Indication of the radiofrequency induced lesion size by pre-ablation measurements

Niels Stagegaard, Helen Høgh Petersen*, Xu Chen, Jesper Hastrup Svendsen

Medical Department B 2012, The Heart Centre, Rigshospitalet, National University Hospital, Blegdamsvej 9, 2100 Copenhagen, Denmark

Submitted 10 August 2004, and accepted after revision 25 May 2005
Available online 8 September 2005

KEYWORDS
- catheter ablation;
- impedance;
- electrode contact;
- external cooling;
- power-controlled ablation;
- temperature-controlled ablation;
- irrigated tip;
- radiofrequency ablation

Abstract
Background
During radiofrequency ablation of arrhythmias tissue heating and hence lesion size depend on electrode–tissue contact and cooling of the electrode tip caused by cavitory blood flow. These factors are unique and unknown for each catheter placement in the beating heart. A tool for assessing these factors prior to ablation may indicate the lesion size which will be obtained for any given catheter position.

Methods and results
Radiofrequency ablation was performed in vitro on strips of left ventricular porcine myocardium during two different levels of convective cooling (0 or 0.1 m/s), two different contact pressures (10 or 30 g) and parallel or perpendicular electrode–tissue orientation using 7F 4 mm tip catheters. Prior to ablation the impedance rise (ΔIMP) caused by the obtained contact and the temperature rise with a 0.6 W 5 s test pulse (ΔT) were measured. Subsequently, during unchanged conditions, radiofrequency ablation was performed as either temperature-controlled, power-controlled or irrigated tip ablation and lesion size was determined.

ΔIMP increased significantly (P < 0.05) by improved contact, whereas it was not affected by convective cooling. ΔT was significantly increased by increasing contact pressure (P < 0.05) and significantly decreased by increased cooling (P < 0.001). ΔT was not systematically affected by electrode orientation. The product of ΔT and ΔIMP showed a significant correlation between the obtained lesion size and power output for temperature-controlled and between lesion size and tip temperature for power-controlled ablation (P < 0.001).
Conclusions  Pre-ablation measurement of ΔIMP and ΔT can indicate the lesion size resulting after ablation in temperature-controlled, power-controlled and irrigated ablation in vitro, since ΔT reflects cavitory cooling and to a smaller extent electrode—tissue contact, and ΔIMP reflects only electrode—tissue contact. © 2005 The European Society of Cardiology. Published by Elsevier Ltd. All rights reserved.

Introduction

Radiofrequency catheter ablation has proven to be a safe and effective means of treatment of many tachycardias [1–5], but during ablation even in the temperature-controlled mode the convective cooling of the electrode tip can cause excess power delivery, thereby causing tissue overheating [6]. It is therefore necessary to control the tissue heating in order to obtain the lesion size needed without excess power delivery. This requires knowledge of, and adjustment for, the factors influencing lesion size. Several factors have been shown to affect the obtained tissue temperatures and thereby lesion size during radiofrequency catheter ablation. Some of these factors can be controlled by the choice of catheter and by the setting of the radiofrequency generator, that is: electrode tip size [7–11], energy application time [12,13], irrigation rate [14–16], power or temperature setting [17–20]. Other factors, which are difficult or impossible to control, such as convective cooling of the electrode tip [6,10,11,21–24], electrode—tissue contact pressure [12,14,21–28] and electrode tip orientation against the endocardium [10,21,23,24,29,30] have also been shown to have major impact on tissue temperatures and hence lesion size. Since these "uncontrollable" factors are unique for each obtained catheter position in the heart, they are unknown.

To control lesion size, one must adjust power or temperature setting according to the actual obtained electrode—tissue contact and actual convective cooling of the electrode tip at the given site. Therefore, pre-ablation evaluation of parameters reflecting these factors might be a valuable tool.

The purpose of the present in vitro study was to evaluate if measurement of the impedance rise caused by the variable electrode—tissue contact correlates with the lesion size obtained and to evaluate whether this impedance change can add information to the correlation between lesion size and the temperature rise from a pre-ablation low power test pulse, which in other studies has been shown to correlate with lesion size [23,26].

Methods

The model

Freshly excised pig hearts, used less than 4 h postmortem, were dissected and strips of left ventricular myocardium were suspended in a bath of isotonic saline at 37 °C.

The electrode was mounted in a holder maintaining the tip either perpendicular or parallel to the tissue. The electrode—tissue contact pressure was controlled by a strain gauge dynamometer adjusted to maintain a pressure of either 10 or 30 g. A pump circulating the saline in the bath releasing it through a laminator close to the electrode tip created external convective cooling around the electrode tip, simulating cavitory blood flow. The pump was adjusted to create a flow velocity of either 0 or 0.1 m/s around the electrode tip measured by pulsed wave Doppler (Toshiba Sonolayer SSA-270A) using an oesophageal probe (Hewlet Packard Omniplane 5 mHz PEF 511-SA).

Ablation equipment

Two radiofrequency generators were used. For pre-ablation impedance measurement a generator capable of measuring impedance at 50 kHz prior to initiating ablation was used (EP-SHUTTLE, Stockert GMBH, Freiburg, Germany).

For test pulse delivery and unipolar ablation a generator delivering radiofrequency current with a frequency of 500 kHz and maximal power output of 100 W (ATAKR II, Medtronic CardioRhythm, Minneapolis, MN, USA) was used. This generator is capable of delivering a short non-destructive output of 0.6 W for 30 s. (LEM™ mode) [26]. The change in electrode-tip temperature during LEM™ is displayed continuously on the generator with one digit. The accuracy of the temperature measurement is 0.1 °C [31].

Thermocouple-type 7F, 4 mm tip catheters, either conventional non-cooled (ABLATR, Medtronic CardioRhythm, San Calif., USA) or irrigated showerhead-type (SPRINKLR, Medtronic CardioRhythm, San Calif., USA) were used. During ablation
the electrode-tip temperature, power output and impedance were continuously monitored. Power output was automatically discontinued if impedance was outside the range of 40–250 $\Omega$ or if tip temperature exceeded 90°C. A Harvard “44” syringe pump was used to control infusion rate through the irrigation catheters.

**Measurement of pre-ablation parameters**

Prior to each ablation impedance at 50 kHz was measured with the convective cooling adjusted according to the protocol (see below) and the tip placed approximately 2 mm above the tissue and then measured again when electrode–tissue contact was obtained with the desired orientation and pressure (see below). The difference between these two impedance measurements, i.e. the increase in impedance obtained by electrode–tissue contact ($\Delta$IMP) was registered.

Then with unchanged electrode position and unchanged cooling in the tissue bath the low power test pulse (0.6 W) was delivered and the increase in tip temperature ($\Delta T$) at 5 s was registered. After approximately 1 min, to allow tip temperature to normalize, ablation was performed with unchanged contact and convective cooling.

**Ablation protocols**

Electrode orientation was either perpendicular or parallel. Electrode–tissue contact pressure was either 10 or 30 g and convective cooling was either 0 or 0.1 m/s.

Pre-ablation measurements were performed as described above.

Ablation with non-cooled catheters was performed in two different modes: temperature-controlled ablation with a target temperature of 70°C and power-controlled ablation with a power setting of 15 W.

Ablation with irrigated catheters was performed in the power-controlled mode with a power setting of 40 W and an irrigation rate of 20 ml/min using isotonic saline at 37°C.

Energy application time was 60 s for all modes of ablation.

After each ablation the average power output and average tip temperature were registered.

**Tissue preparation and lesion volume determination**

The lesions were cut by two incisions through the centre perpendicular to the surface and perpendicular to each other. The tissue blocks were then incubated with 0.5 mg nitroblue tetrazolium/ml 0.2 M Soerenson’s buffer for 10 min at 37°C. The maximum lesion depth and width in both dimensions ($\text{width}_a$ and $\text{width}_b$) were then measured with calipers.

Volume was calculated as $\pi \times 6^{-1} \times \text{depth} \times \text{width}_a \times \text{width}_b$.

**Statistical analysis**

Values are expressed as mean $\pm$ SD. Assessments of relations were performed using linear or parabolic regression, the least squares method was used for curve fitting. Individual groups were compared by two-sample $t$-test. Values of $P < 0.05$ were considered statistically significant. Statistical software Excel 2000 was used.

**Results**

A total of 213 lesions were produced. Eighty-four lesions were performed in the temperature-controlled mode, 86 lesions in the power-controlled mode and 43 lesions were performed with irrigated tip ablation. All applications were continued for the planned 60 s duration.

During four applications popping occurred. In two of these lesions a crater was seen. All of these four applications were performed in the temperature-controlled mode with 10 g pressure and external cooling of 0.1 m/s. Compared with lesions with no popping, these four applications had significantly lower $\Delta T$ and $\Delta$IMP ($P < 0.05$) and mean power output and lesion volume were significantly higher compared with lesions where popping did not occur ($P < 0.05$).

IA. Pre-ablation measurements: relation to electrode–tissue contact and external cooling, non-irrigated ablation ($n = 170$)

1. $\Delta T$: When electrode–tissue contact pressure was increased from 10 to 30 g a significant increase in $\Delta T$ was seen for both electrode orientations and for both flow situations ($P < 0.05$), whereas $\Delta T$ was not significantly altered by changing electrode orientation except in the group of applications with 10 g contact pressure in the flow situation, where $\Delta T$ was slightly, but significantly higher for the parallel orientation compared with the perpendicular orientation ($P < 0.05$). Increasing external cooling by changing the flow in the...
tissue bath from 0 to 0.1 m/s significantly decreased $\Delta T$ for all settings ($P < 0.001$) (Table 1).

2. $\Delta$IMP: When electrode–tissue contact pressure was increased from 10 to 30 g a significant increase in $\Delta$IMP was seen for both electrode orientations and for both flow situations ($P < 0.05$). Changing electrode orientation from parallel to perpendicular caused an increase in $\Delta$IMP for both flow situations, which reached statistical significance for a contact pressure of 30 g ($P < 0.001$), whereas the increase was not statistically significant for a contact pressure of 10 g. Changing external cooling by changing the flow in the tissue bath did not cause any changes in $\Delta$IMP, except for a contact pressure of 10 g in the perpendicular orientation, where $\Delta$IMP was slightly, but significantly higher ($P < 0.05$) in the no-flow situation.

II. Pre-ablation measurements: relation to subsequent ablation parameters and lesion size

As the impact of changing the electrode orientation, contact pressure and flow around the electrode varies with the applied ablation mode, the relations between the two pre-ablation parameters ($\Delta T$ and $\Delta$IMP) and the tip temperature and power output reached during ablation, as well as the lesion size obtained are considered separately for each ablation mode given below.

IIA. Power-controlled ablation

Combining all groups of electrode orientation, electrode contact pressure and flow around the electrode tip ($N = 86$), simulating the clinical situation, where neither of these parameters are known, showed a modest, but significant positive correlation ($r = 0.49$, $P < 0.001$) between $\Delta T$ and lesion volume, and between $\Delta T$ and average tip temperature achieved ($r = 0.90$, $P < 0.001$) (Table 2A and Fig. 1).

We found a significant positive correlation between $\Delta$IMP and lesion volume ($r = 0.64$, $P < 0.001$), and a poor, but significant positive correlation between $\Delta$IMP and average tip temperature achieved ($r = 0.35$, $P < 0.01$). Combining the two pre-ablation parameters improved the correlations for both lesion volume and tip temperature: A significant positive correlation ($r = 0.67$, $P < 0.001$) between the product

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### Table 1  Pre-ablation measurements for standard and irrigated tip ablation

<table>
<thead>
<tr>
<th>Pressure (g)</th>
<th>Orientation</th>
<th>Flow (m/s)</th>
<th>$\Delta T$ (°C)</th>
<th>$\Delta$IMP (Ω)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Perpendicular</td>
<td>0</td>
<td>1.65 ± 0.33</td>
<td>22.5 ± 6.6</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
<td>0</td>
<td>1.64 ± 0.15</td>
<td>19.6 ± 6.9</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
<td>Perpendicular</td>
<td>0</td>
<td>1.90 ± 0.24</td>
<td>31.8 ± 10.7</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
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<td>1.80 ± 0.17</td>
<td>23.1 ± 5.1</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>Perpendicular</td>
<td>0.1</td>
<td>0.41 ± 0.15</td>
<td>18.3 ± 4.8</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Perpendicular</td>
<td>0.1</td>
<td>0.51 ± 0.13</td>
<td>17.3 ± 4.3</td>
<td>29</td>
</tr>
<tr>
<td>30</td>
<td>Perpendicular</td>
<td>0.1</td>
<td>0.56 ± 0.20</td>
<td>33.4 ± 10.0</td>
<td>19</td>
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<tr>
<td></td>
<td>Perpendicular</td>
<td>0.1</td>
<td>0.66 ± 0.24</td>
<td>21.7 ± 6.6</td>
<td>22</td>
</tr>
<tr>
<td><strong>Irrigated</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Perpendicular</td>
<td>0</td>
<td>18.3 ± 3.1</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>Perpendicular</td>
<td>0</td>
<td>29.4 ± 4.5</td>
<td></td>
<td>11</td>
</tr>
<tr>
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<td>Perpendicular</td>
<td>0.1</td>
<td>14.6 ± 4.5</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>30</td>
<td>Perpendicular</td>
<td>0.1</td>
<td>28.6 ± 6.9</td>
<td></td>
<td>11</td>
</tr>
</tbody>
</table>
The impact of pressure, orientation and cooling on lesion size and average power output in the present study is consistent with the findings from earlier studies.

**II B. Temperature-controlled ablation**
Combining all groups of electrode orientation, electrode contact pressure and flow around the electrode tip ($N=43$), simulating the clinical situation, where neither of these parameters are known, showed a significant negative correlation between $\Delta T$ and lesion volume ($r = 0.57$, $P < 0.001$) and also between the product $\Delta T \times \Delta IMP$ and average tip temperature was achieved ($r = 0.90$, $P < 0.001$ (Fig. 1B).

The impact of pressure, orientation and cooling on lesion size and tip temperature achieved in the present study is consistent with the findings from earlier studies.

**II C. Irrigated ablation**
Combining the two levels of external cooling and the two contact pressures ($N=43$) we found a significant positive correlation between $\Delta IMP$ and lesion volume ($r = 0.82$, $P < 0.001$ (Fig. 3) and between $\Delta IMP$ and lesion depth ($r = 0.71$, $P < 0.001$ (Table 3).

Consistent with earlier studies [14] we found that increasing electrode–tissue contact pressure increased lesion dimensions significantly ($P < 0.05$), whereas increasing external cooling did not change lesion dimensions significantly.

**Discussion**
Lesion size is determined by the amount of energy delivered by the generator and by the fraction of this delivered energy that actually enters the tissue. These two parameters, in turn, are determined by the electrode-to-tissue contact and by the...
external cooling of the electrode tip, which are two unknown factors, since they are unique for each electrode position. This can be explained as follows: The lesion size obtained during radiofrequency ablation is correlated with the tissue temperature reached during energy application [10,21,22,32–34]. This, in turn, is determined by the amount of energy entering the tissue. Since the electrode tip is not completely embedded in the tissue, only part of the energy delivered by the radiofrequency generator is entering the tissue, the rest of the energy is "wasted" into the blood. How large the fraction of the energy entering the tissue is, depends almost entirely on the degree of tissue contact obtained, which, as demonstrated in the present study can be estimated by pre-ablation measurement of $\Delta$IMP, since the conductivity of blood (or saline) and tissue differs (0.95 and 0.61 $\Omega^{-1} \text{m}$ at 37 °C, respectively) [35]. The impedance increase which occurs when the electrode tip is moved from "no contact" to "contact", will therefore reflect the fraction of the tip touching tissue.

The amount of energy delivered by the generator is again determined, either by the operator during power-controlled ablation or by automatic regulation during temperature-controlled ablation up to the power limit set by the operator. In both modes the amount of energy that can be or is delivered is highly dependent on the cooling of the

**Figure 1** For all power-controlled applications, independent of the electrode–tissue contact (pressure and orientation) and independent of external cooling, both of which, in a clinical setting, are unknown, the relations between the product of the two pre-ablation parameters and the lesion volume obtained and the average tip temperature reached are shown. For abbreviations see text.
electrode for the particular electrode position obtained, which as demonstrated in the present study, can be estimated by pre-ablation measurement of $D_T$.

Therefore, the combination of evaluating electrode-to-tissue contact (determines the fraction of delivered energy that will enter the tissue) and cooling (determines power output during temperature-controlled ablation, and heat-loss during power-controlled ablation) can give an indication of tissue heating.

$\Delta T$ and $\DeltaIMP$ have to be interpreted with consideration of the planned ablation mode, since the impact on lesion size caused by contact and cooling differs for the different ablation modes. For example, the effect of increasing external convective cooling is directly opposite in the two modes: in the temperature-controlled mode increasing cooling will increase power delivery and, therefore, lesion size, whereas during power-controlled ablation power delivery is constant and increased cooling will cause a slight decrease in lesion size, due to increased heat transfer away from the electrode tip and from the tissue [6,10,11,21–24]. $\Delta T$ is reflecting cooling and this opposite effect of cooling between the two modes is demonstrated by the negative correlation between $\Delta T$ and lesion size for temperature-controlled ablation and by the positive correlation between $\Delta T$ and lesion size for power-controlled ablation.

**Figure 2** For all temperature-controlled applications, independent of the electrode–tissue contact (pressure and orientation) and independent of external cooling, both of which, in a clinical setting, are unknown, the relations between the product of the two pre-ablation parameters and the lesion volume obtained and the average power applied are shown. For abbreviations see text.
Since excessively high temperatures, above approximately 100 °C, of the myocardial tissue entail a risk of pop and crater formation [6,36], pre-ablation measurement evaluating the factors (tissue contact and external cooling) determining the amount of energy entering the tissue and thereby tissue heating, can allow for adjustment of target temperature/power setting to reduce the risk of overheating. Our group has recently demonstrated this for left ventricular ablation in the beating heart in an in vivo study [37]. As shown in the present study, even during temperature-controlled ablation, where the electrode-tip temperature is constant, pop and crater formation occurred in some lesions. These applications had significantly lower ΔT and ΔIMP compared with the applications without popping, indicating high power delivery and increased risk of popping. Adjustment of either target temperature or power limit for these applications could probably have reduced this risk.

The present study demonstrates for the first time that the temperature rise induced by a pre-ablation low power test pulse (ΔT) and the impedance rise caused by the obtained electrode–tissue contact (ΔIMP) can give an indication of the cavitory cooling of the electrode tip and of the electrode–tissue contact in vitro. For irrigated tip ablation, where cavitory cooling has little or no impact on lesion size, since its effect is overcome by the high irrigation rate, and ΔT is not measurable, we demonstrated for the first time that ΔIMP can reflect electrode tip contact pressure and is positively correlated with the obtained lesion size. In recent in vitro studies [23,26] it has been shown that the temperature rise induced by a pre-ablation low power test pulse mainly reflects the external cooling of the electrode tip and to a smaller extent the electrode–tissue contact. The electrode–tissue contact can be evaluated more precisely by measuring the difference in impedance before and after tissue contact [38–41], as illustrated in the present study.

**Clinical implications**

Assuming these findings can be applied to the human heart, they imply a possible means of controlling power delivery to the tissue during

<table>
<thead>
<tr>
<th>Pressure (g)</th>
<th>Cooling (m/s)</th>
<th>ΔIMP (Ω)</th>
<th>Tip temp (°C)</th>
<th>Depth (mm)</th>
<th>Volume (mm³)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0</td>
<td>18.3 ± 3.1</td>
<td>46 ± 2</td>
<td>5.4 ± 0.8</td>
<td>215 ± 111</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>29.4 ± 4.5</td>
<td>44 ± 2</td>
<td>7.1 ± 1.4</td>
<td>499 ± 167</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td>14.6 ± 4.0</td>
<td>41 ± 2</td>
<td>5.9 ± 1.1</td>
<td>255 ± 157</td>
<td>11</td>
</tr>
<tr>
<td>30</td>
<td>0.1</td>
<td>28.6 ± 7.0</td>
<td>40 ± 2</td>
<td>7.3 ± 1.2</td>
<td>503 ± 182</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 3 Irrigated tip ablation
radiofrequency catheter ablation with consideration of each catheter position’s unique electrode–tissue contact and external cooling. This should in theory allow for a more controllable power delivery into the tissue and hence a more controllable lesion size, thereby reducing the risk of tissue overheating, popping and crater formation.

**Study limitations**

This study was performed in non-perfused porcine myocardium in an in vitro model. The movements of the beating heart are likely to increase the variations of both pre-ablation parameters. Further, in the present model the tissue was suspended in saline, which has a lower impedance than blood, and the ∆IMP in the present study might therefore not be quite comparable with the clinical situation. But we have yet unpublished data concerning ∆IMP from an in vivo study of left ventricular ablation [37], where a mean ∆IMP of 31.3 Ω was found, which is comparable with the high pressure situations in the present study. Another factor which might have impact is the perfusion of the cardiac tissue in vivo. The present findings should, therefore, be tested in an in vivo model.

**Acknowledgement**

The radiofrequency generators were kindly placed at our disposal by Medtronic CardioRhythm, Minneapolis, MN, USA and by Stockert GMBH, Freiburg, Germany.

**References**


[3] Fontaine G. The ablative techniques from surgery to radiofrequency catheter ablation with consideration of each catheter position’s unique electrode–tissue contact and external cooling. This should in theory allow for a more controllable power delivery into the tissue and hence a more controllable lesion size, thereby reducing the risk of tissue overheating, popping and crater formation.


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