Catheter Ablation of the Atrioventricular Junction With Radiofrequency Energy

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Catheter ablation of the atrioventricular junction using direct-current defibrillator discharges requires general anesthesia and may have serious side effects. Sixteen patients with drug-refractory supraventricular tachycardia underwent catheter ablation of the atrioventricular junction using radiofrequency energy. A standard 7F quadripolar electrode catheter was positioned to record the largest unipolar His potential (580±640 μV) from the distal electrode. An electrocoagulator (Microvasive Bicap 4005) supplied continuous, unmodulated energy at 550 kHz. One to 14 applications of radiofrequency current were delivered between the distal electrode and a large-diameter chest wall electrode. Transient, mild chest discomfort was reported by seven of 16 patients. None had significant arrhythmias or blood pressure changes during radiofrequency ablation. Complete atrioventricular block was produced in nine of 16 patients and high-grade second-degree atrioventricular block was produced in one patient with radiofrequency current. Attenuated His bundle electrograms could still be recorded in the remaining six patients, four of whom underwent successful atrioventricular junctional ablation using direct-current shock during the same session. Atrioventricular block persisted in all 10 patients successfully treated with radiofrequency ablation during a mean follow-up of 4.2 months. Compared with a group of historic control subjects treated with direct-current shock ablation, the 10 patients successfully treated with radiofrequency current had significantly less creatine kinase–MB isoenzyme release (5.7±5.1 vs. 22±13 IU, p=0.006). A junctional escape rhythm was present in all patients after radiofrequency-induced atrioventricular block. In contrast, three of 10 control patients had an idioventricular escape after direct current shock ablation, and four patients had no escape rhythm at all. We conclude that 1) catheter ablation of the atrioventricular junction with radiofrequency current appears to be safe and successfully induced persistent atrioventricular block in 62% of patients; 2) radiofrequency ablation may result in more stable escape rhythms and less creatine kinase–MB isoenzymes release than direct-current shock ablation; and 3) a majority of patients with drug-refractory supraventricular tachycardia can be successfully treated with application of radiofrequency energy, whereas failure to achieve atrioventricular junctional ablation with this technique does not appear to mitigate against successful application of direct-current shock ablation. (Circulation 1989;80:1527–1535)

Catheter ablation of the atrioventricular junction in humans with direct-current defibrillator discharges was first described in 1982.1,2 This technique has largely replaced the need for surgical division of the bundle of His as definitive therapy for patients with drug-refractory supraventricular tachycardia. Although the technique is effective, it is associated with many disadvantages. The shock is painful, so general anesthesia is required. More important, the high-voltage pulse causes arcing with explosive gas formation.3 The resulting shock wave may, on rare occasions, cause serious side effects, including ventricular tachycardia, hypotension, and cardiac perforation.4–6

These problems have prompted a search for alternative forms of ablative energy. Radiofrequency current has been shown to be safe and effective for

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induction of chronic, complete atrioventricular block in dogs. It produces a small, well-circumscribed area of coagulation necrosis through resistive heating. The high-frequency energy does not depolarize skeletal muscle, obviating the need for general anesthesia. Because the voltages used range between 15 and 50 V, there is no arcing or explosive gas formation. No hemodynamic changes or ventricular ectopy are observed during radiofrequency ablation of the atrioventricular junction in animals.

We investigated the safety and effectiveness of catheter ablation of the atrioventricular junction with radiofrequency energy in patients with drug-resistant supraventricular tachycardia.

Methods

Patient Population

All patients undergoing ablation of the atrioventricular junction with the intention to create complete atrioventricular block between July and November 1988 were included in the study. Clinical characteristics of this cohort are summarized in Table 1. The mean age was 45 years (range, 26–73 years), and nine of the 16 patients were men. Structural heart disease was present in five patients. Two patients had hypertrophic cardiomyopathy, and three patients had mild-to-moderate idiopathic dilated cardiomyopathy, possibly related to a history of ethanol use in two. Atrial fibrillation, atrial flutter, or both was present in nine patients, atrioventricular nodal reentry tachycardia in three patients, and ectopic atrial tachycardia in three patients. Three other patients had orthodromic supraventricular tachycardia in the presence of a concealed extranodal accessory pathway.

Symptomatic tachycardia had been present for 8.3±6.2 years (mean±SD) and resulted in syncope...
in three patients. Two patients with enhanced atrio-
ventricular nodal function had sustained cardiac
arrests believed to be precipitated by extremely
rapid rates during supraventricular tachycardia. The
mean heart rate during spontaneous tachycardia
was 208±52 beats/min. These patients had been
refractory to or intolerant of a mean of 4.4±1.9
antiarrhythmic drugs, including three patients with
persistent tachycardia despite amiodarone therapy.

Ten consecutive patients who underwent ablation
of the atrioventricular junction with direct-current
shock between November 1980 and June 1988 served
as historic controls. There were no significant dif-
fferences in the clinical characteristics of control
versus study patients (Table 1).

**Experimental Protocol**

All patients considered for ablation of the atrio-
ventricular junction agreed to participate in the
study and gave written, informed consent for the
procedure. Two-dimensional echocardiography was
performed before ablation in all patients. A catheter
was placed in the femoral artery for continuous
monitoring of blood pressure. A 6F quadripolar
electrode catheter was introduced into the femoral
vein and advanced into the right ventricular apex to
serve as a temporary pacemaker. A standard 7F
quadripolar electrode catheter (USCI, Inc) with
1-cm interelectrode spacing was positioned across
the tricuspid annulus and was manipulated to record
the largest unipolar His potential from the distal
electrode. Unfiltered (0.05–500 Hz) recordings were
obtained to determine the amplitudes of the atrial
and His bundle electrograms.

An electrosurgical unit (Microvasive Bicap 4005)
supplied a continuous unmodulated sine wave
output at 550 kHz that was variable from 0 to 50 V. The
dial setting of the electrosurgical unit was kept
constant at 40 V (16 W) into a 100-Ω load. How-
ever, because of differences in loading conditions
between patients, actual delivered power was vari-
able. Current was routed through a custom-built
controller that provided 0–1-V direct-current sig-
nals corresponding to applied root-mean-squared
voltage, current, and total energy. Current was
applied between the distal pole of the electrode and
a large diameter skin electrode (R2, Inc) placed
over the left scapula. A custom passive filter was
interposed between the surface electrocardiogram
electrodes and the monitor (Electronics for Medi-
cine VR-16) to allow noise-free recording during the
ablation.

The ablation protocol varied according to the
electrophysiologic response to applied energy (Fig-
ure 1). If no change in conduction was seen, then
current was applied for a total of 120 seconds and
the catheter was repositioned. During some abla-
tions, there was an abrupt fall in current due to a
rise in impedance; this most likely represented
desiccation of tissue and coagulum formation adja-
cent to the distal electrode. Energy application was
discontinued immediately, and the catheter was
withdrawn. Any adherent coagulum was removed
and the catheter was repositioned. When second-
or third-degree atrioventricular block was observed
during energy application, current flow was contin-
ued for an additional 30 seconds. If conduction
resumed after cessation of current flow, then the
ablation was repeated without moving the catheter.
If atrioventricular block persisted for 15 minutes,
then the session was concluded. Temporary pacing
was withheld transiently, and the escape rhythm
was assessed at this time. The patient went on
immediately to permanent pacemaker implantation
after successful induction of atrioventricular block.

During some applications of radiofrequency
energy, transient effects on conduction were
observed. In this situation, current was reapplied
without changing catheter position. If repeating
radiofrequency ablation failed to produce transient
atrioventricular block, then the catheter was repositioned. If even transient conduction block could
not be produced after three successive changes in
catheter position, the procedure was considered
unsuccessful.

![Figure 1. Flow chart summarizing experimental protocol. Duration of current flow and number of applications in each patient was determined by the response to radiofrequency energy. (See text for details.)](image-url)
FIGURE 2. Left panel: Recording of onset of radiofrequency ablation in patient 9. Surface leads $V_6$, $I$, $II$, and $aVF$ are recorded at top. Lower tracings correspond to applied voltage ($V$) and current ($A$). Note occurrence of accelerated junctional rhythm with retrograde P waves ($Pr$) after several seconds of current flow. Right panel: Recording from same patient 30 seconds after onset of radiofrequency energy showing development of atrioventricular dissociation. Note that right bundle branch block occurs coincident with onset of atrioventricular block.

FIGURE 3. Tracing of comparison of escape rhythms in patient 3 after radiofrequency (RF) ablation (top panel) to control patient 6 after direct-current (DC) shock ablation (lower panel). There is stable junctional escape with right bundle branch block after radiofrequency. In contrast, discontinuation of ventricular pacing for 3 seconds (arrow) shows no underlying escape after DC shock.
TABLE 2. Electrophysiologic and Biophysical Parameters During Radiofrequency Ablation of Atrioventricular Junction

<table>
<thead>
<tr>
<th>Patient</th>
<th>Atrial electrogram amplitude (mV)</th>
<th>His electrogram amplitude (µV)</th>
<th>HV interval (msec)</th>
<th>RF applications (n)</th>
<th>Applied power (W)</th>
<th>Impedance (Ω)</th>
<th>Applied energy (J)</th>
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<tbody>
<tr>
<td>Group 1—AVB with RF</td>
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<td></td>
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<td>2</td>
<td>21</td>
<td>98</td>
<td>410</td>
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<td>1,137±940</td>
<td>687±767</td>
<td>55±7.1*</td>
<td>3.9±3*</td>
<td>17.2±5</td>
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<td>857±569*</td>
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<td>400±311</td>
<td>40±4.5*</td>
<td>9.7±3.3*</td>
<td>17.3±5</td>
<td>104±24</td>
<td>2,082±1,720*</td>
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</table>

*p<0.05.

Electrogram amplitudes were recorded in a unipolar fashion from the distal electrode of the catheter used for ablation with minimal filtering (0.05-1,000 Hz). AVB, atrioventricular block; CAVB, complete atrioventricular block; RF, radiofrequency current.

The patient then underwent ablation of the atrioventricular junction with direct-current defibrillator discharges. The technique used for direct-current shock ablation has been described previously. General anesthesia was induced with sodium pentobarbital, and two or more 300-J discharges were applied with the distal electrode of the catheter serving as the cathode and the skin electrode as the anode. Patients were observed for 30 minutes after direct-current ablation and then underwent permanent pacemaker implantation.

Creatine phosphokinase and 12-lead electrocardiograms were obtained 4 and 24 hours after the ablation. Echocardiography was repeated 24-48 hours after the procedure as well. Continuous electrocardiographic monitoring was performed for at least 48 hours after the procedure. Atrioventricular conduction and escape rhythm were assessed on an outpatient basis 1-5 months after the procedure.

Statistical analysis was performed using the two-tailed Student’s t test for unpaired variables.

Results

Electrophysiologic and Biophysical Parameters During Ablation

Clinical characteristics, including age, gender, presence of structural heart disease, and atrial rhythm at the time of ablation, did not correlate with outcome. Findings just before and during radiofrequency ablation are summarized in Table 2. There was no significant difference in unipolar atrial or His bundle electrogram amplitude between those patients who had permanent atrioventricular block induced with radiofrequency (group 1) and those who did not achieve atrioventricular block with radiofrequency application (group 2). The baseline HV interval was significantly longer in group 1 (55±7.1 msec) compared with HV intervals in group 2 (40±4.5 msec, p<0.001).

Radiofrequency current was applied a total of 97 times in the 16 patients. A mean of six applications (range, one to 14) were used in each patient. Transient atrioventricular block during application of radiofrequency current was observed 32 times and persisted in 10 of these 32. An accelerated junctional rhythm preceded the occurrence of atrioventricular block in all 32 of these applications (Figure 2). However, an accelerated junctional rhythm was also observed during 15 of the 65 radiofrequency applications that did not produce atrioventricular block.

Power, impedance, and total delivered energy during the application having the greatest effect on atrioventricular conduction in each patient are shown in Table 2. A mean of 17.2±4.7 W was applied for 37±22 seconds, resulting in a delivered energy of 1,320±1,250 J. There was no significant difference in power or impedance between groups 1 and 2. Because of the longer duration of current flow, the total delivered energy was higher in
TABLE 3. Effects of Radiofrequency Ablation Compared With DC Shock Ablation of Atrioventricular Junction

<table>
<thead>
<tr>
<th>Patient</th>
<th>Escape rhythm</th>
<th>Escape rate</th>
<th>Peak CK</th>
<th>Peak CK/MB</th>
<th>Complications</th>
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<tr>
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<td>41</td>
<td>157</td>
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<tr>
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<td>49±8</td>
<td>179±131</td>
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<td>Control patients—DC shock ablation</td>
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<td>42±15</td>
<td>198±76</td>
<td>22±13*</td>
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</table>

*p=0.006 vs. study patients.

§LBBB was present before ablation.

The 10 study patients had atrioventricular block produced with radiofrequency (RF) current. The historic controls had DC shock ablation of the atrioventricular junction. IDIOVENT, idioventricular escape; JUNCT, junctional escape rhythm; LBBB, left bundle branch block; NON-SUST VT, nonsustained ventricular tachycardia; RBBB, right bundle branch block.

group 2 (2,082±1,720 J) compared with group 1 (857±569 J) (p=0.053).

Effects of Radiofrequency Ablation

The effects of radiofrequency ablation are summarized in Table 3. Persistent atrioventricular block was produced with a mean of four (range, one to 10) applications of radiofrequency current in 10 of 16 patients. Five of these 10 patients in group 1 had new right bundle branch block, and one had new left bundle branch block produced along with atrioventricular block. Despite these effects on infra-nodal conduction, all 10 patients appeared to have a stable junctional escape rhythm after ablation. A His bundle electrogram could be recorded in nine of 10 patients after successful radiofrequency ablation without a significant change in the HV interval (51±8 msec after ablation vs. 55±7 msec before ablation). Patient 8, who had a preexisting left bundle branch block, did not have a visible His bundle electrogram after radiofrequency-induced complete atrioventricular block. However, the morphology of the escape complexes was unchanged, suggesting that it emanated from the common bundle or the proximal right bundle branch. Complete atrioventricular block persisted during 48 hours of continuous monitoring in nine of 10 patients in group 1. Patient 7 had recovery of conduction 30 minutes after ablation. However, high-grade second-degree atrioventricular block persisted with PR intervals in excess of 0.6 seconds for conducted complexes.

Atrioventricular conduction could not be disrupted with a mean of 10 (range, four to 14) applications of radiofrequency current in six of 16 patients (group 2). A new right bundle branch block was produced in five of these six patients. Although decreased in amplitude, His bundle electrograms could be recorded in all group 2 patients after attempted radiofrequency ablation. As with group 1, there was no significant change in HV interval after radiofrequency applications.

The six patients in group 2 underwent ablation of the atrioventricular junction using standard direct-current defibrillator discharges. Two shocks of 300 J were applied in five of six patients. Patient 13 had return of conduction several minutes after receiving two 300-J discharges and received two additional 300-J shocks. This patient, as well as patient 15, had recovery of conduction 1 and 4 hours after the last
ablative shock. Both patients continue to have episodes of symptomatic tachycardia despite drug therapy. Unlike in patients in group 1, His bundle electrograms were not visible in any patients in group 2 after direct-current shock ablation. An idioventricular escape was seen in two patients and a probable junctional rhythm in two of the patients after direct-current shock ablation.

Comparison of Radiofrequency and Direct-Current Shock Ablation

The duration of the ablation procedure (defined as the time from entry to exit of the patient from the electrophysiology suite) was nearly identical between study (groups 1 and 2) and control groups (131±48 and 130±29 minutes, respectively).

One patient in the control group (patient 9) had recovery of conduction approximately 6 hours after the procedure.

The outcome of patients in group 1 treated exclusively with radiofrequency current was compared with controls treated with direct-current shock ablation of the atrioventricular junction (Table 3). All patients in group 1 had stable junctional escape rhythms after ablation. In contrast, four of 10 control patients had no escape after a 3–5-second pause, and three of the remaining six had idioventricular escapes (Figure 3). The peak creatine kinase–MB isoenzyme concentration was significantly less after successful ablation with radiofrequency current compared with controls (5.7±5.1 vs. 22±13 IU, p=0.006).

Complications After Radiofrequency Ablation

No blood pressure changes in excess of 10 mm Hg were seen during any of the 97 applications of radiofrequency current (Figure 2). Premature ventricular contractions were recorded during 18 applications, couplets during one, and a ventricular triplet during one application. No higher grades of ventricular ectopy were observed. Patient 2 had symptomatic, nonsustained, polymorphous ventricular tachycardia 12 hours after ablation. This was treated with an increase in the ventricular paced rate from 50 to 80 and initiation of mexiletine therapy.

Burning chest discomfort was reported by seven of 16 patients during the first application of radiofrequency energy. The discomfort was described as mild by all seven patients, and none requested additional analgesia. Interestingly, the chest pain was completely absent with subsequent applications in four patients and markedly decreased in three patients.

An abrupt rise in impedance, with concomitant fall in current and power output, occurred during 46 of the 97 applications of radiofrequency current. The catheter was withdrawn and inspected after each rise in impedance. In each instance, a thin film of coagulum was observed to be adherent to the distal electrode. No untoward clinical events were precipitated by impedance rise.

Echocardiography after ablation was notable for the absence of pericardial effusion, valvular damage, or new regional wall motion abnormalities. There was no deterioration of overall ventricular function in any patient.

Complications After Direct-Current Shock Ablation

Five of the 10 control patients had minor complications after direct current shocks; two patients had asymptomatic pericardial effusions on follow-up echocardiography and one patient had pleuritic chest pain believed to be due to shock-induced penetration of the right ventricular electrode catheter. Hypotension with a systolic blood pressure of 60 mm Hg occurred in one patient; this resolved after 10 minutes with infusion of 500 ml saline and elevation of the legs. Patient 7 had recurrent nonsustained ventricular tachycardia for approximately 5 minutes after the second ablative shock that resolved spontaneously.

Short-term Follow-up

Pacing system evaluation and assessment of underlying rhythm was performed in 14 of 16 patients 4.2 months (range, 3–9 months) after ablation. All patients discharged from the hospital with complete atrioventricular block induced by radiofrequency remained without atrioventricular conduction. Patient 7 had persistent high-grade, second-degree atrioventricular block. Patient 4, who had atrioventricular reentry tachycardia due to a concealed septal accessory pathway, had elimination of both antegrade conduction via the normal pathway as well as retrograde accessory pathway conduction after radiofrequency ablation. At 1 month follow-up, complete antegrade block persisted, but retrograde conduction via the accessory pathway had recovered.

Discussion

Radiofrequency current was applied to the atrioventricular junction of 16 patients with drug-refractory supraventricular tachycardia. A mean of six applications of 17±5 W resulted in persistent complete atrioventricular block in nine patients and high-grade, second-degree block in one, for an overall success rate of 62%. Direct-current defibrillator discharges were used in the remaining patients and interrupted atrioventricular conduction in four of six patients.

There have been several preliminary reports documenting successful ablation of the atrioventricular junction in small numbers of patients with radiofrequency energy. Lavergne et al11,12 and Huang et al13 describe induction of complete block in four of six patients and note the occurrence of right bundle branch block in one patient who could not be successfully ablated. Borggreve and coworkers14,15
were able to abolish conduction with radiofrequency ablation in four of nine patients, and Bowman et al. were successful in three of three patients. However, to our knowledge, the present study represents the first detailed description of a larger series of patients treated with radiofrequency energy.

Predictors of Success for Radiofrequency Ablation

Although there was a trend toward larger atrial and His bundle electrogram amplitudes in patients successfully treated with radiofrequency current, this did not reach statistical significance. However, the HV interval recorded just before ablation was significantly longer in group 1 (persistent complete atrioventricular block induced with radiofrequency). This suggests that a more proximal catheter position increased the likelihood of successful ablation.

A junctional rhythm was always observed during applications of radiofrequency that resulted in atrioventricular block. Although this finding was associated with a sensitivity of 100%, it was relatively nonspecific because it was observed in 15 of 65 (23%) of applications that did not have long-lasting effects on atrioventricular conduction.

Complications

There were no major complications during any of the 97 applications of radiofrequency. Specifically, no malignant ventricular arrhythmias, hypotension, or myocardial perforation occurred, all of which have been reported as infrequent complications after direct-current shock ablation.4-6

Fifty percent of the patients successfully treated with radiofrequency had involvement of the infranodal conduction system manifest by a new bundle branch block. However, all such patients had a junctional escape without prolongation of the HV interval, suggesting that infranodal injury was fairly discrete and less extensive than with direct-current shock ablation.

Seven patients experienced mild chest discomfort during the initial application of radiofrequency. This was transient and was absent or distinctly diminished with subsequent applications of radiofrequency. This change may be due to destruction of the innervation mediating the discomfort with the first ablation.

One patient had polymorphous ventricular tachycardia 12 hours after radiofrequency-induced complete atrioventricular block. No ventricular ectopy was observed during the procedure itself. The arrhythmia appeared to be bradycardia-dependent and resolved with an increase in pacing rate. The patient was treated with mexiletine for 2 weeks and has not had a clinical recurrence during 4 months of follow-up.

Effects of Radiofrequency as Compared With Direct-Current Shock Ablation

Atrioventricular block was induced with radiofrequency current in 62% of patients. In contrast, complete atrioventricular block was achieved in 71% of 127 patients reported to the Percutaneous Mapping and Ablation Registry using direct-current shock4 and in 90% of the historic control group in the current study. The His bundle electrogram could still be recorded in all six patients after unsuccessful radiofrequency ablation, allowing for successful direct-current shock ablation in four of six. Thus, the overall success rate for the combined technique was 87.5%, comparable to that achieved with direct-current shock alone.

Radiofrequency ablation of the atrioventricular junction appears to offer several advantages over the use of direct-current ablation. General anesthesia was not required. A junctional escape rhythm was present in all patients after radiofrequency-induced atrioventricular block. In contrast, 40% of control patients had no escape rhythm after direct current shock. In addition, creatine kinase–MB isoenzyme concentrations were significantly less in group 1 patients compared with control subjects. This is consistent with observations from studies in animals showing that radiofrequency ablation produces smaller, more discrete lesions than direct-current defibrillator discharges.8

There were five complications in the control group that were most likely the result of shock-induced barotrauma. Although none of these complications produced persistent adverse clinical effects, the potential for serious and even fatal complications after direct-current shock ablation is well recognized.6

Clinical Implications

Radiofrequency current successfully induced atrioventricular block in 62% of patients in this study. There were no significant complications, and general anesthesia was not required. The patients were left with a junctional escape that remained stable during short-term follow-up. Four of six patients who failed radiofrequency ablation had atrioventricular block induced with direct-current shock. If subsequent studies confirm these preliminary results, then radiofrequency ablation may become the initial technique of choice for induction of atrioventricular block in patients with refractory supraventricular tachycardia. Whether changes in catheter design can increase the effectiveness of the procedure is the subject of ongoing investigation.

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