Lesion Dimensions During Temperature-Controlled Radiofrequency Catheter Ablation of Left Ventricular Porcine Myocardium

Impact of Ablation Site, Electrode Size, and Convective Cooling

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Background—It is important to increase lesion size to improve the success rate for radiofrequency ablation of ischemic ventricular tachycardia. This study of radiofrequency ablation, with adjustment of power to approach a preset target temperature, ie, temperature-controlled ablation, explores the effect of catheter-tip length, ablation site, and convective cooling on lesion dimensions.

Methods and Results—In vitro strips of porcine left ventricular myocardium during different levels of convective cooling and in vivo pig hearts at 2 or 3 left ventricular sites were ablated with 2- to 12-mm-tip catheters. We found increased lesion volume for increased catheter-tip length ≤8 mm in vitro (P < 0.05) and 6 mm in vivo (P < 0.0001), but no further increase was found for longer tips. For the 4- to 10-mm catheter tips, we found smaller lesion volume in low-flow areas (apex) than in high-flow areas (free wall and septum) (P < 0.05). Increasing convective cooling of the catheter tip in vitro increased lesion volume (P < 0.0005) for the 4- and 8-mm tips but not for the 12-mm tip as the generator reached maximum output. In contrast to power-controlled ablation, we found a negative correlation between tip temperature reached and lesion volume for applications in which maximum generator output was not achieved (P < 0.0001), whereas delivered power and lesion volume correlated positively (P < 0.0001).

Conclusions—Lesion size differs in different left ventricular target sites, which is probably related to convective cooling, as illustrated in vitro. Longer electrode tips increase lesion size for tip lengths ≤6 to 8 mm. For temperature-controlled ablation, the tip temperature achieved is a poor predictor of lesion size. (Circulation. 1999;99:319-325.)

Key Words: catheter ablation ■ arrhythmia ■ tachycardia

Catheter ablation of ventricular tachycardias in patients with structural heart disease can permanently cure the tachycardia targeted in only ≈60% of cases,1–4 whereas the success rate after ablation of AV node reentrant tachycardias, accessory pathways, or fascicular ventricular tachycardias is ≈95%,5,6 Several features in patients with structural heart disease may limit the applicability of radiofrequency ablation: The ventricular tachycardia can be hemodynamic or electrically unstable; multiple reentrant circuits can be present; or the critical reentrant circuit can be located deep in the myocardium. To improve the success rate in attempts to coagulate the critical parts of the reentrant circuits, 2 approaches can be taken: improving the accuracy of the mapping technique and increasing the size of the lesion created by catheter ablation. Several methods for increasing lesion size have been investigated, ranging from surgery to ablation with direct current,7,8 laser,9 microwaves,10 and alcohol injection11 to radiofrequency ablation with large-tip12–15 or saline-irrigated16–19 electrodes. The chosen ablation site may have significant influence on lesion size because of various degrees of cooling of the electrode tip from the intracavitary blood flow, although this has not yet been evaluated systematically. The purpose of this in vitro and in vivo study was to assess the effect on lesion dimensions of increased catheter-tip length, ablation site, and convective cooling of the electrode tip during temperature-controlled radiofrequency ablation. Another study aim was to evaluate how applied power and reached tip temperature correlated with lesion volume.

Methods

Experimental Preparations

In Vitro

Strips of left ventricular myocardium from freshly excised pig hearts were suspended in a tissue bath with isotonic saline at 37°C controlled by a thermostat. The ablation catheter was mounted in a holder maintaining the tip parallel to the tissue. Catheter pressure
excised, and the lesions were identified and inspected for crater formation. The pigs were killed by infusion of pentobarbital. The hearts were catheterized through a hemostatic sheath attached to the left lateral chest wall. The position of the ablation electrode was controlled by fluoroscopy and recording of a stable electrogram. Arterial blood pressure and surface ECG were monitored continuously. The pigs were intubated and mechanically ventilated. Fentanyl (bolus, 25 mg; infusion, 3 to 6 mg/h) and ketamine (bolus, 750 mg; infusion, 100 to 200 mg/h) supplemented with N2O-02 ratio (bolus, 25). A bolus of 450 mg amiodarone IV was given before ablation to reduce the risk of ventricular fibrillation. Arterial blood pressure and surface ECG were monitored continuously. The pigs were intubated and mechanically ventilated. The left ventricle was catheterized through a hemostatic sheath introduced into the left femoral artery. An indifferent electrode was attached to the left lateral chest wall. The position of the ablation electrode was controlled by fluoroscopy and recording of a stable bipolar electrogram from the electrode tip. Two hours after ablation, the pigs were killed by infusion of pentobarbital. The hearts were excised, and the lesions were identified and inspected for crater formation, which was defined as disruption of the myocardium.

Ablation Equipment

A generator delivering radiofrequency current as an unmodulated sine wave of 500 kHz modified to deliver an output of up to 75 W was used (ATAKR, Medtronic CardioRhythm). The in vivo experiments using 2- and 4-mm tip lengths were performed with a standard 50-W generator (ATAKR, Medtronic CardioRhythm). Power supply, impedance, and electrode tip temperature were continuously monitored during energy application. Power delivery was discontinued automatically if impedance was outside the range of 40 to 250 Ω or if tip temperature was >100°C. Unipolar ablation was performed with 7F thermocouple-type ablation catheters (MARINR Medtronic CardioRhythm). Catheters were modified to conduct up to 100 W.

Tissue Preparation and Lesion Volume Determination

Transmural tissue blocks containing the visible lesion and 5 mm of surrounding tissue were chilled and cut into 1-mm-thick slices with a guillotine. The slices were incubated with 0.5 mg nitroblue tetrazolium per 1 mL 0.2-mol/L Sorenson’s buffer at 37°C for 10 minutes. The reaction was stopped with 10% formalin after staining. The viable area becomes dark purple after staining, whereas the necrotic area remains unstained. The size of the slices was amplified 7 times, and the area of necrosis was planimetered electronically on both sides of each slice. The volume of necrosis in each slice was calculated as the sum of these 2 areas divided by 2 and multiplied by slice thickness, which was 1 mm, except for slices with necrosis visible on only 1 side, which were considered to have a lesion thickness of 0.5 mm. Lesion volume was calculated as the sum of the necrotic volume of all slices. Maximum width and depth of each lesion were measured with a caliper.

Ablation Protocols

All applications were performed with automatic power adjustment to maintain a preset temperature of the electrode tip (temperature-controlled radiofrequency ablation). The target temperature was 80°C for 60 seconds in all applications. Applications were performed in vitro with tip lengths of 4, 8, and 12 mm and in vivo with tip lengths of 2, 4, 6, 8, 10, and 12 mm. Only 1 catheter-tip length was used in each pig. In vivo, 3 different target sites in the left ventricle were chosen: posterior midseptum, left anterior free wall, and apex.

Statistical Analysis

Values are given as mean±SD. For each energy application, the average power delivered and the average tip temperature measured in the 60-second energy delivery time were used for analysis. Individual groups were compared by 1-ANOVA. Relations were assessed with linear regression. The influence of convective cooling in vitro and ablation site in vivo was assessed by multiple regression. Values of P<0.05 were considered statistically significant. Statistical software SAS 6.12 (SAS Institute) was used.

Results

In Vitro

A total of 122 lesions were produced in vitro (Table 1).

Catheter-Tip Length

For each level of convective cooling, lesion volume and width were significantly larger for the 8- than for the 4-mm-tip catheter (P<0.05). Lesion dimensions were not further increased for applications with the 12-mm-tip catheter. Lesion depth was not significantly increased for increasing catheter-tip length. Average power consumption increased significantly with increasing catheter-tip length for all levels of convective cooling (P<0.005), whereas average reached tip temperature decreased significantly (P<0.001).

Convective Cooling

Increasing convective cooling by increasing the flow velocity of the saline in the tissue bath increased lesion volume (P<0.0005), width (P<0.05), and depth (P<0.005) significantly for the 4- and 8-mm-tip catheters. For the 12-mm-tip catheter, maximum generator output was reached when flow was induced in the tissue bath, and lesion dimensions did not increase (Table 1). Average power consumption was not significantly increased for increasing levels of convective cooling for any of the 3 catheter-tip lengths, although there was a trend toward increasing average power consumption for increasing convective cooling (Table 1).
Relation Between Average Tip Temperature Reached, Average Power Consumption, and Lesion Volume

To discriminate between “true temperature-controlled” applications in which the power output of the generator was sufficient to approach the target temperature and applications in which the maximum generator output was reached, resembling power-controlled ablation, data were divided into 2 groups: group 1 included applications with average power consumption <65 W, or true temperature-controlled ablation (n=87), and group 2 included applications with average power consumption ≥65 W, or “pseudo–power-controlled” ablation (n=35).

In group 1, there was a negative correlation between reached tip temperature and lesion volume (P<0.0001) (Figure 2A) and a positive correlation between power consumption and lesion volume (P<0.0001) (Figure 2B). In group 2, there was a positive correlation between reached tip temperature and lesion volume (P<0.0001) (Figure 2A) and a negative correlation between power consumption and lesion volume (P<0.05) (Figure 2B).

In Vivo

A total of 34 pigs were catheterized. Two were excluded, 1 because of incessant ventricular fibrillation after ablation and 1 because of catheter movement in 2 applications, which precluded exact lesion identification. In the remaining 32 pigs, 94 applications produced 85 lesions because 9 applications were excluded, 8 because of catheter displacement and 1 because of hemorrhage. There were no cases of premature termination of energy application owing to impedance rise.

Catheter-Tip Length

For increasing catheter-tip length (Table 2), lesion volume and width increased significantly up to a catheter-tip length of 6 mm (P<0.0001), and lesion depth increased significantly up to a catheter-tip length of 4 mm (P<0.0001). No further significant increase in lesion dimensions was observed for longer catheter tips. Average power consumption increased significantly for increasing catheter-tip length (P<0.0001), whereas average reached tip temperature decreased significantly (P<0.0001).

Application Site

For lesions created with the 4- to 10-mm-tip catheters, when both all applications (n=59) and only applications with no occurrence of ventricular fibrillation (n=39) were analyzed, lesions in the apex had significantly smaller volume, higher reached tip temperature, and lower average power consumption (P<0.05) than applications in the septum and the free wall, which did not differ significantly from each other. For applications performed with the 2- and 12-mm-tip catheters, there was no significant difference in lesion volume for the different application sites (Figure 3).

Relation Between Average Tip Temperature Reached, Average Power Consumption, and Lesion Volume

Lesions were divided as described previously into group 1 (power consumption <65 W; n=62) and group 2 (power consumption ≥65 W; n=23).

Table 1. In Vitro Data

<table>
<thead>
<tr>
<th>n</th>
<th>4-mm Tip</th>
<th>8-mm Tip</th>
<th>12-mm Tip</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-m/s Flow</td>
<td>0.1-m/s Flow</td>
<td>0.2-m/s Flow</td>
<td>0-m/s Flow</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>76±1</td>
<td>75±2</td>
<td>75±2</td>
</tr>
<tr>
<td>Power, W</td>
<td>19±5</td>
<td>28±7</td>
<td>33±7</td>
</tr>
<tr>
<td>Lesion depth, mm</td>
<td>5±0</td>
<td>7±1</td>
<td>3±1</td>
</tr>
<tr>
<td>Lesion width, mm</td>
<td>8±1</td>
<td>10±1</td>
<td>11±1</td>
</tr>
<tr>
<td>Lesion volume, mm³</td>
<td>120±28</td>
<td>272±84</td>
<td>404±119</td>
</tr>
</tbody>
</table>

Values are mean±SD.

*Average reached tip temperature.
In group 1, there was a negative correlation between reached tip temperature and lesion volume \((P<0.0001)\) (Figure 4A) and a positive correlation between power consumption and lesion volume \((P<0.0001)\) (Figure 4B). In group 2, there was a positive correlation between reached tip temperature and lesion volume \((P<0.05)\) (Figure 4A) and no significant correlation between power consumption and lesion volume (Figure 4B).

**Complications**

A total of 21 episodes of ventricular fibrillation developed in 14 of 32 pigs during energy application. Mean time for the start of ventricular fibrillation was 32.8 ± 20 seconds after the onset of radiofrequency energy. In all cases, the 60-second energy application was completed, and then the pig was resuscitated by direct-current conversion. These lesions were included in the data analysis. One other pig was excluded because of incessant ventricular fibrillation. Ventricular fibrillation occurred in 11 of 30 apical applications, in 6 of 28 septal applications, and in 4 of 27 free wall applications. These frequencies were not significantly different. No ventricular tachycardias were observed in the 2-hour period from the end of the procedure until the pig was killed.

Crater formation was seen in 12 lesions, and none of these cases was associated with impedance rise. One crater formation observed with the 6-mm-tip catheter was associated with an audible pop. Two craters were observed after ablation with the 4-mm-tip catheter. The remaining 10 craters were seen after ablation with large-tip catheters (4 of 14 for the 6-mm tip in the septum and free wall, 1 of 12 for the 8-mm tip in the free wall, 2 of 16 for the 10-mm tip in the free wall, and 3 of 12 for the 12-mm tip in the apex). For equal catheter-tip lengths, applications with crater formation were not associated with higher-power delivery or higher average tip temperature than the applications without crater formation, except for the 12-mm-tip electrode. This was the only tip length that produced craters in the apex, and these applications were associated with higher average tip temperatures \((68±7°C)\) than the 12-mm-tip applications without crater formation \((49±8°C)\) \((P<0.05)\).

### Table 2. In Vivo Data

<table>
<thead>
<tr>
<th>Tip Length</th>
<th>2-mm Tip</th>
<th>4-mm Tip</th>
<th>6-mm Tip</th>
<th>8-mm Tip</th>
<th>10-mm Tip</th>
<th>12-mm Tip</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>14</td>
<td>17</td>
<td>14</td>
<td>12</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>78±4</td>
<td>71±10</td>
<td>71±8</td>
<td>66±10</td>
<td>62±10</td>
<td>54±11</td>
</tr>
<tr>
<td>Power, W</td>
<td>8±9</td>
<td>22±18</td>
<td>37±24</td>
<td>49±24</td>
<td>57±21</td>
<td>67±19</td>
</tr>
<tr>
<td>Lesion depth, mm</td>
<td>5±1</td>
<td>8±1</td>
<td>8±2</td>
<td>8±2</td>
<td>9±2</td>
<td>9±1</td>
</tr>
<tr>
<td>Lesion width, mm</td>
<td>6±1</td>
<td>10±2</td>
<td>14±2</td>
<td>13±3</td>
<td>14±3</td>
<td>13±3</td>
</tr>
<tr>
<td>Lesion volume, mm³</td>
<td>103±28</td>
<td>325±194</td>
<td>814±324</td>
<td>655±325</td>
<td>922±462</td>
<td>755±319</td>
</tr>
<tr>
<td>Crater formation, n</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Values are mean ± SD. *Average reached tip temperature.
Discussion

Main Findings
We found increased lesion volume for increasing catheter-tip lengths ≤8 mm in vitro and 6 mm in vivo and no further increase for longer catheter tips. In vitro, increased lesion volume for increasing levels of convective cooling was found, and in vivo, apical lesions were significantly smaller than septal and free wall lesions for the 4- to 10-mm catheter tips. For true temperature-controlled ablation, lesion volume and average reached tip temperature were negatively correlated, whereas there was a positive correlation between lesion volume and average power consumption. For applications close to the maximum generator output, there was a positive correlation between reached tip temperature and lesion volume.

Ablation Site
In the in vivo experiments, we demonstrated significantly smaller lesion volume and higher average reached tip temperature in apical applications than in septal and free wall applications for the 4- to 10-mm catheter tips. The main differences between applications in the apex and the 2 other application sites are that better electrode-tissue contact can be established in the apex and lower convective cooling of the electrode tip will occur in the apex because it is filled with blood from the very early phase of diastole. Because this difference in convective cooling is not present during cardiac arrest, this analysis was also performed with exclusion of applications in which ventricular fibrillation occurred.

Better electrode-tissue contact increases lesion volume, but as illustrated in the in vitro experiments, less convective cooling reduces power consumption and decreases lesion size. Because apical lesions were smaller in the in vivo applications, the effect of the convective cooling must be the more important of the 2 factors. This was supported by the in vitro experiments in which controlled catheter-tissue contact was established and convective cooling was varied. This showed that reducing convective cooling around the catheter tip decreased lesion volume.

No differences in lesion volume for different ablation sites for the 2- and 12-mm catheter tips were found. For the 12-mm-tip catheter, output of the radiofrequency generator was insufficient to achieve the target temperature, and catheter-tissue contact could probably be established only along a section of this very long electrode tip. For the 2-mm-tip catheter, it is probable that the small size allowed the tip to be in contact with the endocardium around almost its entire surface, thus protecting it from the effect of the cooling blood in all 3 application sites. This might explain why the lesions created with the 2-mm-tip catheter showed no difference in lesion volume for the 3 different application sites.

To the best of our knowledge, no previous studies have demonstrated the importance of ablation site for lesion dimensions. There are a few clinical observations, however, on how the ablation site affects the reached tip temperature, supporting our observation of differences between separate ablation sites.

Two studies concerning temperature-controlled radiofrequency ablation of accessory pathways in humans found that applications on the atrial side of the tricuspid annulus (high-flow site) had significantly higher power consumption and lower reached average tip temperature than applications under the mitral valve (low-flow site, because the electrode tip is sheltered by the mitral leaflet). This is consistent with our finding that applications in the apex (low-flow area) had higher reached temperature and lower power consumption.

In addition, during power-controlled radiofrequency ablation of accessory pathways in humans, differences between separate application sites have been observed. Langberg et al found lower reached tip temperatures for applications on the atrial side of the tricuspid annulus compared with applications on the ventricular side of the mitral annulus. These observations cannot be extended to temperature-controlled ablation, in which the effect of increased cooling is the opposite, because the generator increases power output in high-flow conditions to maintain the target temperature, which causes enlargement of the lesion size.

External Convective Cooling
In the in vitro experiments, we found significantly increased lesion volume and a trend toward increased power consumption for increasing levels of convective cooling of the electrode tip for the 4- and 8-mm-tip electrode but not for the 12-mm electrode tip, in which the maximum power output of the radiofrequency generator was reached. This suggests that our finding in vivo of differences in lesion volumes in different ablation sites is probably related to the differences in convective cooling of the electrode tip in the beating heart according to the specific area ablated, although the quality of electrode-tissue contact also affects lesion size. Only a few other studies have examined the effect of the convective cooling of the ablation electrode during temperature-controlled ablation in vitro, and they are consistent with our findings.

Tip Length
The present results are in agreement with the findings of earlier published in vivo and in vitro studies of temperature- and power-controlled radiofrequency ablation in which increased lesion dimensions were found for increasing catheter-tip lengths ≤6 or 8 mm and no further increase was found for longer catheter tips. However, ablation site and convective cooling were not considered in these studies.

Lesion Volume Related to Average Delivered Power and Average Tip Temperature Reached
For true temperature-controlled ablation, there is a negative correlation between reached tip temperature and lesion volume, whereas a positive correlation exists between average power consumption and lesion volume. This implies that during temperature-controlled ablation, for a given preset target temperature (here 80°C), the tip temperature actually reached does not give any indication of the lesion size. This is in accordance with 2 clinical studies that showed a lack of correlation between reached tip temperature and success or
recurrence rate after temperature-controlled ablation of accessory pathways.

In the temperature-controlled mode of radiofrequency ablation in which a preset tip temperature is aimed for by regulation of the power output, the power delivered will reflect the electrode-tissue contact and the level of convective cooling caused by intracavitary blood flow in vivo, and the reached tip temperature does not correlate positively with lesion volume, as illustrated in our study. In vivo, this has also been illustrated by Kongsgaard et al.,28 who found no correlation between reached peak tip temperature and lesion size during temperature-controlled radiofrequency ablation.

Most experimental studies, however, have been performed in the power-controlled mode. In contrast to the temperature-controlled mode, the power is preset, and the reached tip temperature will reflect the quality of electrode-tissue contact and convective cooling caused by intracavitary blood flow in vivo.

During power-controlled ablation, convective cooling will reduce lesion dimensions. In power-controlled ablation, increased tip temperature is associated with larger lesion dimensions, as illustrated by Hindricks et al.12 and Rosenbaum et al.13 This was also illustrated in those of our experiments in which power consumption approached the maximum generator output (pseudo–power-controlled ablation); in this group, reached tip temperature was positively correlated with lesion volume (Figures 2A and 4A).

Haines and Watson50 have shown that increasing target temperature increases lesion volume, but to the best of our knowledge, the relation with reached tip temperature for a given chosen target temperature has not been studied before. We found that for a given chosen target temperature, the reached tip temperature is not a good predictor of lesion size when there are different levels of convective cooling, as in the beating heart.

Clinical Implications

Assuming that the experimental data can be applied to the human heart, there are 3 main clinical implications of our study concerning temperature-controlled radiofrequency ablation. First, in areas with low convective cooling, such as the apex or ventricular aneurysms, the lesion is likely to be smaller than expected, even though the target temperature is reached. Ablation with large- or irrigated-tip catheters could be considered when the tachycardia cannot be ablated with a standard catheter despite high reached tip temperature. Second, in areas with high convective cooling, ie, ablation of slow pathways in AV node reentrant tachycardia, right-sided accessory pathways, and especially anteroseptal pathways, the lesion is likely to be larger than in other areas when the same target temperature is used. Reducing target temperature or using smaller tip size could be considered for ablation of the tachycardia and might reduce the risk of AV block. Third, once a target temperature is chosen, the reached tip temperature does not correlate positively with lesion size; thus, high reached tip temperatures do not indicate large lesion dimensions.

Study Limitations

This study was performed in normal porcine left ventricular myocardium, and the properties of diseased myocardium probably differ, affecting heat transfer in the tissue and thus lesion size. However, there is recent evidence from dog experiments that the tissue temperatures during radiofrequency ablation in scarred and normal myocardium do not differ.31

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References


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