Radiofrequency lesions produced by handheld temperature controlled probes for use in atrial fibrillation surgery

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Abstract

Objectives: Detailed analysis of the size and shape of lesions produced by handheld radiofrequency ablation devices at open heart surgery has not been reported previously. Methods: Radiofrequency lesions were made from the epicardial surface of the cardiac ventricles in open-chested dogs. The effects of electrode size, electrode temperature and duration of ablation were studied. In a second group of experiments simultaneous multielectrode ablation was performed on the ventricular epicardium after cold cardioplegia. Results: Using a single 12 £ 2.5 mm electrode and a target temperature of 80 $^\circ$C the lesion depth increased from 3.8 ± 0.9 mm at 15 s, to 6.1 ± 0.9 mm at 120 s ($P = 0.01$). Increasing the target temperature from 70 to 90 $^\circ$C (for 60 s) increased lesion depth from 5.0 ± 1.2 to 5.6 ± 1.7 mm ($P = 0.2$). There was no difference in depth of lesions with the two electrode widths (4.0 ± 0.5 mm (large) vs. 3.9 ± 1.0 mm (small)). Lesions produced using the multielectrode probe (80 $^\circ$C, 60 s) were 30–35 mm long with even penetration into the tissue. The mean depth of these lesions on microscopic sections was 3.9 mm. The mean width was 7.1 mm. Conclusions: Handheld probes can be used to make deep linear lesions in the myocardium. Lesions expand rapidly and are wider than they are deep. A multitelectrode ablation device allows rapid formation of linear lesions. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Radiofrequency; Ablation; Atrial fibrillation

1. Introduction

Cox demonstrated that atrial fibrillation can be cured by segmenting the atrial mass with linear lesions [1,2]. Recently several groups have reported similar procedures with the atrial incisions replaced by linear lesions formed using radiofrequency energy [3–7]. Previous studies of the effects of application of radiofrequency energy on myocardial tissue relate to endocardial catheter ablation. Different lesions may be expected during intraoperative ablation. Unlike catheter ablation there is no circulating blood directly cooling the electrode and the heart may be cooled and arrested with no myocardial blood flow. There is little data on the characteristics of radiofrequency lesions in these circumstances.

The aim of the present study was to characterize in detail the lesions made by handheld probes designed for intraoperative radiofrequency ablation. The effect of electrode size, electrode temperature and duration of ablation were examined using epicardial ablation in the dog ventricle. Simultaneous multielectrode ablation was also examined. The studies of multielectrode ablation were performed after the unipolar ablation studies. By that time it had become clear that the best approach for intraoperative ablation would be with the aorta cross-clamped and the heart stopped by cold cardioplegic solution. This approach improved visibility, particularly in the left atrium and reduced the risk of unnecessary trauma to the atria.

2. Materials and methods

Handheld instrument were designed and built to perform linear ablation intraoperatively. Our aim was to produce a device that was easy to operate and capable of producing transmural continuous linear lesions as rapidly as possible.

Ablation was performed using a radiofrequency generator with a fundamental frequency of 600 kHz and a maximum power output of 60 W (Zencor MF 1, Melbourne, Australia). The ablation electrodes were mounted on handheld probes suitable for intraoperative use. Two types of ablation instrument were tested.
2.1. Unipolar probes

Radiofrequency lesions were produced using a straight or J tipped electrode at the end of a 20 cm long handle (Fig. 1B–D). The electrode was flat with a length of 12 mm and a width of either 2.5 or 1.25 mm. Rectangular electrodes have been shown to produce larger lesions than cylindrical electrodes of a similar size [8]. The long handle and shape of the probe was designed to allow the electrode to be positioned firmly against the epicardial or the endocardial surface through an atriotomy. Radiofrequency current was delivered between the probe electrode and a large diathermy electrode positioned on the skin. A thermistor on the probe electrode and a closed loop feedback system were used to control radiofrequency current delivery during ablation at a preset temperature.

2.2. The effect of temperature, duration of ablation and electrode size on lesion dimensions

Six mongrel dogs were anaesthetized using propofol (10–15 mg/kg) for induction and halothane (0.5–2%) for maintenance of anaesthesia. After intubation and intermittent positive pressure ventilation, a thoracotomy was performed and a pericardial cradle formed to expose the ventricles. Target temperatures of 70, 80 and 90°C and the 2.5 mm wide electrode were used to test the effect of altering the target temperature on lesion size. The duration of ablation was kept constant at 60 s. The 2.5 mm wide probe and a target temperature of 80°C were used to examine the effect of altering the duration of ablation on lesion size. Lesions were examined after 15, 30, 60 and 120 s ablations. The effect of electrode width was tested by comparing the 2.5 mm wide to the 1.25 mm wide probe using a target temperature of 80°C and ablation duration of 60 s. Seven lesions were made in each dog.

2.3. Simultaneous multielectrode ablation

A multielectrode handheld ablation device was tested (Fig. 1A) in another three dogs. This probe had four 6 × 2 mm electrodes with an interelectrode distance of 3 mm mounted in sequence on a 33 mm long flexible tip. Simultaneous, in-phase, unipolar ablation was performed between all four electrodes and the large surface electrode. A closed loop temperature control system independently and simultaneously controlled the temperature on each electrode [9]. In these studies ablation was performed after perfusing the heart with cold (0–5°C) cardioplegia solution. The target temperature was 80°C and the duration of ablation was 60 s.

2.4. Histological analysis

Lesions were examined macroscopically and microscopically in all cases. Animals were sacrificed 20 min after the conclusion of the study and the hearts were excised rapidly and placed in formalin. Blocks were made from each lesion and macroscopic measurements made using a translucent grid. Microscopic sections were made in the plane perpendicular to the long axis of the ablation electrodes. Four sections were made from each lesion. Gomori’s Trichrome stain was used to help identify the lesion margins. The length, width, depth and cross-sectional area of lesions were measured.

The study was approved by the Western Sydney Area Health Service Animal Ethics Committee and conducted in a manner conforming with the ethical and scientific principles set out by the National Health and Medical Research Council of Australia and the European Convention on Animal Care.

2.5. Statistics

Analysis of variance was used to assess the effects of power and duration of ablation on lesion volume. Student’s t-test was used for the other comparisons. Differences were considered statistically significant if the P value was less than 0.05. Continuous variables are expressed as means ± SD.

3. Results

In all cases radiofrequency lesions were completed without impedance rises, charring or crater formation. Soon after application of radiofrequency energy the endocardium became blanched in an elliptical area extending 3–5 mm around the ablation electrode. After fixation the lesions were easily visible on cut sections and had clearly defined borders. Lesions were pale compared to the surrounding tissue. There was often a region of haemorrhage close to the border of the lesion. Microscopic examination showed loss of cell definition, separation of the fibres by oedema, loss of nuclei and cross-striations, and formation of contrac-
tion bands. Extravascular red blood cells were present at the margins of the lesions. The borders of the lesions were readily identifiable with the Gomori Trichrome stain (Fig. 2A,B).

3.1. The effect of duration of ablation on lesion size

The time taken to achieve 90% of the target temperature was 11 ± 5 s. The target temperature was not achieved during any of the 15 s radiofrequency applications. The average maximum temperature for these ablations was 74 ± 4°C. The target temperature was achieved in 57% of the 30 s ablation applications. The mean settling time (time taken to reach the target temperature) for the 30 s ablations was 23 ± 6 s. The target temperature was reached in all applications at 60 and 120 s. The mean settling time for these ablations was 30 ± 10 s. The maximum temperature, and the current and impedance values recorded immediately prior to termination of the radiofrequency current are shown in Table 1.

The depth of lesions increased as the duration of ablation increased from 3.9 ± 0.9 mm after 15 s to 6.1 ± 0.9 mm after 120 s ($P = 0.01$). The maximum cross-sectional area increased from 14 ± 6 mm$^2$ after 15 s to 36 ± 19 mm$^2$ after 120 s ($P = 0.02$). Table 1 shows the full details of these lesions.

3.2. Target temperature and lesion size

The target temperature was achieved in all of the 60 s radiofrequency applications in a mean time of 30 ± 10 s. The time taken to achieve 90% of the target temperature was 12 ± 6 s. There was no significant difference between these values for lesions produced with the three target temperatures. In all cases there was a small overshoot in the temperature. The maximum temperatures achieved for the target temperatures of 70, 80 and 90°C were 72 ± 3, 83 ± 2 and 94 ± 5°C, respectively. There was no significant difference in the current (389 ± 199 mA) or impedance (87 ± 43 Ω) measurements at the three target temperatures.

Depth, width and cross-sectional area of lesions increased with increasing target temperature but these increases were not statistically significant. There was no change in the aspect ratio over the range of temperatures tested ($P = 0.5$). The details are listed in Table 2.

3.3. Comparison of different electrode widths

There was no significant difference between the lesion sizes using the two different electrode widths. The details of these results and other ablation details are listed in Table 3. There was a trend toward more rapid heating of the electrode when the thin electrode was used but the differences were not statistically significant. Less current was required to maintain the temperature of the thin electrode and the overshoot caused a higher maximum temperature.

<table>
<thead>
<tr>
<th>Duration of ablation</th>
<th>15 s</th>
<th>30 s</th>
<th>60 s</th>
<th>120 s</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum temperature (°C)$^a$</td>
<td>74 ± 4</td>
<td>81 ± 3</td>
<td>83 ± 2</td>
<td>85 ± 4</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>393 ± 183</td>
<td>378 ± 193</td>
<td>410 ± 181</td>
<td>390 ± 219</td>
<td>NS$^b$</td>
</tr>
<tr>
<td>Impedance (Ω)</td>
<td>93 ± 44</td>
<td>90 ± 44</td>
<td>90 ± 45</td>
<td>91 ± 48</td>
<td>NS$^b$</td>
</tr>
<tr>
<td>Depth (mm)</td>
<td>3.9 ± 0.9</td>
<td>4.6 ± 0.8</td>
<td>5.3 ± 1.3</td>
<td>6.1 ± 0.9</td>
<td>0.01</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>6.0 ± 1.6</td>
<td>6.7 ± 1.1</td>
<td>9.1 ± 2.9</td>
<td>10.6 ± 4.1</td>
<td>0.06</td>
</tr>
<tr>
<td>Cross-sectional area (mm$^2$)</td>
<td>14 ± 6</td>
<td>19 ± 6</td>
<td>25 ± 13</td>
<td>36 ± 19</td>
<td>0.02</td>
</tr>
<tr>
<td>Aspect</td>
<td>0.68 ± 0.20</td>
<td>0.70 ± 0.15</td>
<td>0.61 ± 0.18</td>
<td>0.64 ± 0.19</td>
<td>0.5</td>
</tr>
</tbody>
</table>

$^a$ Target temperature 80°C.

$^b$ NS, not significant ($>0.05$).
3.4. Multielectrode ablation

Lesions produced using the multielectrode probe in cold cardioplegied ventricular myocardium were 30–35 mm long with even penetration into the tissue. The mean depth of these lesions on microscopic sections was 3.9 mm. The mean width was 7.1 mm.

4. Discussion

The ideal instrument for intraoperative radiofrequency ablation should be capable of making long lesions in a short period of time. The long multielectrode ablation probe described in this study can be used with a radiofrequency splitting device to make lesions 30–35 mm in length in 60 s. The section of the probe containing the electrodes was malleable, allowing it to be shaped to conform to the endocardial or epicardial surface.

The depth of lesions was adequate to produce transmural lesions in most parts of the atria [10,11] but care needs to be taken in very thick areas such as the crista terminalis, right atrial free wall trabeculations, atrial septum and the atrio-ventricular junction. As expected radiofrequency lesions were wider than they were deep, so deep penetration of lesions into the myocardium can only be achieved by producing broad lesions with large volumes.

4.1. The time course of lesion formation

The lesions expanded rapidly. sixty three percent of the lesion depth achieved at 120 s was present after 15 s. Doubling the duration of ablation from 30 to 60 s increased the lesion depth by a further 16%. Doubling the duration of ablation again to 120 s added another 16% to the lesion depth (Fig. 3). It is likely that with ablation longer than 120 s the lesion size would increase further before a steady state was reached but these times would be impractical when creating multiple lesions for linear ablation.

Similar findings were reported when radiofrequency energy was delivered by catheter [12]. Wittkampf et al. [13] using a 2 mm catheter tip electrode found that the maximum lesion size was achieved in less than 20 s. Bardy et al. [14] found that lesion size increased with increasing duration of ablation. The maximum lesion size was achieved within 15 s of onset. Haines et al. [15] studied temperature controlled ablation in isolated perfused and superfused canine atra. The temperature half time in their study was 19 s. Wittkampf drew attention to the increased time required to reach steady state temperature as the distance from the electrode increased [15,16]. Temperatures at a depth of 5 mm approached their asymptotic values only after approximately 2 min.

The present study indicates the duration of ablation required to produce transmural linear lesions. The precise duration required depends on the thickness of the atrial myocardium. Thin areas of the atria such as those near the junction of the inferior vena cava and the right atrial free

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**Table 2**

Duration of ablation analysis: current, impedance and maximum temperature achieved

<table>
<thead>
<tr>
<th>Target temperature (°C)</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (mm)</td>
<td>5.0 ± 1.2</td>
<td>5.3 ± 1.3</td>
<td>5.6 ± 1.7</td>
<td>0.19</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>8.4 ± 3.5</td>
<td>9.1 ± 2.9</td>
<td>8.6 ± 1.5</td>
<td>0.39</td>
</tr>
<tr>
<td>Cross-sectional area (mm²)</td>
<td>22 ± 11</td>
<td>25 ± 13</td>
<td>41 ± 33</td>
<td>0.25</td>
</tr>
<tr>
<td>Aspect (depth/width)</td>
<td>0.67 ± 0.25</td>
<td>0.61 ± 0.18</td>
<td>0.64 ± 0.13</td>
<td>0.52</td>
</tr>
</tbody>
</table>

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**Table 3**

A comparison of lesions made with wide (2.5 mm) and narrow (1.25 mm) electrodes

<table>
<thead>
<tr>
<th></th>
<th>Wide electrode</th>
<th>Narrow electrode</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling time 90% (s)*</td>
<td>10 ± 4</td>
<td>8 ± 5</td>
<td>0.13</td>
</tr>
<tr>
<td>Settling time 100% (s)</td>
<td>29 ± 7</td>
<td>23 ± 5</td>
<td>0.15</td>
</tr>
<tr>
<td>Maximum temperature (°C)</td>
<td>83 ± 2</td>
<td>87 ± 3</td>
<td>0.01</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>410 ± 181</td>
<td>308 ± 186</td>
<td>0.02</td>
</tr>
<tr>
<td>Impedance (Ω)</td>
<td>90 ± 45</td>
<td>91 ± 46</td>
<td>0.84</td>
</tr>
<tr>
<td>Depth (mm)</td>
<td>4.0 ± 0.5</td>
<td>3.9 ± 1.0</td>
<td>0.95</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>7.1 ± 1.2</td>
<td>7.9 ± 3.0</td>
<td>0.49</td>
</tr>
<tr>
<td>Cross-sectional area (mm²)</td>
<td>21 ± 6</td>
<td>25 ± 13</td>
<td>0.32</td>
</tr>
<tr>
<td>Aspect</td>
<td>0.57 ± 0.09</td>
<td>0.55 ± 0.21</td>
<td>0.83</td>
</tr>
</tbody>
</table>

*Time taken to achieve 90% of the target temperature.
wall require shorter ablation times (15–30 s) than thick areas such as the roof of the left atrium and the crista terminalis. The duration of ablation could be adjusted during the procedure depending on the usual regional differences in atrial thickness [10,11] or the thickness of the atrial wall observed by the operator. This refinement may allow more rapid completion of the surgery, reducing the duration of cardiopulmonary bypass and its associated risk.

4.2. Target temperature and lesion size

Lesion dimensions increased with increases in the target temperature but within the small range of temperatures tested in this study this increase was not statistically significant. In this study ablation was performed without tissue disruption or rises in impedance.

4.3. Limitations of the model

The ventricle was chosen as the site of radiofrequency ablation to allow accurate assessment of the maximum depth of lesions. The thin wall of most of the atria and variable thickness of the trabeculated region would prevent this type of assessment. Atrial thickness varies considerably between species. A comparison of atrial thickness in humans and animals commonly used in models of atrial fibrillation was published by Jensen et al. [10,17]. Most of the human atria were less than 5 mm thick but structures such as the crista terminalis and the trabeculations of the right atrial free wall in hypertrophic hearts were up to 6 mm thick. In dogs most of the atrial muscle was less than 3 mm deep. The thickest region, in the superior left atrium above the pulmonary veins was $5.2 \pm 1.6$ mm. The results of the present study indicate that lesions in the thicker parts of the human atria are unlikely to be transmural. Patterns of linear radiofrequency lesions should be designed with the regional differences in atrial wall thickness in mind to reduce the risk of discontinuities in lines of ablation.

The depths of the lesions in this study may not accurately reflect those made in the atria during cardiac surgery in humans where some of the lesions are performed during cold cardiopedia with reduced baseline myocardial temperature and no blood flow. An in vitro study by Haines et al. [15] demonstrated that presence or absence of perfusion during temperature controlled ablation is unlikely to influence lesion size. However, a lower baseline tissue temperature due to cardioplegia will reduce the size of lesions. More energy is required to increase the tissue temperature above the level necessary for irreversible tissue damage. As expected, smaller lesions were observed in the evaluation of the multielectrode ablation device after perfusing with cold cardioplegia solution. In thick areas of atrial myocardium this effect may prevent lesions from penetrating the full thickness of myocardial tissue and create discontinuities in lines of ablation.

Another potential study limitation is that lesions were created in normal canine myocardium. Longstanding atrial fibrillation is characterized histopathologically by diffuse interstitial fibrosis [18]. Scarring in the myocardium may alter the biophysics of radiofrequency ablation. However, a study of radiofrequency ablation in normal and scarred myocardium performed using the percutaneous catheter technique suggests this effect is small and unlikely to be clinically significant. Although the present study indicates the potential of radiofrequency ablation using a handheld device to create deep lesions, further evaluation is necessary in humans.

5. Conclusions

A handheld radiofrequency ablation probe can be used to make deep linear lesions in myocardium. Lesion size increased rapidly with increased duration of ablation but most of the lesion (~75%) was formed during the first 30 s of ablation. Radiofrequency lesions were wider than they were deep, so deep penetration of lesions into the myocardium can only be achieved by producing broad lesions with perhaps unnecessarily large volumes. A handheld multielectrode ablation tool can be used with a radiofrequency splitting device to allow simultaneous radiofrequency ablation from a single radiofrequency generator. This produced long linear lesions in the myocardium in a relatively short period of time. This approach should reduce the time required for linear ablation procedures at both surgery and catheter ablation.

Acknowledgements

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[5] Chen MC, Gao GB, Chang JP, Yeh KH, Fu M. Radiofrequency and...


