Catheter Ablation of Atrioventricular Junction Using Radiofrequency Current in 17 Patients

Comparison of Standard and Large-Tip Catheter Electrodes

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Background. Two catheter electrode systems were compared for delivering radiofrequency current for ablation of the atrioventricular junction. Seventeen patients with drug-resistant supraventricular tachyarrhythmias were studied.

Methods and Results. A 6F or 7F catheter with six or eight standard electrodes (1.25 mm wide, 2.5-mm spacing) was used in the first seven patients (group 1). A 7F quadripolar catheter with a large-tip electrode (4 mm long; surface area, 27 mm²) was used in the final 10 patients (group 2). Both ablation catheters were positioned to record a large atrial potential and a small but sharp His bundle potential from the distal bipolar electrode pair. Radiofrequency current was applied between a large skin electrode on the left posterior chest and either 1) each individual electrode on the standard-tip electrode catheter at 40 V (group 1) or 2) the large-tip electrode at 50–60 V (group 2). Radiofrequency current was limited to 40 V in group patients because of the strong potential for an early impedance rise when higher voltage is applied through standard electrodes. Complete atrioventricular block was achieved in six of seven group 1 patients and all 10 group 2 patients. A junctional escape rhythm followed ablation in five or six group 1 patients (mean cycle length, 1,066±162 msec) and eight of 10 group 2 patients (mean cycle length, 1,281±231 msec). Atrioventricular block was produced in a mean of 4.7±4.6 radiofrequency current applications delivered over a period of 42±45 minutes using the large-tip electrode (group 2) compared with 46±22 applications using standard electrodes (15.9±10.2 applications delivered through the standard-tip electrode) over a period of 147±59 minutes (group 1). For the application producing atrioventricular block, the large-tip electrode used higher voltage (58±17 versus 38±5 V, p<0.03) and had lower impedance (103±22 versus 148±40 Ω, p<0.01), resulting in greater power (33.0±13.0 versus 10.2±0.6 W, p<0.003) and shorter time to block (8±3 versus 22±3 seconds, p<0.001). Current delivery through standard electrodes was limited by an impedance rise occurring 7±7 seconds after the onset of one or more radiofrequency current applications at 10±1 W in six of seven patients. Using the large-tip electrode, an impedance rise occurred in five of 10 patients, but at 25±10 W and after 21±9 seconds. Atrioventricular block occurred before the impedance rise in three of these five patients. Complete atrioventricular block persisted in 15 of 16 patients at a mean follow-up of 8.7 months. Atrioventricular conduction returned at 1 month in one group 2 patient and was successfully ablated by a second procedure. Three group 1 patients died 0.5–2 months after ablation, and a fourth patient underwent cardiac transplantation after 10 months. Pathological examination of the heart in two of these patients showed necrosis of the atrioventricular node and origin of the His bundle, without injury to the middle or distal His bundle. All 10 group 2 patients are alive and subjectively improved after ablation.

Conclusions. We conclude that catheter-delivered radiofrequency current effectively produces complete atrioventricular block (94%) without requiring general anesthesia or the risk of ventricular dysfunction or cardiac perforation. The large-tip electrode allows a threefold increase in delivered power and markedly decreases the number of pulses and time required to produce atrioventricular block. (Circulation 1991;83:1562–1576)
Since the first reports in 1982 by Scheinman et al. and Gallagher et al., catheter-mediated ablation of the atrioventricular junction has come into relatively frequent use in patients with drug-resistant supraventricular tachyarrhythmias. The catheter-ablation technique involves the delivery of high-energy DC shocks (from a conventional defibrillator) to catheter electrodes positioned close to the junction of the atrioventricular node and His bundle. This technique is quick and effective in producing permanent complete atrioventricular block, but hemodynamic collapse, ventricular arrhythmias, and cardiac rupture have occasionally resulted. Other limitations of DC shocks include the requirement for general anesthesia (usually a short-acting barbiturate).

Alternative energy sources are under investigation in an attempt to reduce the morbidity associated with DC shocks. One source, radiofrequency current, is often used in electrosurgery. The high-frequency AC flow through the tissue produces resistive heating. Necrosis results without barotrauma or significant neuromuscular stimulation, eliminating the need for general anesthesia. Recent clinical studies have shown that radiofrequency current can safely produce permanent complete atrioventricular block. However, this approach was successful in only 47–67% of patients. These preliminary studies used standard catheter electrodes to deliver radiofrequency current. Standard electrodes limit radiofrequency power to a relatively low level (approximately 10 W) because of a marked, sudden impedance rise that occurs at higher power. The impedance rise occurs when temperatures at the electrode–tissue interface reach 100°C and is associated with formation of coagulum on the electrode and carbonization if current delivery is not immediately terminated. One approach to prevention of the impedance rise uses a temperature probe within the electrode. The output of the electrosurgical unit is automatically varied to maintain a constant electrode temperature. High power (more than 15 W) is applied for the first few seconds as the temperature increases to the desired level (usually 70–90°C). The power is then rapidly reduced to a low level (less than 5 W) to maintain the desired temperature for the duration of the application (usually 20–60 seconds). This approach is based on the assumption that only a thin rim of tissue surrounding the electrode undergoes direct resistive heating, and the remainder of the lesion is produced by the conduction of heat to the surrounding tissue (i.e., electrode–tissue interface functions as a pure heat source, or “hot tip”).

Another approach attempts to increase lesion size by producing direct resistive heating at sites farther from the electrode. Higher power is applied while the electrode is cooled by saline irrigation to keep the electrode temperature below 100°C and prevent the impedance rise. Increasing electrode surface area might also reduce temperature and allow the application of radiofrequency current at higher power. A larger electrode may maintain lower temperatures at higher power by reducing local current density or by providing a large surface for convective heat loss to the blood pool. The purpose of the present study was to compare the efficacy of using a special large-tip electrode and higher power with the efficacy of standard catheter electrodes and standard power for producing complete atrioventricular block with radiofrequency current.

**Methods**

The study population comprised 17 patients with drug-resistant supraventricular tachyarrhythmias referred for atrioventricular junctional ablation (Table 1). Class IA and IC antiarrhythmic drugs were unsuccessful in maintaining sinus rhythm in all patients, and digoxin, β-adrenergic antagonists, and/or calcium channel blockers were unsuccessful in controlling the ventricular response. Details of the benefits and potential complications of catheter ablation of the atrioventricular junction and pacemaker implantation were presented to the patients. The investigational status of radiofrequency current and the option of using DC shocks were also discussed, and written informed consent was obtained.

For the ablation procedure, the patient was sedated with fentanyl and/or midazolam. Under local anesthesia (lidocaine), a 6F bipolar or quadripolar catheter was inserted percutaneously into the right subclavian vein and advanced into the right ventricular apex to be used for temporary ventricular pacing after ablation. Two catheters were inserted percutaneously into the right or left femoral vein—a 6F quadripolar catheter that was advanced into the right ventricle to be used for ventricular pacing should the other (subclavian) catheter become dislodged, and an ablation catheter as described below and illustrated in Figure 1.

In the first seven patients (group 1), radiofrequency current was delivered through a 6F (patients 1–5) or 7F (patients 6 and 7) catheter with six or eight conventional electrodes (1.25 mm wide, 2.5 mm spacing center-to-center; Mansfield/Webster Catheters, Boston Scientific Corp., Watertown, Mass.). The short interelectrode spacing restricts the bipolar recording range, allowing close localization of the electrodes with regard to the atrium and His bundle. The ablation catheter was initially positioned so that the distal bipolar pair recorded the largest His bundle potential. The catheter was then withdrawn until the distal electrode pair recorded a small but sharp
His bundle potential and a relatively large atrial potential. We postulated that a large, confluent lesion encompassing the junction of the atrioventricular node and His bundle could be created by delivering radiofrequency current separately to each of the six or eight closely packed electrodes positioned in this manner.

Radiofrequency current (continuous wave, 550–750 kHz) was generated by a conventional electrosurgical unit (Microvasive Bicap 4005, Boston Scientific Corp.). The electrosurgical unit was calibrated to deliver 40 V into a 200-Ω resistor. Earlier studies using the same system in animals found that delivery of radiofrequency current at more than 40 V frequently resulted in a prompt, 10-fold increase in impedance, preventing further significant energy delivery. Actual root-mean-square voltage and current output during ablation were recorded using a custom-made device (Mansfield Scientific, Boston Scientific Corp.). Power and impedance were estimated as the product and quotient, respectively, of voltage and current. Radiofrequency current was applied (for 20–90 seconds) separately to each of the electrodes on the ablation catheter using a standard adhesive electrosurgical dispersive electrode (11×19 cm) placed vertically on the left posterior chest (between the spine and scapula) for the return electrode. If complete atrioventricular block was not achieved, the catheter was repositioned slightly, and radiofrequency current was reapplied to the tip electrode and possibly one or more of the proximal electrodes. This sequence was repeated until atrioventricular block was produced and persisted for 30 minutes. Current application was immediately discontinued in the event of an impedance rise, and the catheter was exchanged or the coagulum was removed with a damp sterile gauze before repeating current delivery.

In the last 10 patients (group 2), radiofrequency current was delivered through a 7F quadripolar catheter (4 mm interelectrode spacing) with a special large-tip electrode (4 mm long; surface area, 27 mm²; Mansfield/Webster Catheters). This catheter (Figure 1) has a variable-tip curve, which is controlled by a

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (yr)</th>
<th>Sex</th>
<th>Heart disease</th>
<th>Arrhythmia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>69</td>
<td>F</td>
<td>Rheumatic heart disease; mitral stenosis</td>
<td>Chronic atrial fibrillation</td>
</tr>
<tr>
<td>2</td>
<td>54</td>
<td>M</td>
<td>Cor pulmonale</td>
<td>Chronic atrial fibrillation</td>
</tr>
<tr>
<td>3</td>
<td>67</td>
<td>M</td>
<td>Rheumatic heart disease status post aortic valve replacement; dilated cardiomyopathy</td>
<td>Chronic atrial flutter</td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>M</td>
<td>Idiopathic dilated cardiomyopathy</td>
<td>Ectopic atrial tachycardia</td>
</tr>
<tr>
<td>5</td>
<td>57</td>
<td>M</td>
<td>Coronary artery disease mitral valve prolapse with regurgitation</td>
<td>Paroxysmal atrial flutter</td>
</tr>
<tr>
<td>6</td>
<td>62</td>
<td>F</td>
<td>Coronary artery disease; mitral stenosis; dilated cardiomyopathy</td>
<td>Chronic atrial fibrillation</td>
</tr>
<tr>
<td>7</td>
<td>17</td>
<td>M</td>
<td>Restrictive cardiomyopathy</td>
<td>Paroxysmal atrial flutter; ventricular fibrillation</td>
</tr>
<tr>
<td>Group 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>62</td>
<td>M</td>
<td>Coronary artery disease</td>
<td>Paroxysmal atrial fibrillation</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>M</td>
<td>Concealed accessory pathway</td>
<td>Atrioventricular reentrant tachycardia</td>
</tr>
<tr>
<td>10</td>
<td>46</td>
<td>F</td>
<td>Rheumatic heart disease; dilated cardiomyopathy status post mitral valve replacement</td>
<td>Chronic atrial fibrillation</td>
</tr>
<tr>
<td>11</td>
<td>56</td>
<td>F</td>
<td>Coronary artery disease</td>
<td>Paroxysmal atrial flutter</td>
</tr>
<tr>
<td>12</td>
<td>76</td>
<td>M</td>
<td>Coronary artery disease; cor pulmonale</td>
<td>Chronic atrial fibrillation</td>
</tr>
<tr>
<td>13</td>
<td>56</td>
<td>F</td>
<td>No structural heart disease</td>
<td>Paroxysmal atrial flutter</td>
</tr>
<tr>
<td>14</td>
<td>70</td>
<td>M</td>
<td>Coronary artery disease; dilated cardiomyopathy</td>
<td>Paroxysmal atrial flutter</td>
</tr>
<tr>
<td>15</td>
<td>69</td>
<td>M</td>
<td>Coronary artery disease; cor pulmonale</td>
<td>Paroxysmal atrial fibrillation</td>
</tr>
<tr>
<td>16</td>
<td>63</td>
<td>M</td>
<td>Idiopathic dilated cardiomyopathy</td>
<td>Chronic atrial fibrillation</td>
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<tr>
<td>17</td>
<td>61</td>
<td>F</td>
<td>Restrictive cardiomyopathy</td>
<td>Chronic atrial fibrillation</td>
</tr>
</tbody>
</table>
device at the base of the catheter, to facilitate positioning of the catheter. The catheter was placed for recording from the distal bipolar pair, a small but sharp His bundle potential and a large atrial potential, as in group 1 patients. However, radiofrequency current was delivered to only the large-tip electrode, and the output was varied manually at the onset of the application to achieve the desired voltage (usually 50–60 V). A transformer was added to the electrosurgical unit to allow the increase in voltage. Radiofrequency current was reapplied until complete atrioventricular block occurred and persisted for 30 minutes. A radiofrequency filter (Medical Scientific, Inc., Foxboro, Mass.) was used in group 2 patients to allow undistorted recording of the electrocardiogram during radiofrequency current application.

A permanent pacemaker (VVIR or DDD) was implanted in the 16 patients who developed complete atrioventricular block, including patients with a junctional escape rhythm. In patients 1–4 and 6–15, pacemaker implantation was delayed until 24–48 hours after ablation to ensure persistence of complete atrioventricular block. In patients 16 and 17, the pacemaker was implanted 1 hour after ablation.

In these two patients, the insertion of a temporary pacing catheter into the right subclavian vein was omitted. Temporary ventricular pacing was performed from the catheter inserted through the femoral vein.

The effects of atropine (2 mg i.v.) on the postablation junctional escape rhythm was assessed in nine patients. In six of these patients, isoproterenol (1.5 μg/min i.v.) was administered 10 minutes after atropine.

The significance of the difference between group 1 and group 2 patients in the number of radiofrequency current applications, time required to produce atrioventricular block, parameters of the current applications, and junctional escape rhythm cycle lengths was assessed using the Student’s t test for unpaired data.

**Results**

**Ablation Success**

Using standard electrodes, complete atrioventricular block was achieved in six of seven group 1 patients (Tables 2 and 3). In four patients (patients 2–4 and 6), complete block proximal to the His bundle potential occurred during the procedure. In
TABLE 2. Range of Radiofrequency Current Parameters

<table>
<thead>
<tr>
<th>Patient</th>
<th>Result</th>
<th>RF applications</th>
<th>Tip electrode</th>
<th>Total time (min)</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Impedance (Ω)</th>
<th>Duration (sec)</th>
<th>Energy (J)</th>
<th>Peak CPK (IU/l)</th>
<th>CPK (% MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Group 1 (standard electrodes)</td>
<td>Proximal block*</td>
<td>32</td>
<td>6</td>
<td>135</td>
<td>36–46</td>
<td>0.17–0.31</td>
<td>7.6–11.8</td>
<td>112–258</td>
<td>1.6–47</td>
<td>25–543</td>
<td>63</td>
<td>0</td>
</tr>
<tr>
<td>2 Patient</td>
<td>Proximal block</td>
<td>15</td>
<td>4</td>
<td>69</td>
<td>40–46</td>
<td>0.20–0.24</td>
<td>8.6–10.1</td>
<td>167–220</td>
<td>3.5–48</td>
<td>35–488</td>
<td>197</td>
<td>2.5</td>
</tr>
<tr>
<td>3 Proximal block</td>
<td>63</td>
<td>29</td>
<td>NA</td>
<td>34–42</td>
<td>0.12–0.29</td>
<td>4.9–10.0</td>
<td>82–344</td>
<td>2.8–90</td>
<td>39–900</td>
<td>31</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>4 Proximal block</td>
<td>36</td>
<td>10</td>
<td>NA</td>
<td>35–39</td>
<td>0.15–0.29</td>
<td>5.9–10.0</td>
<td>121–273</td>
<td>2.0–53</td>
<td>18–528</td>
<td>42</td>
<td>NA</td>
<td></td>
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<tr>
<td>5 No response</td>
<td>73</td>
<td>29</td>
<td>NA</td>
<td>31–43</td>
<td>0.10–0.29</td>
<td>4.3–10.3</td>
<td>107–325</td>
<td>3.0–62</td>
<td>27–502</td>
<td>80</td>
<td>NA</td>
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<tr>
<td>6† Distal block</td>
<td>52</td>
<td>18</td>
<td>178</td>
<td>37–40</td>
<td>0.25–0.30</td>
<td>10.5–12.1</td>
<td>126–161</td>
<td>25–60</td>
<td>272–672</td>
<td>NA</td>
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<tr>
<td>7‡ Mean±SD</td>
<td>76</td>
<td>15</td>
<td>205</td>
<td>36–40</td>
<td>0.23–0.30</td>
<td>9.5–11.8</td>
<td>112–174</td>
<td>3.0–90</td>
<td>30–972</td>
<td>257</td>
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<tr>
<td>8 Group 2 (large-tip electrode)</td>
<td>Proximal block</td>
<td>8</td>
<td>86</td>
<td>45–95</td>
<td>0.33–0.66</td>
<td>14.8–62.4</td>
<td>135–189</td>
<td>11–30</td>
<td>262–1,667</td>
<td>116</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>9 Proximal block</td>
<td>7</td>
<td>78</td>
<td>30–52</td>
<td>0.31–0.65</td>
<td>9.2–35.9</td>
<td>80–96</td>
<td>10–36</td>
<td>107–1,018</td>
<td>292</td>
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<tr>
<td>10 Proximal block</td>
<td>6</td>
<td>44</td>
<td>50–57</td>
<td>0.52–0.62</td>
<td>28.6–34.1</td>
<td>81–107</td>
<td>11–40</td>
<td>333–1,363</td>
<td>114</td>
<td>1.3</td>
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<tr>
<td>11 Proximal block</td>
<td>1</td>
<td>1</td>
<td>56</td>
<td>0.60</td>
<td>33.3</td>
<td>93</td>
<td>31</td>
<td>1,026</td>
<td>68</td>
<td>15.7</td>
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<tr>
<td>12 Proximal block</td>
<td>1</td>
<td>1</td>
<td>78</td>
<td>0.58</td>
<td>45.5</td>
<td>135</td>
<td>55</td>
<td>2,475</td>
<td>NA</td>
<td>NA</td>
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<td></td>
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<tr>
<td>13 Distal block‡</td>
<td>9</td>
<td>134</td>
<td>48–59</td>
<td>0.39–0.57</td>
<td>22.6–31.6</td>
<td>93–238</td>
<td>26–49</td>
<td>46–1,519</td>
<td>117</td>
<td>2.6</td>
<td></td>
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<tr>
<td>14 Proximal block</td>
<td>4</td>
<td>30</td>
<td>56–66</td>
<td>0.27–0.50</td>
<td>17.0–28.0</td>
<td>112</td>
<td>31–45</td>
<td>588–1,274</td>
<td>146</td>
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<tr>
<td>15 Proximal block</td>
<td>2</td>
<td>45</td>
<td>50</td>
<td>0.60–0.62</td>
<td>30.0–31.0</td>
<td>80–83</td>
<td>41–45</td>
<td>1,215–1,350</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>16 Proximal block</td>
<td>1</td>
<td>1</td>
<td>50</td>
<td>0.63</td>
<td>31.5</td>
<td>79</td>
<td>17</td>
<td>527</td>
<td>37</td>
<td>NA</td>
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<tr>
<td>17 Proximal block</td>
<td>1</td>
<td>1</td>
<td>55</td>
<td>0.51</td>
<td>28.2</td>
<td>108</td>
<td>17</td>
<td>479</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Mean±SD</td>
<td>4.7±4.6</td>
<td>42±45</td>
<td>6.1±6.6</td>
<td>138±149</td>
<td>13.3±14.5</td>
<td>136±148</td>
<td>11.7±3.6</td>
<td>25.4±9.3</td>
<td>229±90</td>
<td>14.2±3.9</td>
<td>39.7±10.7</td>
<td>2.2±0.9</td>
</tr>
</tbody>
</table>

RF applications, number of applications of radiofrequency current required to produce permanent complete atrioventricular block; total time, time between first and last applications of radiofrequency current; CPK, creatine phosphokinase (normal range, 16–160 IU/l); proximal block, complete atrioventricular block occurring proximal to His bundle potential; distal block, complete atrioventricular block occurring distal to His bundle potential.

*Block occurred 18 hours after ablation.
†7F catheter (6F catheter used in patients 1–5).
‡Dual atrioventricular nodal pathway physiology.

Patient 1, complete atrioventricular block did not develop until 18 hours after the procedure, but atrioventricular nodal conduction had been modified during the procedure (increase in the mean ventricular cycle length during atrial fibrillation, 565 to 1,315 msec). Patient 7 had dual atrioventricular nodal pathway physiology. Radiofrequency current delivered near the origin of the His bundle ablated the fast atrioventricular nodal pathway, prolonging the AH interval from 80 to 130 msec (Figures 2A and 2B). Additional pulses in that region failed to eliminate slow pathway conduction and ultimately resulted in block distal to the His bundle potential (Figure 2C). Radiofrequency current had been reapplied until complete atrioventricular block occurred in this 17-year-old patient with a restrictive myopathy because two episodes of spontaneous atrial flutter had degenerated to ventricular fibrillation.
Table 3. Radiofrequency Current Parameters for Application That Produced Complete Atrioventricular Block

<table>
<thead>
<tr>
<th>Patient</th>
<th>Result</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Impedance (Ω)</th>
<th>Duration (sec)</th>
<th>Time to block (sec)</th>
<th>Energy to block (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>(standard electrodes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Proximal block*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Proximal block</td>
<td>46</td>
<td>0.21</td>
<td>9.7</td>
<td>219</td>
<td>37</td>
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</tr>
<tr>
<td>3</td>
<td>Proximal block</td>
<td>34</td>
<td>0.29</td>
<td>10.0</td>
<td>118</td>
<td>90</td>
<td>21</td>
<td>210</td>
</tr>
<tr>
<td>4</td>
<td>Proximal block</td>
<td>36</td>
<td>0.27</td>
<td>9.8</td>
<td>133</td>
<td>53</td>
<td>20</td>
<td>196</td>
</tr>
<tr>
<td>5</td>
<td>No response</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Proximal block</td>
<td>40</td>
<td>0.28</td>
<td>11.2</td>
<td>143</td>
<td>60</td>
<td>NA</td>
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<td>31.5</td>
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<td>28.2</td>
<td>108</td>
<td>17</td>
<td>3</td>
<td>85</td>
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<tr>
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<td>33.0±13.0</td>
<td>103±22</td>
<td>33±13</td>
<td>8±3</td>
<td>212±39</td>
</tr>
</tbody>
</table>

*Block occurred 18 hours after ablation.

NA, not available (high-frequency artifact obliterated electrograms, precluding determination); proximal block, complete atrioventricular block occurring proximal to His bundle potential; distal block, complete atrioventricular block occurring distal to His bundle potential.

Comparison of Standard and Large-Tip Electrodes

Although the success rates were comparable with each of the two techniques, the number of applications of radiofrequency current required to produce permanent complete atrioventricular block differed significantly (Table 2). In group 1 patients, energy was applied to each of the closely spaced standard electrodes, but permanent atrioventricular block was produced only when radiofrequency current was delivered through the tip electrode. An average of 15.9 applications through standard-tip electrodes was required to produce complete atrioventricular block in group 1 patients, and the average required time was 147 minutes (which includes application of energy to all electrodes, not just the tip electrodes). In comparison, atrioventricular block was produced by an average of 4.7 applications (over an average of 42 minutes) using the large-tip electrode in group 2 patients (Table 2).

An accelerated junctional rhythm preceded the appearance of atrioventricular block (Figure 4). This junctional rhythm slowed and atrioventricular block was evident at an average of 8 seconds after the onset of the radiofrequency current application using the large-tip electrode compared with 22 seconds with the use of the standard-tip electrode (Table 3).

Transient atrioventricular block was produced by an application of radiofrequency current in five patients (two in group 1 and three in group 2). Atrioventricular conduction returned within 30 minutes, and radiofrequency current was reapplied. The procedure was terminated when complete atrioventricu-
**Figure 2.** Ablation of "fast atrioventricular (AV) nodal pathway" followed by complete AV block distal to His bundle potential produced by radiofrequency current in a 17-year-old patient with a restrictive cardiomyopathy, paroxysmal atrial flutter, and dual AV nodal pathway physiology (patient 7). Panel A: Electrocardiographic lead II and intracardiac electrograms recorded before ablation. Tracings 4, 5, 6, and 7 are electrograms recorded from distal, second, third, and proximal bipolar electrode pairs on an octapolar catheter (2.5 mm spacing) positioned over AV node and proximal His bundle. Tracings 1, 2, and 3 are electrograms from distal, middle, and proximal bipolar pairs on a hexapolar catheter (2.5 mm spacing) positioned just distal to octapolar catheter so that distal pair (electrogram 1) recorded activation of proximal right bundle branch. Before ablation, AH interval was 80 msec, and HV interval was 60 msec. Octapolar catheter was withdrawn a few millimeters, so that electrogram 4 appeared similar to electrogram 5 in this figure, and radiofrequency current was delivered to each of the eight electrodes on this catheter. Panel B: Recorded after initial applications of radiofrequency current and shows prolongation of AH interval to 130 msec and slight shortening of HV interval to 55 msec, suggesting conduction through the "slow AV nodal pathway." Additional applications of radiofrequency current delivered to same region failed to eliminate slow AV nodal pathway conduction. Panel C: Additional energy delivered more distally produced complete block distal to His bundle potential (arrows). Right ventricular (RV) pacing was interrupted, showing absence of a ventricular escape rhythm. S, pacing stimulus artifact.
A. 

CL 400 msec

Arterial Pressure (mm Hg)

B. 

CL 350 msec

Arterial Pressure (mm Hg)

Figure 3. Recording of effects of atrial pacing on arterial pressure in patient 7, who had a restrictive cardiomyopathy and two episodes of atrial flutter that degenerated to ventricular fibrillation when the ventricular rate reached 160 min⁻¹. Tracings are electrocardiographic lead II and femoral arterial pressure. Panel A: Right atrial pacing at cycle length (CL) 400 msec (150 min⁻¹) for 4.8 seconds resulted in a decrease in arterial pressure from 134/82 to 78/62 mm Hg. Systolic, diastolic, and pulse pressures began to increase after 4 seconds. Panel B: Right atrial pacing at CL 350 msec (171 min⁻¹) for 7.7 seconds resulted in a sustained decrease in arterial pressure to 70/56 mm Hg. Note that arterial pressure did not increase until pacing was terminated.

Atrioventricular block was present for 30 minutes, and atrioventricular conduction did not recur in any patient during the remainder of the hospital stay.

For the large-tip electrode, compared with the standard electrode, the application of radiofrequency current that produced permanent complete atrioventricular block had significantly higher voltage (mean, 58 versus 38 V) with lower impedance (103 versus 148 Ω), resulting in higher current (0.56 versus 0.27 A) and an even greater difference in power (33.0 versus 10.2 W) as shown in Table 3. An impedance rise limiting further delivery of radiofrequency current occurred with at least one pulse in six of seven patients using the standard electrodes compared with five of 10 patients using the large-tip electrodes (Table 4). Using the large-tip electrode, the impedance rise occurred at higher power (25 versus 10 W) and after a significantly longer interval of current delivery (21 versus 7 seconds). In three of the five group 2 patients (patients 14, 16, and 17), the impedance rise did not occur until after complete atrioventricular block was produced.

No complication occurred during the ablation procedure in any patient. Delivery of radiofrequency current was generally painless at 55 V or less. At higher voltages, some patients described dull, substernal chest discomfort. The chest discomfort subsided immediately on termination of energy delivery, and there were no ischemic changes on electrocardiographic leads I, II, or V₅. Serum creatine phosphokinase was measured at 1, 6, 12, and 24 hours after ablation in 13 patients. Peak creatine phosphokinase was 292 IU/l or less (1.8 x the upper limit of normal for this laboratory) in all 13 patients, and the MB isoenzyme exceeded 5% of total creatine phosphokinase in only one patient (Table 2).

Junctional Escape Rhythm

A junctional escape rhythm was present after ablation in all five group 1 and eight of nine group 2
FIGURE 4. Recording of complete atrioventricular block produced by application of radiofrequency current through a large-tip electrode in patient 15. Tracings (from top) are electrocardiographic lead II (*, low-amplitude P waves) and root-mean-square current and voltage output from electrosurgical unit. Radiofrequency current was applied at 50 V with a current of 0.6 A and power of 30 W. An accelerated junctional rhythm begins 2.5 seconds after onset of radiofrequency current delivery. The cycle length of the junctional rhythm gradually lengthened, allowing presence of complete atrioventricular block to be identified 4.1 seconds later. Numbers above electrocardiographic lead II provide RR interval between each of junctional complexes.

Table 4. Radiofrequency Parameters Immediately Before and After Impedance Rise

<table>
<thead>
<tr>
<th>Patient</th>
<th>Applications (n)</th>
<th>Before impedance rise</th>
<th>After impedance rise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time to rise (sec)</td>
<td>Voltage (V)</td>
</tr>
<tr>
<td>Group 1</td>
<td>(standard electrodes)</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>1.6–22</td>
<td>35–42</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3.4–42</td>
<td>42–44</td>
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<td>11–35</td>
<td>34–38</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>2.0–7.0</td>
<td>35–38</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>2.0–11</td>
<td>34–38</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>7</td>
<td>7</td>
<td>3.0–37</td>
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<td>Mean±SD</td>
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<td>Group 2</td>
<td>(large-tip electrode)</td>
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<td>26–38</td>
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<td>ρ</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
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Table 5. Clinical Follow-up

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<tr>
<th>Patient</th>
<th>Ablation result</th>
<th>Junctional escape rhythm cycle length (msec)</th>
<th>Pacemaker type</th>
<th>Length (mo)</th>
<th>AV block</th>
<th>Status</th>
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<td>Atropine</td>
<td>Atropine plus isoproterenol</td>
<td>Follow-up</td>
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<td>750</td>
<td>VVI-R</td>
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<tr>
<td>3</td>
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<td>1,000</td>
<td>1,280</td>
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<td>1,020</td>
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<td>...</td>
<td>...</td>
<td>...</td>
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<td>985</td>
<td>890</td>
<td>VVI-R</td>
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Group 2

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<th>Length (mo)</th>
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<td>1,360</td>
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<td>None</td>
<td>DDD</td>
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<tr>
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<td>900</td>
<td>810</td>
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<tr>
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<td>DDD</td>
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<tr>
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AV, atrioventricular.

*Patient with mitral stenosis and atrial fibrillation did not receive warfarin after hospital discharge.

be determined, was 5–15 msec shorter than the HV interval before ablation.

Atropine (2 mg i.v.) was administered to nine patients (Table 5 and Figure 5), and the junctional rhythm cycle length was shortened by only a median of 10 msec (range, 0–120 msec). Isoproterenol was administered 10 minutes after atropine in six patients and shortened the junctional rhythm cycle length by an additional 50–290 msec (median, 88 msec).

One group 2 patient with block proximal to the His bundle potential (and both patients with block distal to the His bundle potential) had no junctional escape rhythm (Figure 2).

Follow-up

Patients were followed for 2 weeks to 25 months (median, 8 months) after ablation (Table 5). Three patients in group 1 died 2 weeks to 2 months after ablation. One patient (patient 1) with mitral stenosis and chronic atrial fibrillation had not received warfarin after hospital discharge and died of a thromboembolic cerebrovascular event. One patient (patient 3) with an aortic valve prosthesis and chronic severe left ventricular dysfunction had recurrent episodes of profound hypotension before ablation, which were associated with atrial flutter and a rapid ventricular response. It was thought that eliminating the rapid ventricular rate during atrial flutter might prevent or lessen the episodes of hypotension. However, two subsequent episodes occurred on days 3 and 14 after ablation, while he was still hospitalized and on continuous electrocardiographic monitoring. During each episode, the patient had complete atrioventricular block with a paced ventricular rhythm. He was not resuscitated from the second episode. Postmortem examination revealed no pericardial effusion, no thrombus within the heart or pulmonary arteries, and no prosthetic valve dysfunction. The third patient (patient 7), a 17-year-old boy with a restrictive cardiomyopathy and paroxysmal atrial flutter degenerating to ventricular fibrillation, died suddenly 2 months after ablation. The pacemaker (DDD) upper rate limit had been increased from 100 to 125 pulses/min 2 weeks earlier by his referring physician after
A. Pre-ablation

B. Post-ablation

C. Atropine 2 mg

D. Atropine plus Isoproterenol 1.5 mcg/min

Figure 5. Recording of junctional escape rhythm after ablation of atrioventricular conduction in patient 6. Panel A: Atrial fibrillation with rapid ventricular response before ablation (mean ventricular cycle length, 450 msec). Panel B: Radiofrequency current produced complete atrioventricular block with a junctional escape rhythm (cycle length, 1,015 msec). Panel C: Atropine 2 mg i.v. shortened junctional cycle length by only 30 msec (985 msec). Panel D: Isoproterenol (1.5 mcg/min i.v.) given shortly after atropine shortened cycle length of junctional escape rhythm by an additional 95 msec (890 msec).

uneventful treadmill exercise testing at the higher programmed rate. Patient 4 underwent cardiac transplantation 10 months after ablation. These four patients had persistent, complete atrioventricular block at last follow-up.

Of the remaining 12 patients with successful ablation, 11 have persistent complete atrioventricular block and are clinically stable (and subjectively improved) 0.5–25 months after ablation. Patient 16 had recurrence of atrioventricular conduction at 1 month, which was manifest by a rapid ventricular response during atrial fibrillation. A second ablation procedure using the same technique produced complete atrioventricular block that has persisted to the present time (2 months). A junctional escape rhythm persisted in nine of the 11 patients, although the cycle length was less than 1,000 msec in only three patients (Table 5). The junctional rhythm predominated over the pacemaker lower rate limit in only two patients (2 and 12).

Anatomical Correlation

Pathological examination of the heart was performed in two group 1 patients (patients 3 and 4). Each had successful ablation with a junctional escape rhythm (Table 5). Patient 3 died 13 days after ablation with acute heart failure. Examination of the right heart showed a 1.0x0.5-cm area of flat hemorrhagic discoloration in the region of the atrioventricular node (Figure 6). Microscopic examination of the lesion showed atrial necrosis extending to a depth of 2 mm posteriorly (lower end of lesion in Figure 6) involving the outer third of the atrioventricular node and to a depth of 5 mm anteriorly (upper end of lesion in Figure 6) including the full thickness of the proximal His bundle. The distal His bundle was free of necrosis.

Patient 4 underwent heart transplantation 10 months after ablation. Examination of the heart showed an area of smooth endocardial fibrosis, measuring 1.5x1.3 cm, overlying the region of the atrioventricular node (Figure 7A). Microscopically, there was nearly transmural fibrosis, completely replacing the atrioventricular node and extending into the proximal His bundle (Figures 7B and 7C); the distal His bundle was spared (Figure 7D).

The patient in whom atrioventricular block was not produced (patient 5) underwent surgical ablation of the atrioventricular node in association with mitral anuloplasty 14 weeks later. Examination of the right heart at surgery showed at 1.0x0.5-cm scar overlying the region of the atrioventricular node, similar in size and orientation to the lesion demonstrated in Figure 6. The surface was smooth and glistening and without thrombus. The right atrium and right ventricle appeared diffusely thickened at 3 and 5–6 mm, respectively. A cryoprobe (−60°C) applied directly over the scar produced complete atrioventricular block but only after 60 seconds.

Discussion

Results from the present study demonstrate that catheter-delivered radiofrequency current can consistently produce complete atrioventricular block. Complete atrioventricular block was achieved in 94% of patients (one patient required two procedures), which compares favorably with the 51–100% success rates reported with DC shocks.3–7 Using standard catheter electrodes, ablation required many applications of energy over a period of hours (Table 2). Successful ablation was achieved only when energy was delivered through the tip electrode, but an average of 15.9 applications through standard-tip electrodes were still required to produce atrioventricular block. The time and number of applications required for successful ablation were significantly reduced by using a large-tip electrode and higher power. The use of standard-tip electrodes limited the power delivered to approximately 10 W. Higher power generally resulted in an abrupt impedance rise within a few seconds, which was associated with coagulum formation on the electrode. The impedance rise prevented further energy delivery without exchanging or cleaning the electrode. The large-tip electrode allowed a threefold increase in delivered power. With the large electrode, impedance rises were less frequent, occurred at much higher power (25 W), and were delayed to an average of 21 seconds after the onset of the pulse, which is longer than the average time required to produce complete atrioventricular block (8 seconds). The large surface area of the electrode may limit the temperature increase at the
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The increase in efficiency provided by the large-tip electrode and high power suggests that this combination results in a larger or deeper lesion. Preliminary in vitro studies have shown that lesion size increases with increasing electrode diameter and increasing electrode length. In the latter study, the investigators found that when using a constant power (13 W), lesion size increased and the occurrence of an impedance rise decreased as the electrode length was increased from 2 to 4 mm. Additional increases in electrode length to 6–10 mm completely eliminated the impedance rise but resulted in progressively smaller lesions. This might suggest that 4 mm is the optimum electrode length. However, electrodes longer than 4 mm might allow the use of higher power (by preventing the impedance rise) with a possible increase in lesion size.

Radiofrequency current offers three advantages over the use of high-energy DC shocks for ablation of the atrioventricular junction: 1) absence of barotrauma, which eliminates the deleterious hemodynamic effects as well as the risk of cardiac perforation; 2) elimination of the requirement for general anesthesia; and 3) a stable junctional escape rhythm frequently follows the development of atrioventricular block. The absence of both the deleterious hemodynamic effects and the requirement for a general anesthetic allows ablation of the atrioventricular junction to be performed more easily in patients with severe cardiac or pulmonary disease. Patient 2 had severe chronic obstructive pulmonary disease (chronically elevated Pco2), which would have made the administration of a short-acting barbiturate hazardous. Patient 17 was denied catheter-mediated ablation of the atrioventricular junction (using DC shocks) at another institution because of a precarious hemodynamic state.

A junctional escape rhythm at rates of 38–72 min\(^{-1}\) (median, 50 min\(^{-1}\)) followed ablation in 13 of 14 patients developing block proximal to the His bundle potential. In contrast, atrioventricular junctional ablation with DC shocks is frequently associated with a slow and intermittent ventricular escape rhythm. The presence of a stable junctional escape rhythm eases the transition between catheter ablation and permanent pacemaker implantation by

FIGURE 6. Photograph of right septal atrioventricular region in patient 3, who died 14 days after atrioventricular junctional ablation. Right atrial septum (A) is at left, right ventricular septum (V) is at right, and coronary sinus ostium (CS) is at bottom. Arrows mark a 1×0.5-cm lesion located over atrioventricular nodal region. Surface of lesion is smooth and without thrombus, and septal leaflet of tricuspid valve (T) is undamaged.
FIGURE 7. Photograph of healed lesion after successful atroventricular junctional ablation. Specimen was obtained at time of cardiac transplantation, 10 months after ablation. Panel A: Tricuspid valve with rim of right atrium (A) at top, revealing a 1.5×1.3-cm scar (asterisk and arrows) centered about the atroventricular conduction system. T_S and T_A mark septal and anterior leaflets of tricuspid valve. Panel B: Section through region of atroventricular node shows thickened endocardium and nearly transmural fibrosis (arrows). Atrioventricular node is completely replaced (dots outline expected location). V, ventricular septum. Panel C: Proximal His bundle (H, arrows) is partially replaced by fibrosis (mostly in central and upper regions). Fibrous tissue surrounding bundle is thickened. Panel D: Distal His bundle (H) and left bundle branch (LB) are essentially intact. There is increased fibrosis in crest of V.

eliminating the dependence on continuous ventricular pacing. The junctional rhythm may play a lesser role in long-term management. In the present study, the cycle length of the junctional escape rhythm at last follow-up was less than 1,000 msec in only three patients. The rate of the junctional escape rhythm exceeded the programmed lower rate limit for the pacemaker in only two patients. Langberg et al.\textsuperscript{12} also reported the presence of a junctional escape rhythm after ablation with radiofrequency current, although the rates were not provided.

Pathological examination of the heart in patients 3 and 4 suggests that the presence of a junctional escape rhythm is dependent on avoidance of injury to much of the His bundle. Limiting the extent of injury may be easier to accomplish with radiofrequency current than with DC shocks. We attempted to place the tip electrode just proximal to the His bundle in the present study by positioning the catheter so that the distal bipolar electrode recorded a small but sharp His bundle potential and a relatively large atrial potential. The presumed larger lesion produced by the large-tip electrode and higher power may account for the significantly slower junctional escape rates in group 2 patients (mean, 46 min\(^{-1}\)) than in group 1 patients (mean, 56 min\(^{-1}\)).

Two patients (7 and 13) exhibited dual atroventricular nodal pathway physiology during pro-
programmed atrial stimulation. Radiofrequency current delivered near the junction of the atrioventricular node and the His bundle selectively ablated the “fast atrioventricular nodal pathway.” Multiple additional energy applications in the same region had no significant effect on “slow atrioventricular nodal pathway” conduction. These findings suggest that the slow atrioventricular nodal pathway may be anatomically separate from the fast atrioventricular nodal pathway. Recent reports describing new techniques for selective catheter-mediated ablation of atrioventricular nodal reentrant tachycardia provide strong evidence that the fast atrioventricular nodal pathway is located close to the His bundle, with a more remote location for the slow pathway. The use of DC shocks or radiofrequency current delivered to sites recording a large atrial potential with a small but sharp His bundle potential has eliminated retrograde conduction and prolonged antegrade conduction times, possibly indicating selective ablation of the fast atrioventricular nodal pathway. Preliminary studies attempting to selectively ablate the slow atrioventricular nodal pathway in patients with atrioventricular nodal reentrant tachycardia suggest that the proximal insertion of the slow atrioventricular nodal pathway may be located posteriorly in the atrial septum, close to the coronary sinus. The inability to produce atrioventricular block until the distal His bundle was ablated in the two patients in the present study suggests a His bundle insertion (extranodal location) for the slow pathway.

In summary, catheter-delivered radiofrequency current effectively produces complete atrioventricular block without the requirement for general anesthesia or risk of ventricular dysfunction or cardiac perforation. The use of a large-tip catheter electrode allows a substantial increase in delivered power, which reduces the duration of the procedure to roughly the same range as when using high-energy, DC shocks.

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