation of AV conduction. Although most patients are rendered free of arrhythmia, there appear to be several disadvantages with the use of high-voltage shocks for this procedure. Because transient, high-grade AV block often occurs after each shock, titration of the ablative energy dose to achieve the desired electrophysiological effect is difficult. The arcing and explosive gas formation that result from an ablative shock are associated with a low, but finite, incidence of serious side effects.

The use of radiofrequency energy to produce lesions in the region of the AV node may have advantages over direct current shocks. Radiofrequency energy appears to be safe and effective for complete ablation of the AV junction. The lesions produced are small and well delineated and are formed through resistive heating. Little or no ventricular ectopy or hemodynamic changes were present during radiofrequency ablation of the AV junction, and the creatine kinase–MB isoenzyme release was less than that after ablation with direct current energy. High-frequency alternating current in the radiofrequency range does not depolarize excitable membranes. This obviates the need for general anesthesia and allows monitoring of the electrocardiogram during ablation. A recent study in animals has shown that radiofrequency ablation can be titrated to achieve attenuation of AV nodal function without complete AV block.

In the present study, we report the use of transcatheter delivery of radiofrequency energy to abolish AVNRT while maintaining antegrade AV nodal conduction in 39 patients.

**Methods**

**Patient Population**

All patients who underwent perinodal radiofrequency ablation for the purpose of treating the typical form of AVNRT between November 1988 and March 1990 at the University of California, San Francisco, and at the University of Michigan, Ann Arbor, were included in the study (an intent-to-treat analysis). The study protocol was approved by institutional review boards at both hospitals. The clinical characteristics of this cohort are summarized in Table 1. The mean age was 53 ± 20 years, and 26 of the 39 patients were women. All experienced disabling symptoms due to recurrent tachycardia. The mean duration of symptoms was 15.3 ± 14.8 years, and patients had been unsuccessfully treated with a mean of 3.7 ± 2.4 antiarrhythmic drugs. The mean tachycardia rate was 188 ± 41 beats/min. Six of the patients had a history of coronary artery disease, one had a surgically repaired atrial septal defect with an attempt at intraoperative cryosurgical treatment of AVNRT 5 years before, one had a history of aborted sudden death felt to be precipitated by very rapid AVNRT, and one (patient 33) had persistent disabling symptoms despite treatment with an antichy- 

**Experimental Procedure**

Written consent was obtained in all patients. All patients had a baseline electrophysiological study to confirm the diagnosis and to demonstrate the inducibility of the typical form of AVNRT. Criteria used to support the diagnosis of AVNRT have been described previously. Antegrade and retrograde AV conduction and refractoriness were assessed before and during infusion of isoproterenol at a dose sufficient to increase the baseline heart rate by 20%.

Radiofrequency energy was delivered as a continuous unmodulated sine-wave output from an electrosurgical unit. A device that operated at 550 kHz (Bicap 4005, Microvasive, Watertown, Mass.) was used at the University of California, and a device that operated at 350 kHz (RFG-3B, Radionics, Burlington, Mass.) was used at the University of Michigan. Studies in vitro have shown no differences in tissue dielectric properties between these two frequencies. A power setting of 16 W was used in all cases. Because of differences in tissue impedance between patients, the actual delivered power was variable. The applied root–mean-squared voltage and current were continuously recorded during each ablation.

The ablation catheter used in the majority of cases was a custom-designed 6F bipolar catheter with a distal electrode 3 mm in length and an interelectrode separation of 2 mm. If proper catheter positioning was difficult, a 7F steerable catheter with a distal electrode 3 mm in length was substituted. The ablation catheter was introduced via a sheath in the femoral vein and advanced across the tricuspid anulus under fluoroscopic guidance and initially positioned to record the largest His electrogram possible. The catheter was then slowly withdrawn while maintaining clockwise torque until the atrial:ventricular electrogram ratio was maximized and the His bundle electrogram was either small (<100 µV) or not seen (Figure 1). The ablation catheter was typically positioned several millimeters proximal to the site of the maximal His bundle electrogram. Standard quadripolar catheters positioned at the high right atrium and right ventricular apex during the baseline study were left in position to allow assessment of antegrade and retrograde conduction during the ablation session.

Radiofrequency current was applied between the distal electrode of the ablation catheter and a large skin electrode (R2, Darox, Inc., Niles, Ill.) applied over the left scapula. The electrocardiogram was continuously monitored during energy delivery. The ablation protocol varied in accordance with the electrophysiological response. During some applications of radiofrequency energy, PR interval prolongation by greater than 50% above baseline was noted. When this occurred, energy delivery was discontinued, and assessment of retrograde conduction was performed. If after application of radiofrequency current there was retrograde block
or a 50% increase in the ventriculoatrial (VA) conduction time, then reassessment of AV nodal function and inducibility of AVNRT was performed during an infusion of isoproterenol.

During some applications of radiofrequency energy, junctional tachycardia was noted. When this occurred, atrial overdrive pacing was performed to allow monitoring of AV conduction during energy delivery.

During some ablations, a sudden drop in current due to an impedance rise was observed. Impedance rise is the result of tissue desiccation and coagulum formation on the surface of the electrode.17 When this occurred, energy application was stopped, the catheter was withdrawn, and any adherent material was removed. If no effects on conduction were noted after 60 seconds, current delivery was stopped, and if abla-
tions at four fluoroscopically distinct sites failed to result in even transient effects on AV conduction, the procedure was considered unsuccessful.

Follow-up
Electrophysiological studies were repeated at 2–4 days and 2–4 months after the procedure in patients who were successfully treated. As with the baseline study, antegrade and retrograde conduction and refractoriness were assessed, as well as inducibility of AVNRT before and during isoproterenol infusion. All patients with episodic palpitations after the procedure were evaluated by either Holter recordings or transtelephonic event monitors.

Statistical Analysis
Statistical analysis of electrophysiological parameters before and after ablation was performed using the two-tailed Student’s t test for paired variables.

Results

Electrophysiological and Clinical Parameters During Ablation
Radiofrequency energy was applied a total of 289 times in the 39 patients. A mean of 6.8±3.5 applications was delivered per session at a power level of 16.2±5.2 W and a mean duration of 48.1±11.2 seconds per application (Table 2).

No significant pain was noted by the patients during application of the radiofrequency current. Although some perceived a burning sensation, additional analgesia or anesthesia was never required. No ventricular ectopy was induced by current delivery, and no hemodynamic changes were noted. The mean maximal creatine kinase level after ablation was 82±42 IU/L (normal, 62–177 IU/L), and creatine kinase–MB isoenzyme levels were normal.

Effects of Ablations
Early results. The initial effects of radiofrequency ablation are summarized in Figure 2. Thirty of 39 patients (77%) had no inducible AVNRT after the ablation and had intact AV conduction. Three patients (8%) had inadvertent complete AV block and received permanent pacemakers. AVNRT continued to be present in six patients (15%). Three (patients 19, 21, and 23) of these six patients had repeat ablations with successful outcomes. One (patient 17) experienced arrhythmia control on medications that were previously ineffective. The remaining two of these six patients (patients 8 and 27) were symptomatically unchanged.

AVNRT was induced at early restudy in two patients (patients 22 and 24), and both had successful repeat ablations. The 30 patients with initially successful procedures plus the three that had a favorable outcome after repeat ablation resulted in 33 of 39 patients (85%) having no spontaneous or inducible AVNRT at time of hospital discharge.

Late results. The effects of radiofrequency ablation at follow-up are summarized in Figure 3. Thirty-three patients were successfully treated and followed up for 8±3.0 months. An additional patient (patient 17) who was controlled on previously ineffective medical treatment developed first-degree AV block and has remained asymptomatic without drugs.

Of these 34 patients, 19 have not had spontaneous recurrences, and follow-up electrophysiological studies performed at 2–4 months have shown no inducible AVNRT. Nine patients have had no recurrences, and follow-up studies were either refused or are pending. Four patients have had recurrences during follow-up. Two of these (patients 36 and 37) underwent repeat procedures and were successfully treated. One (patient 21) is being treated with an atrial antitachycardia pacemaker, and one (patient 19) elected to have complete AV junction ablation and a permanent pacemaker. Two patients were withdrawn from the study. One (patient 18), aged 79, was successfully treated but died 1 month later from cardiogenic shock during a myocardial infarction. The other (patient 5), although cured of AVNRT, requested a complete AV junction ablation because of symptoms of inappropriate sinus tachycardia that had existed before the procedure. Therefore, of the 32 successfully treated patients available for follow-up, 30 (94%) have been free of recurrent AVNRT.

Complications. Two patients (patients 4 and 18) had deep venous thrombosis at the site of femoral venipuncture. As mentioned previously, three patients had complete AV block. Two of the three had complete AV block during ablation. The third (pa-
TABLE 2. Biophysical Parameters and Outcomes of Radiofrequency Ablation of the Perinodal Region

<table>
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<tr>
<th>Patient</th>
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<td>15</td>
<td>69</td>
<td>No SVT</td>
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RF, radiofrequency ablation; No SVT, no induced atrioventricular nodal reentrant tachycardia after ablation; SVT, atrioventricular nodal reentrant tachycardia still inducible, or spontaneous recurrence noted; C AV block, inadvertent complete atrioventricular block produced.

Patient 10) had stable 2:1 conduction throughout hospitalization but was readmitted several weeks later with complete AV block and a junctional escape at 50 beats/min. A permanent pacemaker was implanted at that time. No other high-grade AV block was seen during the follow-up period.

Early Effects on Atrioventricular Conduction

Antegrade function. After successful treatment, only three of the 17 patients with dual AV nodal physiology had a persistent sudden increase (>50 msec) in the AH interval in response to progressively premature atrial extrastimuli. Figure 4 demonstrates
AV nodal function curves before and after ablation in a typical patient. Note that the curve after ablation appears similar to the slow pathway curve before ablation.

After successful ablation, a significant increase in the AH interval was noted at comparable sinus cycle lengths (Table 3). The AH interval increased from 93±24 msec at the baseline study to 177±74 msec at early restudy (p=0.008) and from 74±16 to 146±73 msec during isoproterenol infusion (p=0.006). Antegrade AV nodal function before and after ablation are compared in Table 3. Despite nearly a 100% increase in the AH interval, there was no significant change in the AV nodal Wenckebach cycle length or in the antegrade effective refractory period.

Retrograde function. Of the 33 patients who were successfully treated, 14 had complete VA block. In the 19 patients who continued to have VA conduction, there was a significant increase in the retrograde block length from 247±28 msec at the baseline study to 363±112 msec at restudy 2–4 days later (p<0.05).

At follow-up study, two patients (patients 7 and 13) had nonsustained AV nodal reentrant echo complexes induced during isoproterenol infusion (Figure 5). These echo complexes had long VA and AV times; however, the retrograde conduction time was longer than the antegrade conduction time. The echo complexes were reproducibly brought on by a critically timed ventricular extrastimulus, and the VA and AV relations were consistent in each patient. Two patients (patients 16 and 38) had sustained “atypical” AVNRT induced by isoproterenol with retrograde conduction times longer than antegrade. Neither patient has been treated, nor have they had symptomatic arrhythmias.

Late Electrophysiological Results: Antegrade and Retrograde Function

The AH interval and antegrade AV nodal conduction and refractoriness were unchanged in the 19 patients that had electrophysiological studies at 2–4 months compared with those obtained 2–4 days after ablation. None of these patients had AVNRT induced before or during isoproterenol infusion. Four patients (patients 24, 25, 26, and 28) had dual antegrade AV nodal physiology demonstrated. Thirteen of the 19 had VA conduction, including four patients who had VA block at the early restudy. One
TABLE 3. Atrioventricular Nodal Function Before and After Ablations

<table>
<thead>
<tr>
<th></th>
<th>Successfully treated patients</th>
<th>Unsuccessfully treated patients</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Restudy at 2–4 days</td>
</tr>
<tr>
<td>SCL (msec)</td>
<td>820±239</td>
<td>793±141</td>
</tr>
<tr>
<td>AH (msec)</td>
<td>74±15.7</td>
<td>146±73.3</td>
</tr>
<tr>
<td>AVN-BCL (msec)</td>
<td>271±64.2</td>
<td>282±55.4</td>
</tr>
<tr>
<td>AVN-erp (msec)</td>
<td>217±31.4</td>
<td>232±50.5</td>
</tr>
<tr>
<td>VA-BCL (msec)</td>
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<td>363±111.5</td>
</tr>
<tr>
<td>VA-erp (msec)</td>
<td>209±10.5</td>
<td>250±99.8</td>
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</table>

Values are mean±SEM. Drive cycle lengths were 400 msec. Retrograde conduction and refactoriness were compared in those patients who had intact retrograde conduction after ablation.

SCL, cycle length during normal sinus rhythm (all other values were recorded using isoproterenol); AH, atrial-His interval; AVN-BCL, longest paced cycle length at which Wenckebach or higher grade antegrade block occurred; AVN-erp, antegrade effective refractory period of the slow pathway; VA-BCL, longest paced cycle length at which ventriculoatrial dissociation was noted; VA-erp, retrograde effective refractory period.

(patient 25) had nonsustained AV nodal reentrant echo beats with long VA and AV times, and another (patient 26) had sustained atypical AVNRT induced with isoproterenol. This patient, along with the other two noted to have atypical AVNRT at early restudy, have been free of symptomatic arrhythmias in the absence of treatment.

Predictors of Success

There were no clinical characteristics (e.g., age, sex, or duration of symptoms) that were correlated with a successful outcome. Similarly, there were no differences in baseline electrophysiological parameters (AH, antegrade, and retrograde conduction and refactoriness) between those patients who subsequently had successful or unsuccessful procedures.

As expected from the ablation protocol, there was a tendency toward a greater number of radiofrequency applications in patients who had unsuccessful procedures, but this did not reach statistical significance (p=0.09). The power and duration of each application were not different.

Although a significant increase in the AH interval (from 77±19 to 114±30 msec, p=0.015) was noted immediately after the procedure in patients who were unsuccessfully treated, by early restudy, the AH had decreased to 99±23.6 msec (p=NS). In contrast, patients who had successful procedures had a greater initial change in the AH interval (from 74±16 to 138±61 msec, p=0.006), which persisted at restudy (Table 3).

All patients unsuccessfully treated continued to have VA conduction, with no significant change in the VA block cycle length or in the retrograde effective refractory period. In contrast, patients successfully treated had complete VA block or a mean prolongation of VA block cycle length of 47% if retrograde conduction persisted.

Discussion

Summary of Clinical Results

Thirty-nine patients with the typical form of AVNRT were treated with radiofrequency catheter ablation of the perinodal region. Tachycardia could no longer be induced, and AV conduction was preserved in 33 of 39 (85%) patients. All but two patients successfully treated have remained free of tachycardia during a mean follow-up of 8 months. Inadvertent complete AV block requiring permanent

![FIGURE 5. Recordings showing two beats of "atypical" atrioventricular nodal reentrant tachycardia after perinodal ablation in a successfully treated patient. The drive cycle length was 450 msec, and the interval between the last driven complex (S1) and the premature ventricular complex (S2) was 340 msec. Note that the ventriculoatrial intervals in the echo complexes exceed those of the atrioventricular interval. HRA, high right atrial electrocardiogram; HBE(d), bipolar His bundle electrocardiogram recorded from the distal poles of a quadripolar catheter; HBE(p), bipolar His bundle electrocardiogram recorded from the proximal poles of a quadripolar catheter.](http://circ.ahajournals.org/Download.png)
pacing occurred in three of 39 patients (8%). There was no significant difference in efficacy rates between the two institutions.

Comparison to Reports of Catheter Modification Using Direct Current Shock

Two recent studies have described percutaneous catheter ablation with high-voltage defibrillator discharges for the treatment of AVNRT. Haissaguerre and associates\(^25\) delivered shocks to the interatrial septum after withdrawing the catheter several millimeters from the site of the largest recorded His electrogram. This area corresponded to the site of earliest retrograde atrial activation during tachycardia. This catheter position was probably similar to the ablation site in the current study, since the mean atrial to ventricular electrogram ratio was 4.7 and the His electrogram amplitude was less than 100 \(\mu\)V. Tachycardia was eliminated in 76% of patients, and 10% required permanent pacemakers. Epstein et al\(^12\) reported results of catheter modification of the AV junction with direct current shocks in nine patients with AV node reentry tachycardia. Shocks were delivered in multiple locations in most patients, and all received discharges posteriorly, between the His bundle and the ostium of the coronary sinus. Tachycardia was eliminated in six of nine patients (67%), and none required permanent pacing.

Although efficacy rates are similar, the use of radiofrequency current to treat AVNRT may have advantages over direct current shock ablation. General anesthesia is not required. Also, the need for repeat ablation sessions in this study was less than half that reported by Haissaguerre et al.\(^25\) This difference may reflect the fact that transient AV block occurred in all but one patient in their series, making titration of the ablative energy dose problematic.

Electrophysiological Effects of the Ablation

Several observations suggest that AVNRT was eliminated via selective effects on the retrograde fast pathway. The AH interval increased from 74 to 146 msec in successfully treated patients. However, the AV node block cycle length and effective refractory period did not change, suggesting that this dramatic increase in conduction time was not simply a manifestation of generalized damage to the AV node. Perinodal radiofrequency lesions in dogs have produced similar effects.\(^23\) In contrast, retrograde conduction was eliminated or attenuated (as manifested by an increase in VA block cycle length or prolongation of retrograde conduction time) in all but one successfully treated patient. The elimination of the abrupt increase in AH interval typical of conversion from fast to slow pathway conduction with progressively premature atrial extrastimulation in 14 of 17 patients is also consistent with this hypothesis.

The electrophysiological effects of radiofrequency ablation of the perinodal region are distinctly different from those following direct current shock ablation. Both antegrade and retrograde AV conduc-

tion may be significantly attenuated after direct current ablation, perhaps reflecting the more diffuse and variable nature of tissue injury with this energy source.

Three patients who had typical AVNRT eliminated by the ablation had atypical reentry induced during isoproterenol infusion. This was characterized by retrograde conduction times longer than antegrade. Since none of these patients had a spontaneous episode of tachycardia during follow-up, the clinical significance of this arrhythmia is uncertain. There are several possible explanations for this intriguing observation. Damage to the fast pathway may have resulted in prolongation of retrograde conduction times, which, in turn, might be expected to shorten antegrade conduction time during tachycardia. Multiple nodal-atrial pathways may be capable of mediating reentry such that ablation of one retrograde pathway could unmask a second, slower pathway. Alternatively, the ablative lesion might have altered pathway refractoriness such that the impulse negotiated the slow pathway retrogradely and the fast pathway antegrade (true atypical AVNRT).

Three successfully treated patients had persistence of dual AV nodal physiology, and one of these three had no detectable change in retrograde conduction. It is possible that ablative lesions in these patients may have had their predominant effect on the upper final common pathway of reentry or ablated atrial fibers critical for maintenance of the tachycardia rather than directly on the antegrade or retrograde limbs. Some patients treated with intraoperative ablation of the perinodal atrium have also had long-term arrhythmia control with minimal change in retrograde AV nodal function.

Limitations

Detailed mapping of the sequence of retrograde atrial activation during tachycardia was not performed. It is possible that some of the patients who could not have tachycardia eliminated had retrograde pathway insertion in a location different from the site of ablation. Comparison of retrograde activation sequences before and after ablation might have been useful to confirm selective effects of the procedure on the fast pathway.

The duration of follow-up was relatively brief. Although progressive AV block was not observed after 8 months, the long-term effects of the procedure on AV conduction are unknown.

The 8% incidence of inadvertent AV block is comparable with that reported by Haissaguerre et al\(^25\) for direct current shock ablation of AVNRT. Preliminary surgical reports by Holman et al,\(^8\) Wood et al,\(^9\) Ross et al,\(^10\) and Guiraudon et al\(^11\) describe a low incidence (0–2%) of postoperative AV block. This apparent advantage of operative ablation must be considered in context of the increased expense and morbidity of open heart surgery. Also, detailed reports of larger series of surgically treated patients are lacking, making estimation of operative risk difficult.
Clinical Implications

Radiofrequency catheter modification of the peri-nodal region appears to be effective for elimination of AVNRT. Unlike direct current shock, this energy source is not associated with explosive gas formation, eliminating the risk of barotraumatic side effects. Titration of the extent of ablative injury to achieve a desired electrophysiological effect may be less problematic with radiofrequency as compared with direct current energy, as reflected by the lower incidence of repeat sessions.

Improvements in mapping and catheter design offer the hope of reducing the incidence of conduc tion block in the future. Careful long-term follow-up studies of patients treated with both operative and catheter ablation are mandatory to determine the possibility of delayed effects on AV conduction.

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