Temperature-controlled radiofrequency catheter ablation of manifest accessory pathways

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Objectives The primary objectives of this study were to assess the feasibility of temperature-controlled radiofrequency catheter ablation of left and right sided manifest accessory pathways in patients with Wolf–Parkinson–White syndrome and to gain more insights into biophysical aspects of temperature-controlled catheter ablation in humans.

Background The electrode–tissue interface temperature and other biophysical parameters are among important variables determining the efficacy and safety of radiofrequency ablation of accessory pathways. Experimental studies have shown that radiofrequency-induced tissue necrosis can be accurately predicted by monitoring of catheter tip temperature.

Methods 38 consecutive patients (14 f, 24 m; aged 42 ± 12 years) with anterograde conducting accessory pathways (left sided: n = 22; right sided: n=16) underwent temperature-controlled radiofrequency ablation (HAT 200S, Dr Osypka, Germany). The electrode temperature was monitored via a thermistor embedded into a 4 mm catheter tip. Power output was adjusted automatically during energy delivery in a closed loop system (preselected temp.: 70.1 ± 5·8 °C).

Results Accessory pathway conduction was successfully abolished in all patients after the delivery of 2·3 ± 2·1 radiofrequency pulses (range: 1–9, median: 2). Interruption of the accessory pathway as evidenced by loss of preexcitation occurred after 5·9 ± 5·4 s. At the time of the interruption of the accessory pathway the catheter tip temperature measured 54·2 ± 11·2 °C in patients with left and 44·9 ± 5·0 °C in patients with right sided accessory pathways, respectively (P<0.008). Higher temperature levels during left sided applications did not shorten the time it took for the effect to appear (left sided accessory pathway: 7·5 ± 6·3 s, right sided accessory pathway: 3·7 ± 2·9 s; ns). The catheter tip temperature was significantly higher during left compared to right sided applications after 5 (52·1 ± 3·1 °C vs 47·2 ± 4·3 °C) and 10 s (61·5 ± 6·2 °C vs 52·7 ± 4·2 °C) following initiation of the impulse (P<0·005). Power output and delivered energy did not differ significantly at the time of accessory pathway abolition. Peak values of delivered power (45·1 ± 10·9 W vs 41·3 ± 10·6 W; P<0·05) and total delivered energy (2452 ± 1335 J vs 1392 ± 762 J; P<0·02) were significantly higher in the group of right sided pathways compared to left sided applications. The peak temperature measured 77·1 ± 13 °C during effective and 69·9 ± 14 °C during ineffective energy applications (P<0·05). The time it took for the effect to appear was significantly longer in transiently effective pulses (10·4 ± 7·2 s) compared to permanently effective applications (5·9 ± 5·4 s; P<0·02). Despite temperature control, an abrupt rise in impedance was observed in 10 of 89 (11%) energy applications. No procedure-related complications occurred.

Conclusions Temperature-controlled radiofrequency ablation of manifest accessory pathways is highly effective and safe. The temperature response is faster and significantly higher in left-sided energy applications compared to right-sided pulses. Peak temperature levels measured at the electrode tip are significantly higher during effective than ineffective pulses. Sudden rises in impedance are not completely prevented during temperature-controlled radiofrequency ablation of accessory pathway, although no procedure-related complications were noted in this patient cohort.

Key Words: WPW-syndrome, accessory pathways, temperature monitoring, radiofrequency catheter ablation.
**Introduction**

Catheter ablation using power regulated radiofrequency current has become the treatment of choice for symptomatic patients with paroxysmal supraventricular tachycardia involving accessory pathways. Several clinical studies have demonstrated the feasibility of this curative approach\(^{[1-5]}\). The definition of local bipolar electrogram criteria to identify appropriate target sites for ablation\(^{[6-8]}\) and the introduction of unipolar electrogram recording techniques\(^{[9]}\) led to a high success rate and widespread clinical application of this method\(^{[1-9]}\).

Several biophysical variables govern the volume of radiofrequency current-induced lesions. Important factors are the electrode–tissue coupling and the amount of electrical energy converted to heat at the interface between catheter tip and adjacent tissue\(^{[10,11]}\). On-line measurements of power output and impedance are important during radiofrequency current delivery to avoid insulation defects of the catheter and vaporization but do not predict the size of necrosis\(^{[12,13]}\). Experimental studies under in vivo conditions have shown that the extent of lesion size can be accurately controlled by monitoring of the catheter–tissue interface temperature\(^{[14]}\).

In the clinical setting catheter ablation of accessory pathways is associated with a low, but definite risk of procedure-related complications\(^{[15]}\). Experimental studies have shown that potentially thrombogenic coagulum formation is critically dependent on abrupt changes in impedance and increased catheter tip temperature\(^{[11,13]}\). Monitoring of the electrode tip temperature during energy delivery may therefore be useful to prevent overheating of the catheter and thus might improve the efficacy and safety of the procedure.

In the present study, our recent experiences of temperature-controlled radiofrequency catheter ablation in 38 consecutive patients with manifest accessory pathways will be reported and clinical feasibility as well as biophysical aspects will be presented in detail.

**Methods**

**Patient data**

Thirty-eight consecutive patients with the Wolff–Parkinson–White syndrome and a history of recurrent paroxysms of supraventricular tachycardia were investigated. Twenty four males and 14 females with a mean age of 42 ± 12 (range 19–68) years were included in the study. A history of syncope was present in 10 patients. One patient had been resuscitated during ventricular fibrillation because of rapid conduction via the accessory pathway during atrial fibrillation. No patients had evidence of underlying heart disease.

**Electrophysiological study**

Electrophysiological studies were performed in a fasting lightly sedative state after written informed consent had been obtained. Antiarrhythmic therapy has been discontinued for at least five half-lives. The investigations were performed using a conventional method of intracardiac recording and stimulation techniques as previously reported\(^{[16]}\). Multipolar electrode catheters with an interelectrode spacing of 5 or 10 mm were introduced via the femoral veins and positioned into the right atrium, His-bundle region and right ventricular apex under fluoroscopic guidance. A bipolar 7F deflectable electrode catheter (Osyanka ‘Cerablate’, Dr P. Osypka, Grenzach-Whelen, Germany) with an interelectrode spacing of 2 mm was introduced via the femoral artery or vein and used for endocardial mapping and ablation. A thermistor was incorporated into the centre of the 4 mm distal electrode. Effective anticoagulation was maintained throughout the procedure. A continuous infusion of heparin was administered after an initial bolus injection of 4000 units. A bipolar electrogram of the distal and proximal electrode of the mapping catheter (filter setting: 40–500 Hz) and the unipolar electrogram from the distal electrode of the ablation catheter were recorded simultaneously at a paper speed of 100 or 200 mm.s\(^{-1}\).

Endocardial mapping was guided by the following criteria\(^{[6-8]}\): (1) detection of an accessory pathway potential; (2) localization of earliest ventricular activation; (3) unipolar recording via the distal tip of the electrode catheter with a solely negative deflection preceding the QRS onset of maximally preexcited beats (QS complex); (4) electrogram stability.

Endocardial mapping, electrocardiographic measurements and catheter ablation were performed during sinus rhythm. Accessory pathway potentials were defined as distinct deflections between local atrial and ventricular activation preceding the onset of the delta wave. The unipolar recordings were classified according to a report of Haissaguerre et al.\(^{[9]}\).

**Radiofrequency catheter ablation**

Using the radiofrequency generator HAT 200 S (Dr Osypka, Grenzach-Whelen, Germany), energy (500 kHz unmodulated current) was delivered during sinus rhythm between the tip electrode of the ablation catheter and the indifferent patch electrode positioned on the patient’s back. The catheter position was monitored using fluoroscopy with LAO 30° and RAO 60° standard views. Actual power output, impedance, energy delivery and catheter tip temperature were continuously monitored and displayed via an interface on a personal computer. There was no significant difference in preselected temperature (70 ± 5 °C) between right vs left sided applications. Power output between 0 to 50 watt was adjusted automatically by the generator to reach and maintain the preselected temperature. During the first 2 s of the application, power output was increased gradually to avoid overheating the catheter tip. In the initial phase, measurements of the temperature-time integral, the steepness of the temperature curve and
the actual temperature values were included into the algorithm for closed temperature-controlled radiofrequency delivery. Subsequently, power adjustment was performed every 500 ms according to the actual catheter tip temperature. Energy delivery was discontinued immediately when sudden rises in impedance occurred or the catheter-tip temperature had reached 90 °C. A sudden impedance rise of more than 50 Ohm was considered to be a significant impedance 'jump'. Due to previous studies from our laboratory[16] energy delivery was discontinued at the latest after 30 s when preexcitation persisted thus far. Ineffective radiofrequency ablation was not terminated in the very early phase of the application because of the initial stepwise increase in power output as mentioned above.

Energy was delivered to the atrial insertion site in all patients with right sided accessory pathways and to the ventricular insertion in all patients with left sided accessory pathways, respectively. Energy application was stopped immediately when dislocation of the catheter was noted. Following the ablation procedure, effective i.v. heparinization was continued for 48 h. Subsequently, all patients received 100 mg aspirin orally for 3 months. A repeat electrophysiological study was not performed routinely. All patients underwent an echocardiographic investigation following the ablation session in order to exclude thrombus formation or pericardial effusion.

Data analysis

Continuous data are expressed as mean value ± SD or as median. Variables were compared by Student's t-test or Mann–Whitney U test as appropriate. P values <0.05 were considered significant. Statistical analysis was performed using a commercially available computer software (SPSS; SPSS Inc., USA).

Results

In 22 patients, the accessory pathways were localized on the left side; the ventricular insertion site was detected in the lateral (n=9), posterior (n=7), posterolateral (n=4) and posteroseptal (n=2) area of the mitral annulus during endocardial mapping. The accessory pathways were right sided in the other 16 patients and located in the posteroseptal (n=6), midseptal (n=4), posterior (n=3), anterior (n=2) and anteroseptal (n=1) region, respectively. All patients had single accessory pathways. Catheter ablation was successful in all patients after the delivery of 2-3 ±21 radiofrequency pulses (median 2; range 1–9) following detailed endocardial mapping. The mean duration of the procedure was 144 ± 106 min including a mapping time of 56 ± 34 min. The mean fluoroscopy time was 38 ± 23 min. Interruption of the accessory pathways was observed 5.9 ± 5.4 s after initiation of radiofrequency current at a preselected temperature of 70.1 ± 5.8 °C (range 60–90 °C). The actual tip temperature measured 50.4 ± 10.2 °C at the time of accessory pathway interruption; the actual power output was 26.5 ± 12.6 W. The maximum temperature was 77.1 ± 13.5 °C with a total delivered energy of 1834 ± 1151 J.

An abrupt rise in impedance was observed in 10 out of a total of 89 energy applications (11%). The temperature maximum measured 86.4 ± 11.2 °C in cases with sudden rises in impedance and was thus higher compared with 74.9 ± 13.2 °C measured during the other applications. However, this difference did not reach statistical significance. Carbonized material adherent to the distal electrode was observed in six of these 10 applications. The catheter surface itself did not reveal any sign of insulation defect in these instances. Thromboembolic events or other procedure-related complications were not observed. There was no significant difference in maximal power output (45.7 ± 12.4 W vs 42.3 ± 10.5 W) or preselected temperature (72.9 ± 4.9 °C vs 70.5 ± 5.7 °C) between pulses with and without a sudden rise in impedance. No sudden rise in impedance was caused by an initial overshoot of the catheter tip temperature. This was prevented, because power output was increased gradually according to the algorithm mentioned above. The incidence of sudden rises in impedance was equally distributed with respect to pulse duration and effective or ineffective applications.

Biophysical parameters during ablation of left and right sided accessory pathways

Figures 1 and 2 show two representative graphs of simultaneous recordings of catheter tip temperature, power output and impedance during successful energy delivery to the ventricular insertion in a patient with a left posterior accessory pathway and to the atrial site in a patient with a right posterior accessory pathway. In the case of the left posterior accessory pathway (Fig. 1) the preselected temperature (70 °C) was reached within 10 s. Thereafter, power output was automatically regulated down after an initial peak at a maximum of 17 watts. Subsequently, a relatively constant temperature was achieved with power output varying only between 4–8 watts, indicating stable catheter positioning. The temperature level was maintained and overheating of the electrode could be prevented. Interruption of the accessory pathway was observed after 6 s. Figure 2 depicts the biophysical parameter of an application, in which the time it took for the effect to appear was 1.2 s in a patient with a right posterior accessory pathway. This graph demonstrates a slightly slower temperature rise and a higher power output level. Both curves oscillate during the plateau phase due to only moderately stable catheter–tissue coupling. No sudden rise in impedance occurred.

Detailed analysis of the biophysical parameters and a comparison between successful left and right sided energy applications are depicted in Table 1. At the time of the accessory pathway interruption, as evidenced

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Figure 1 Depicted is the graph of delivered power (——), impedance (H 6686) and catheter tip temperature (——) obtained during successful abolition of a left posterior accessory pathway from the ventricular insertion site. The preselected temperature of 70 °C was achieved after 10 s. Power output was regulated down to approximately 4-8 watt to maintain the temperature plateau but avoid overheating of the catheter tip. The temperature curve was stable, reflecting a good electrode–tissue coupling. No sudden rise in impedance occurred during this pulse. Interruption of the accessory pathway was observed after 6 s (as indicated by the arrow).

Figure 2 This graph gives an example of the time course of delivered power (H 6792), impedance (——) and catheter tip temperature (——) during successful ablation of a right posterior accessory pathway. In this case, the accessory pathway had been approached from the atrial site. A block of accessory pathway conduction, as evidenced by the sudden disappearance of preexcitation, was noticed immediately after the onset of radiofrequency current (1-2 s). The power output level required was markedly higher compared to the application shown in Fig. 1. An overshoot of the catheter tip temperature occurred when power output is regulated down. Subsequently, the power output level remained at about 15–25 watt. Note the oscillation of temperature and power output curves during the plateau phase of the pulse delivery, indicating only moderately stable catheter–tissue coupling.

by the sudden disappearance of preexcitation during sinus rhythm, the catheter tip temperature measured 54-2 ± 11-2 °C in left sided compared to 44-9 ± 5-0 °C in right sided pathways (P<0-008). This significantly higher temperature level did not result in a shorter time for the effect to appear in left sided pulses. This ‘effect appearing time’ was longer on the left (7-5 ± 6-3) than the right side (3-7 ± 2-9 s), but the difference did not reach statistical significance. Power output (26-9 ± 13-0 vs 25-9 ± 12-3 W) and delivered energy (173-4 ± 195 vs 78-8 ± 84 J) did not differ at the time of accessory pathway interruption.

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interrupted AP conduction

Total energy (joule)  Temp. max. (°C)  Temp. 10 s (°C)  Temp. 5 s (°C)  Time eff. (s)  Temp. eff. (°C)  Power max. (watt)  Power 10 s (watt)  Power 5 s (watt)  Energy eff. (joule)  Power eff. (watt)  Imp. max. (ohm)

The interruption of accessory pathway conduction was achieved or exceeded in 19 out of 22 (86%) successful applications to left atrial sites and in eight out of 16 (50%) effective right atrial pulses.

A sudden impedance rise was observed in eight out of 45 (18%) energy applications to left sided and in two out of 44 (5%) pulses delivered to right sided accessory pathways. In four of these cases no material adherent to the electrode was visible when the catheter was withdrawn. However, concomitant material adherence of the catheter tip without clinical evidence for thromboembolic events was present in five cases with left and one patient with a right sided pathway. In three patients (including the one with the right sided pathway) carbonization and thrombotic material was only detected at the proximal end of the distal electrode. Clot formation adherent to the electrode tip was observed in three patients with left sided accessory pathways.

Table 2 summarizes the biophysical parameters of permanently effective, transiently effective and ineffective pulses. There was a significant difference of the maximal catheter tip temperature between effective and ineffective pulses. The peak temperature measured 77.1 ± 13 °C during effective and 69.9 ± 14 °C during ineffective energy applications (P<0.05). As mentioned previously, the energy delivery was discontinued at the latest after 30 s when preexcitation persisted thus far. Thus, the total delivered energy was higher in effective pulses compared to transiently or ineffective pulses.

The effect appearing time was significantly longer in transiently effective pulses (10.4 ± 7.2 s) compared to permanently effective applications (5.9 ± 5.4 s; P<0.02). The delivered energy at the time of accessory pathway abolition was significantly higher in transiently than in permanently effective pulses (268 ± 253 joule vs 134 ± 163 joule; P<0.02).

Table 1 Biophysical parameters of pulses that effectively interrupted AP conduction

<table>
<thead>
<tr>
<th></th>
<th>Left (n=22)</th>
<th>Right (n=16)</th>
<th>P value</th>
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<tbody>
<tr>
<td>Temp. eff. (°C)</td>
<td>54.2 ± 11.2</td>
<td>44.9 ± 5.0</td>
<td>P&lt;0.008</td>
</tr>
<tr>
<td>Power eff. (watt)</td>
<td>26.9 ± 13.0</td>
<td>25.9 ± 12.3</td>
<td>ns</td>
</tr>
<tr>
<td>Energy eff. (joule)</td>
<td>173 ± 195</td>
<td>78.8 ± 84</td>
<td>ns</td>
</tr>
<tr>
<td>Time eff. (s)</td>
<td>7.5 ± 6.3</td>
<td>3.7 ± 2.9</td>
<td>ns</td>
</tr>
<tr>
<td>Temp. 5 s (°C)</td>
<td>52.1 ± 3.1</td>
<td>47.2 ± 4.3</td>
<td>P&lt;0.005</td>
</tr>
<tr>
<td>Power 5 s (watt)</td>
<td>21.5 ± 9.3</td>
<td>25.8 ± 9.9</td>
<td>ns</td>
</tr>
<tr>
<td>Temp. 10 s (°C)</td>
<td>61.5 ± 6.2</td>
<td>52.7 ± 4.2</td>
<td>P&lt;0.005</td>
</tr>
<tr>
<td>Power 10 s (watt)</td>
<td>31.3 ± 12.8</td>
<td>39.0 ± 11.7</td>
<td>ns</td>
</tr>
<tr>
<td>Temp. max. (°C)</td>
<td>81.2 ± 10.2</td>
<td>71.4 ± 15.7</td>
<td>ns</td>
</tr>
<tr>
<td>Power max. (watt)</td>
<td>41.3 ± 10.6</td>
<td>45.1 ± 10.9</td>
<td>P&lt;0.05</td>
</tr>
<tr>
<td>Total energy (joule)</td>
<td>1392 ± 762</td>
<td>2452 ± 1335</td>
<td>P&lt;0.02</td>
</tr>
<tr>
<td>Imp. max. (ohm)</td>
<td>162.4 ± 113</td>
<td>123.3 ± 33</td>
<td>ns</td>
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</tbody>
</table>

The temperature levels were markedly different in left and right sided applications. The catheter tip temperature was significantly higher during left as compared to right sided applications at 5 (52.1 ± 3.1 °C vs 47.2 ± 4.3 °C) and 10 s (61.5 ± 6.2 °C vs 52.7 ± 4.2 °C) of energy delivery (P<0.005).

The average maximum of delivered power (41.3 ± 10.6 W vs 45.1 ± 10.9 W) which was achieved after accessory pathway conduction block in most cases (79%) and the total delivered energy (1392 ± 762 J vs 2452 ± 1335 J) were significantly higher in right sided pathways (P<0.05/Table 1). The maximum values of catheter tip temperature and impedance did not differ significantly (Table 1). The preselected temperature was significantly higher during left as compared to right sided applications at 5 (52.1 ± 3.1 °C vs 47.2 ± 4.3 °C) and 10 s (61.5 ± 6.2 °C vs 52.7 ± 4.2 °C) of energy delivery (P<0.005).

The temperature levels were markedly different in left and right sided applications. The catheter tip temperature was significantly higher during left as compared to right sided applications at 5 (52.1 ± 3.1 °C vs 47.2 ± 4.3 °C) and 10 s (61.5 ± 6.2 °C vs 52.7 ± 4.2 °C) of energy delivery (P<0.005).

Table 2 Biophysical parameters of effective, transiently effective and ineffective pulses

<table>
<thead>
<tr>
<th></th>
<th>Effective (n=38)</th>
<th>Transiently effective (n=16)</th>
<th>Ineffective (n=35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. eff. (°C)</td>
<td>50.3 ± 10</td>
<td>54.1 ± 8.9</td>
<td></td>
</tr>
<tr>
<td>Power eff. (watt)</td>
<td>26.5 ± 13</td>
<td>29.3 ± 15</td>
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<tr>
<td>Energy eff. (joule)</td>
<td>134 ± 163</td>
<td>268 ± 253</td>
<td></td>
</tr>
<tr>
<td>Time eff. (s)</td>
<td>5.9 ± 5.4</td>
<td>10.4 ± 7.2*</td>
<td></td>
</tr>
<tr>
<td>Temp. max. (°C)</td>
<td>72.1 ± 13</td>
<td>72.5 ± 14.1</td>
<td>69.9 ± 14**</td>
</tr>
<tr>
<td>Imp. max. (ohm)</td>
<td>146 ± 90</td>
<td>141 ± 112</td>
<td>132 ± 82</td>
</tr>
<tr>
<td>Power max. (watt)</td>
<td>42.9 ± 11</td>
<td>40.7 ± 12</td>
<td>41.5 ± 12</td>
</tr>
<tr>
<td>Total energy (joule)</td>
<td>1834 ± 1151</td>
<td>1595 ± 1407</td>
<td>1372 ± 1046</td>
</tr>
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</table>

Shown are catheter tip temperature (Temp.), power output, delivered energy at the moment of accessory pathway conduction block and the time period between onset of radiofrequency current and abolition of accessory pathway (upper panel). Peak values during pulse application and total delivered energy are compared at the lower panel.

*P<0.02 vs effective pulses; **P<0.05 vs effective pulses.

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Follow-up

A repeat electrophysiological study was not routinely performed, since all patients had manifest preexcitation prior to ablation and no patient revealed preexcitation prior to hospital discharge. Repeat echocardiographic studies after the ablation showed no evidence of peri-cardial effusion or intracardiac thrombi. Creatinine kinase activity remained within normal limits in all patients. During a total follow-up period of 18.7 ± 4.6 months accessory pathway conduction resumed in three patients (left: n = 1; right: n = 2). All recurrences were observed within 3 months. A second ablation was successful in all patients.

Discussion

Main findings

In the era of power-regulated radiofrequency catheter ablation, as a well-established method, the present study reports on the initial clinical results of temperature-controlled ablation in patients with the Wolff-Parkinson-White syndrome. The study also provides information on the biophysical aspects of temperature-controlled ablation in humans: in this patient cohort the mean catheter tip temperature required for accessory pathway interruption was 50°C. Temperature levels achieved during right sided applications were significantly lower than left sided pulses, although maximal power output was higher. Nevertheless, 'the effect appearing time', indicated by loss of preexcitation, tended to be longer in left sided applications compared to pulses delivered to the tricuspid annulus. This time period was significantly longer in transiently effective compared to permanently effective pulses. Also, during temperature-controlled mode of energy delivery, sudden rises in impedance could be observed. Despite controlled energy delivery with a similar preselected temperature, the temperature maximum during these pulses measured 86°C compared to 75°C during the other applications. However, this difference was statistically not significant. Experimental and clinical studies have revealed that an abrupt rise in impedance is associated with overheating of the catheter tip with consecutive peak temperatures up to 95-120°C and formation of a small layer of carbonized material adjacent to the electrode. A potential reason for the occurrence of this phenomenon, despite the temperature-controlled mode of energy delivery, is the delay of every closed loop system with respect to the time interval required for temperature measurement and power adjustment according to the actual electrode temperature. Furthermore, transmission of changes in the actual catheter tip-interface temperature to the thermistor located in the centre of the electrode requires a certain interval. Due to this latency, a sudden increase in catheter tissue coupling with prior upregulation of power output may cause a significant temperature overshoot and immediate formation of a carbonized layer adherent to the electrode. Shortening of the time interval for closed loop control and a lower preselected temperature may decrease the number of pulses with sudden rises in impedance and coagulum formation.

Abrupt rises in impedance are potentially hazardous and may cause thromboembolic complications. In the present study, no clinical signs of thromboembolic complications occurred following coagulum formation adherent to the catheter tip. Nonetheless, development of undetected microemboli not adherent to the catheter tip and potential thrombogenic areas of localized myocardial vaporisations could not be excluded.

Relevance of catheter tip temperature monitoring during ablation

Delivered power impedance, current density, configuration of the electrode and contact pressure are important determinants for radiofrequency current-induced lesion size. In contrast to standardized in vitro studies, regulation of power output alone does not accurately predict lesion size under in vivo conditions, due to the variation of catheter–tissue coupling. Current density and thus myocardial temperature decreases in a hyperbolic way with increasing distance for the tissue–electrode interface. Therefore, the temperature measured at the electrode–tissue interface during catheter ablation does not necessarily represent the temperature level achieved within the neighbouring structures. However, experimental investigations with in vivo coagulations of biological tissue revealed a good correlation between the temperature determined at the electrode–tissue interface and the induced lesion volume. Temperature measurement and adjustment of delivered power to the actual catheter tip temperature is the only biophysical method currently available to control lesion size during radiofrequency catheter ablation.

Biophysical findings during left and right sided temperature-controlled energy delivery

Following the initiation of radiofrequency current the catheter tissue–interface temperature exponentially rises and reaches a plateau phase. Our data show that the increase in temperature is faster when pulses are delivered to left ventricular compared to right atrial insertion sites of accessory pathways. The actual catheter–tissue interface temperature is significantly lower after 5 and 10 s following radiofrequency initiation at the atrial aspect of the tricuspid valve than at the mitral annulus. This temperature difference is also significant at the moment of accessory pathway abolition. Interestingly, there is no significant difference in actual power output between either site. Although
the differences in maximal catheter tip temperatures were not statistically significant, there was a trend towards higher peak temperatures in the group of left sided pulses in the present study. Thus, higher temperature levels were achieved during left compared to right sided applications without requiring higher power output.

A major reason for these observations is the different anatomical substrate. At the mitral annulus the catheter tip is usually placed with more contact pressure and positioned adjacent to the underlying tissue with a close electrode-tissue coupling. Figure 2 gives an example of a successful right sided application with an oscillating temperature curve during energy delivery due to only moderately stable catheter-tissue contact. In the clinical setting, a stable catheter tip position is more difficult to achieve at the atrial aspect of the tricuspid valve than at the mitral annulus when the electrode is wedged beneath the valve. Consequently, in right sided applications the well established phenomenon of power dissipation due to heat loss to the cavitary blood is increased when the electrode-tissue coupling is poor. These factors may have also contributed to the lower incidence of abrupt rises in impedance at right atrial sites. Lower contact pressure and electrode-tissue coupling at atrial sites may have decreased current density at the electrode-tissue interface. Cooling of the catheter tip by cavitary blood flow might also be a reason for the significantly higher amount of total delivered energy and maximal power output in right vs left sided energy applications. The catheter tip is positioned more parallel in relation to the endocardium at the atrial aspect of the tricuspid valve compared to nearly rectangular positions achieved at the ventricular side of the mitral annulus. Thus, the electrode has more contact with the circulating blood and fewer areas of myocardial tissue are affected by radiofrequency current. Therefore, heating of myocardium caused by direct resistive heating at the catheter-tissue interface and thus lesion size are reduced. The trend towards a longer 'effect appearing time' and higher temperature levels during ventricular applications at the left side may also reflect a longer distance and larger mass of myocardial tissue between the distal electrode and the anatomical target site compared to the atrial aspect.

Langberg and coworkers presented the first study using temperature monitoring during radiofrequency current application at several preselected constant power output levels in patients with anterogradely conducting accessory pathways. In this study, catheter tip temperature was only passively measured without continuous adjustment of the delivered power output. Temperature measurements in the present study are concordant with the study by Langberg and coworkers. They have shown that radiofrequency application to right atrial sites produced significantly lower temperature levels compared to left sided energy delivery. In the study of Langberg, power output did not predict temperature at the catheter tip and thus lesion size. A recently published retrospective multicentre study of temperature-controlled radiofrequency current ablation has also demonstrated a higher electrode temperature level during left compared to right sided applications for ablation of accessory pathways.

**Effective, transiently effective and ineffective pulses**

In transiently effective energy applications preexcitation was abolished after a markedly longer time compared to permanently effective pulses. It has been shown that the 'effect appearing time' during power-regulated radiofrequency ablation of left sided pathways is significantly longer in transiently compared to permanently effective pulses. In transiently effective applications the catheter tip might be placed not in close proximity to the insertion site of the accessory pathway. The pathway is only affected by the edge of the lesion with relatively low current density and intramyocardial temperature. Thus, transient effects might be induced by tissue oedema rather than myocardial necrosis.

The peak value of the catheter tip temperature was considerably higher in permanently effective pulses compared to ineffective applications. Poor catheter-tissue coupling is probably the major reason for this difference. Interpretation of temperature curves may become a useful tool during the ablation procedure to discriminate between inefficacy due to poor electrode-tissue contact or inappropriate target site selection.

Langberg et al. have also observed lower temperature levels during ineffective compared to effective pulses. In contrast to the present study, a multicentre analysis by Calkins and coworkers did not show a relationship between the achieved temperature level and the ablation result. However, they did not evaluate transiently effective and ineffective pulses separately. This might be of importance and could be a reason for the different results because during the present study there was a trend towards higher peak temperatures in transiently compared to ineffective energy deliveries. Consecutively transiently effective pulses did not exhibit a significantly lower temperature maximum compared to effective pulses.

**Limitations**

Measurements of the catheter–tissue interface temperature do not necessarily represent the myocardial temperature at the vicinity of the accessory pathway. Nevertheless, current monitoring and control of catheter–tissue interface temperature seems to be the best parameter for guidance of radiofrequency current application and lesion volume.

Conductivity of the tissue may have been altered due to previous energy applications and influenced the temperature curves of subsequent pulses. However, following ineffective pulses, radiofrequency current was exclusively applied after repeat and detailed endocardial
mapping. A prospective, randomized trial comparing power- and temperature-controlled radiofrequency current ablation is required to assess the potential benefit of this method with respect to duration and safety of the procedure.

References