Electrogram-Gated Radiofrequency Ablations With Duty Cycle Power Delivery Negate Effects of Ablation Catheter Motion

William W.B. Chik, MBBS, MD, PhD; Michael Anthony Barry, BSc; Jim Poulipoulos, MSc, PhD; Karen Byth, PhD, CStat (RSS); Christine Midekin, MBBS; Abhishek Bhaskaran, MBBS, PhD; Gopal Sivagangabalan, MBBS, PhD; Stuart P. Thomas, MBBS, PhD; David L. Ross, MBBS; Alistair McEwan, BEng, PhD; Pramesh Kovoor, MBBS, PhD; Aravinda Thiagalingam, MB ChB, PhD

Background—Cardiac and respiratory movements cause catheter instability. Lateral catheter sliding over target endocardial surface can lead to poor tissue contact and unpredictable lesion formation. We describe a novel method of overcoming the effects of lateral catheter sliding movements using an electrogram-gated pulsed power ablation.

Methods and Results—All ablations were performed on a thermochromic gel myocardial phantom. Ablation settings were randomized to conventional (nongated) 30 W versus electrogram-gated at 20% duty cycle (30 W average power) at 0-, 3-, 6-, and 9-mm lateral sliding distances. Forty-eight radiofrequency ablations were performed. Deeper lesions were created in electrogram-gated versus conventional ablations at 3 mm (4.36±0.08 versus 4.05±0.17 mm; P=0.009), 6 mm (4.39±0.10 versus 3.44±0.15 mm; P<0.001), and 9 mm (4.41±0.06 versus 2.94±0.16 mm; P<0.001) sliding distances. Electrogram-gated ablations created consistent lesions at a quicker rate of growth in depth when compared with conventional ablations (P<0.001).

Conclusions—(1) Lesion depth decreases and length increases in conventional ablations with greater degrees of lateral catheter movements; (2) electrogram-gated pulsed radiofrequency delivery negated the effects from lateral catheter movement by creating consistently deeper lesions irrespective of the degree of catheter movement; and (3) target lesion depths were reached significantly faster in electrogram-gated than in conventional ablations. (Circ Arrhythm Electrophysiol. 2014;7:920-928.)

Key Words: ablation techniques ■ biophysics ■ cardiac arrhythmias ■ cardiac electrophysiology ■ catheter ablation ■ radiofrequency ablation

Radiofrequency catheter ablation has emerged as an important therapy for the treatment of cardiac arrhythmias. Radiofrequency energy is delivered by direct tissue contact with the catheter electrode resulting in coagulative necrosis by resistive heating.1,2 Radiofrequency ablations delivered with stable catheter position guided by optimal contact force have been shown to achieve transmural and durable lesions.3,4 However, Kalman et al5 demonstrated that apparent stable catheter position on fluoroscopy was associated with highly unpredictable and variable catheter tip lateral sliding (>5 mm in 18% and >2 mm in >50% of ablations) depending on catheter orientation, contact force, and local tissue characteristics in the right atria secondary to cardiac and respiratory movements seen on intracardiac echocardiography. Not only does lateral catheter sliding result in poor tissue contact and compromise lesion efficacy but also may create unpredictable lesion dimensions leading to ablation of structures adjacent to the target tissue (eg, AV node).5

Editorial see p 781
Clinical Perspective on p 928

The catheter in this situation is presumed to move relative to (and in the same plane as) the heart wall, in a reciprocating motion during the course of the cardiac cycle. During ablation, the energy delivered is spread out over a larger area of myocardium and thus produces less heating of the target. The amplitude and direction of this motion with respect to the catheter orientation is unknown but is synchronized with the electrogram and is a repetitive phenomenon. This synchronization provides a potential solution to the degradation of ablation efficiency caused by lateral sliding motion—an electrogram-gated, duty cycle pulsed power ablation regime that delivers the same average power as a conventional ablation.
The energy is delivered for a short duration ending on the onset of the local electrogram (Figure 1).

To test this solution, our hypothesis was that catheter lateral sliding movements would decrease lesion depth during conventional radiofrequency ablations, and that electrogram-gated pulsed radiofrequency delivery would create lesions of consistent predictable depth without regard for the varying degrees of catheter sliding movements. The aims of this study were, therefore, to (1) demonstrate the effects of catheter surface skating on radiofrequency ablation lesion dimensions in a thermochromic myocardial phantom model; (2) evaluate the effect of electrogram-gated duty cycle radiofrequency power delivery on efficacy of lesion creation; and (3) compare the rate of lesion growth for gated versus conventional (nongated) ablations during variable degrees of catheter lateral surface sliding movements.

Methods

Lateral Catheter Movement Simulation on Electrode–Tissue Interface Because Of Cardiac Motion

A thermochromic liquid crystal myocardial phantom previously described was used to test the hypotheses. The study protocol was conducted in accordance with the Western Sydney Local Health District Research Committee guidelines. Cardiac motion and local electrogram generation were simulated by a rotating wheel on a servo (Model S03T; GWS Incorporated, Taipei, Taiwan), which produced an index pulse corresponding to the R wave of the QRS at a given time in the rotational cycle. A catheter support was constructed and driven by the servo, whose rotational velocity and stroke distance were determined by an Atmel AVR 328 microcontroller (Arduino Duemilanove, Ivrea, Italy) under PC control. The support structure allowed the catheter tip to be positioned against the substrate with varying amounts of lateral sliding movement applied (0, 3, 6, and 9 mm). The maximum sliding distance of 9 mm was chosen because this was greater than the largest amount of travel observed by Kalman et al., and equally spaced lateral sliding distances optimized the statistical efficiency of the design. The catheter motion was driven by a wheel, resulting in a sinusoidal (derived from a cyclic) velocity being described by the catheter tip (Figure 1).

Electrogram-Gated Delivery of Duty Cycle Radiofrequency Energy During Simulated Lateral Sliding Catheter Movements in a Thermochromic Myocardial Phantom

The electrogram sense switch circuit was gated with a signal from the microcontroller controlling the catheter position servo, corresponding in time and motion to the point when the local electrogram would occur. The switch (Farnell, part 430–7653) was activated when the simulated local electrogram was sensed, diverting energy from the catheter to the load resistor ($R_L$, Farnell, part 117–4297×2) in the switch box. At a later time point, $T_{on}$ (time when radiofrequency delivery is ON), the switch was released and allowed radiofrequency ablation energy to be delivered into the catheter. The duration of $T_{on}$ was calculated to be 20% of the R–R interval. The load resistor, $R_L$, was used to present a dummy load to the generator during the time the tip was not in circuit. This prevented the generator from perceiving an apparent open circuit and shutting down the ablation. An arbitrary R–R interval of 750 ms was chosen; therefore, the on and off times were 160 and 590 ms in duration.

Electrogram-Gated Versus Conventional Ablation Lateral Surface Sliding Catheter Ablation Protocol

All ablations were performed using a standard 3.5-mm open-irrigated tip ablation catheter (Thermocool; Biosense Webster, Inc, Diamond Bar, CA) and a radiofrequency ablation generator (EPT-1000XP; EP Technologies, Boston, MA) to deliver radiofrequency power for 60-s duration. Saline irrigation was delivered at 30 mL/min using a conventional CoolFlow pump and tubing set (Biosense Webster Inc).

Ablations were performed under 8 conditions. These comprised either (1) electrogram-gated or (2) conventional ablations for each of the 4 lateral catheter surface sliding distance settings: (1) no lateral sliding movements (0 mm); (2) minimal movements (3 mm); (3) moderate movements (6 mm); and (4) maximal movements (9 mm).

A single run of the experiment consisted of 8 ablations, 1 under each of these 8 conditions applied in random order. A total of 6 runs (48 ablations) were performed. For conventional ablations, standard radiofrequency power of 30 W was used. For gated ablations, 20% duty cycle (30 W average power) was delivered.
The catheters were oriented in the parallel configuration for all cases, with a force sensing plate positioned under the catheter as it slid along the axis of motion and measured the contact force presented by the tip. A uniform pressure of 10 g was applied via the catheter tip at the electrode–gel interface and it remained within 1 g of this for the length and duration of the skating excursion. Impedances of ablation circuit for the thermochromic phantom were kept to within clinical values (range from 100 to 120 Ω).

**Radiofrequency Ablation Lesion Measurements**

Digital photographs of thermochromic color changes at the ablation site within the thermochromic phantoms were taken at 5-s intervals until 60 s had lapsed after commencement of ablation. Digital images were analyzed offline using software described previously. The thermochromic phantom lesion dimensions were defined by the color corresponding to a lethal isotherm temperature of 53°C on the thermochromic liquid crystal film. The transmural depth was considered to be 3 mm, reflective of average atrial tissue thickness. Surface area measurements were thus calculated by summing the number of pixels encompassed by the lethal isotherm and multiplying by the scale of the picture. The scale was measured by a known length at the focal plane. The volume was measured using Simpson Rule as described in Chik et al.

**Statistical Analysis**

Data are summarized as mean±SD. Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS) version 21.0 (SPSS, Inc, Chicago, IL) and S-PLUS version 8 (Insightful Corporation, Seattle, WA). Two-tailed tests with a significance level of 5% were used throughout. Plots of mean values with associated 95% confidence intervals (CIs) were used to illustrate the distributions of the outcome variables within subgroups of interest. Linear mixed-effect models were used to investigate the joint effects of gating status and catheter lateral sliding distance (CLS distance) on the dimensions of lesions achieved after 60-s ablations. In these models, run was considered as the group identifier, and gating status (2 levels) and CLS distance (4 levels) as both random and fixed effects. A statistically significant interaction between the fixed effects of gating status and CLS distance was taken as evidence that the relationship between increasing CLS and ablation dimension depended on the gating status. Appropriate parameterizations and linear contrasts together with 95%CIs were used to estimate these differences.

**Results**

A total of 48 radiofrequency ablations were performed in the thermochromic myocardial phantom (6 runs each comprising 8 ablations). Within a run, each lateral sliding movement distance (0, 3, 6, and 9 mm) was performed under electrogram-gated and conventional conditions in an operator randomized blinded fashion. All analyses of the digital photographs for lesion dimensions were undertaken in a blinded fashion by 2 independent observers.

**Ablation Parameters**

For gated ablations, the duty cycle was measured corresponding to 21.3% (target 20%). The average power delivered was measured at 33.7 W (target 30 W). For conventional ablations, the average power was measured at 31.4 W (target 30 W).

**Depth Decreases With Greater Catheter Lateral Sliding Distances in Conventional but Not in Gated Ablations**

Lesion depth mean±SD for 60-s ablations are shown in Table 1 for each catheter lateral sliding distance (mm) for conventional and gated ablations. There was a significant 2-way interaction between the fixed effects of catheter sliding distances and

<table>
<thead>
<tr>
<th>Catheter Lateral Sliding Distance, mm</th>
<th>Lesion Depth After 60 S Mean±SD, mm</th>
<th>Estimated Mean Change in Depth From 0-mm Lateral Sliding With 95% CI, mm</th>
<th>Estimated Mean Change in Depth From 3-mm Lateral Sliding With 95% CI, mm</th>
<th>Estimated Mean Change in Depth From 6-mm Lateral Sliding With 95% CI, mm</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (non–EGM-gated ablations)</td>
<td>0 (n=6)</td>
<td>4.17±0.15</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>3 (n=6)</td>
<td>4.05±0.17</td>
<td>−0.12 (−0.24 to 0.002)</td>
<td>0.054</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>6 (n=6)</td>
<td>3.44±0.15</td>
<td>−0.73 (−0.87 to −0.58)</td>
<td>&lt;0.001</td>
<td>−0.61 (−0.78 to −0.44)</td>
</tr>
<tr>
<td></td>
<td>9 (n=6)</td>
<td>2.94±0.16</td>
<td>−1.23 (−1.41 to −1.05)</td>
<td>&lt;0.001</td>
<td>−1.11 (−1.29 to −0.94)</td>
</tr>
<tr>
<td>EGM-gated ablations</td>
<td>0 (n=6)</td>
<td>4.34±0.11</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>3 (n=6)</td>
<td>4.36±0.08</td>
<td>0.02 (−0.09 to 0.13)</td>
<td>0.688</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>6 (n=6)</td>
<td>4.39±0.10</td>
<td>0.06 (−0.05 to 0.17)</td>
<td>0.303</td>
<td>0.04 (−0.05 to 0.12)</td>
</tr>
<tr>
<td></td>
<td>9 (n=6)</td>
<td>4.41±0.06</td>
<td>0.08 (−0.04 to 0.19)</td>
<td>0.175</td>
<td>0.05 (−0.03 to 0.14)</td>
</tr>
</tbody>
</table>

There was a significant 2-way interaction between the fixed effects of catheter sliding distance and gating status in the linear mixed-effects model (P<0.001). Appropriate model parameterization and linear contrasts provided the estimated mean change in depth and 95% CI associated with increasing lateral sliding distances by gating status. In conventional ablations, significant reductions in lesion depth when compared with depth for 0-mm sliding were observed at both 6 mm (<0.73 mm; P<0.001) and 9 mm (<1.23 mm; P<0.001). A smaller reduction in lesion depth for conventional ablations was observed for 3-mm when compared with 6-mm (<0.61 mm; P<0.001) or 9-mm sliding (<1.11 mm; P<0.001). In gated ablations, no significant changes in lesion depth were observed as sliding distance increased. CI indicates confidence interval; and EGM, electrogram.
gating status ($P<0.001$). Table 1 shows the estimated mean change in depth and 95% CI associated with increasing lateral sliding distances by gating status. For conventional ablations, there was a statistically significant reduction in lesion depth from that achieved with no sliding when the sliding distance was 6 mm ($<0.73$ mm; $P<0.001$) or 9 mm ($<1.23$ mm; $P<0.001$). The reduction in lesion depth of conventional ablations was smaller but still significant when those with 3-mm sliding were compared with those with 6-mm sliding ($<0.61$ mm; $P=0.001$) or with 9-mm sliding ($<1.11$ mm; $P<0.001$). In gated ablations, no statistically significant changes in lesion depth were observed as the catheter sliding distance increased.

**Deeper Lesions Created in Gated Versus Conventional 60-S Ablations at 3-, 6-, and 9-mm Catheter Lateral Sliding Distances**

Table 2 shows the estimated mean difference in lesion depth between gated and conventional 60-s ablations and the associated 95% CIs for each of the 4 lateral catheter sliding distances. The mean lesion depths were comparable between gated and conventional ablations when the catheter sliding distance was zero (4.34 versus 4.17 mm). However at 3-mm lateral sliding distance, gated lesions were significantly deeper than conventional (4.36 versus 4.05 mm; $P=0.009$). At 6-mm sliding distance, this difference was 4.39 versus 3.44 mm ($P<0.001$), and at 9 mm it was 4.41 mm versus 2.94 mm ($P<0.001$). Figure 2 diagrammatically depicts lethal isotherms in high spatial resolution in the thermochronic phantom. This illustrated progressively shallower lesions under conventional ablation conditions versus gated ablations with greater catheter sliding distance. However, a consistent lesion depth was maintained when the same averaged power (30 W) was used with gating regardless of the amount of catheter lateral sliding. Figure 3 illustrates the significant reduction in lesion depth at 3, 6, and 9 mm with conventional 60-s ablations. In comparison, the lesion depths for gated ablations remained essentially unchanged as catheter sliding distance increased from 0 mm. Movies of both gated and conventional ablations at each of the 4 sliding distances are available in the Data Supplement for comparing the dynamic evolution of thermal distribution within lesion sets.

**Lesion Length Increases With Greater Catheter Sliding in Conventional but Not in Gated Ablations**

Lesion length mean (±SD) for 60-s ablations is shown in Table 3 for each catheter lateral sliding distance (mm) for conventional and gated ablations. There was a significant 2-way interaction between the fixed effects of catheter sliding distance and gating status ($P<0.001$). Table 3 shows the estimated mean change in length and 95% CI associated with increasing lateral sliding distances by gating status. For conventional ablations, there was a statistically significant increase in lesion length from that achieved with no sliding when the sliding distance was 3 mm (0.24-mm longer; $P=0.024$), 6 mm (1.48-mm longer; $P<0.001$), or 9 mm (2.21-mm longer; $P<0.001$). The increase in lesion length of conventional ablations was smaller but still significant when those with 3-mm sliding were compared with those with 6-mm sliding (1.24-mm longer; $P<0.001$) or with 9-mm sliding (1.97-mm longer; $P<0.001$). In gated ablations, no statistically significant changes in lesion length were observed as the catheter sliding distance increased.

**Effect of Duration on Lesion Dimension at Varying Degrees of Catheter Sliding Distances**

**Table 2. Estimated Mean Differences in Lesion Depth (mm) Between Gated and Conventional 60-S Radiofrequency Ablations With 95% CI (mm) by Sliding Distance (Estimates Obtained From Appropriate Linear Mixed-Effects Model Parameterization and Linear Contrasts)**

<table>
<thead>
<tr>
<th>Catheter Lateral Sliding Distance, mm</th>
<th>Estimated Mean Difference, mm, in Lesion Depth Between Gated and Conventional 60-S Ablations (With 95% CI)</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.17 (−0.08 to 0.42)</td>
<td>0.149</td>
</tr>
<tr>
<td>3</td>
<td>0.31 (0.12 to 0.49)</td>
<td>0.009</td>
</tr>
<tr>
<td>6</td>
<td>0.95 (0.74 to 1.16)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>9</td>
<td>1.47 (1.35 to 1.59)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

The mean difference in lesion depths were comparable between gated and conventional ablations when the catheter sliding distance was zero (0.17 mm; $P=0.149$). However, at 3-mm lateral sliding distance, gated lesions were significantly deeper than conventional with a mean difference of 0.31 mm (4.36 vs 4.05 mm; $P=0.009$). At 6-mm sliding distance, this difference was 0.95 mm (4.39 vs 3.44 mm; $P<0.001$), and at 9 mm it was 1.47 mm (4.41 vs 2.94 mm; $P<0.001$).

**Rate of Lesion Depth Growth Significantly Reduced in Conventional Ablations When Compared With That in Gated Ablations Irrespective of Catheter Sliding Motion**

Figure 4 plots the evolution of lesion depth over time for each catheter lateral sliding distance under conventional (left-hand panel) and electrogram-gated (right-hand panel) ablation conditions. Neither was there a statistically significant 3-way interaction among the fixed effects of time, gating status, and lateral sliding distance ($P=0.718$) nor was there a statistically significant interaction between time and lateral sliding distance ($P=0.841$). There was, however, a significant interaction ($P<0.001$) between the effects of time and gating status with the rate of growth in lesion depth being an estimated 0.207 mm (SE, 0.029 mm) per 10 s more for gated ablations than for conventional. For gated ablations, the 4 lesion depth growth curves at 0, 3, 6, and 9 mm of catheter sliding distances overlapped and achieved significantly greater lesion depths when compared with those of conventional ablations at 3, 6, and 9 mm by 30 and 60 s. The depth of 3 mm in our study is similar to atrial tissue thickness. All gated ablations consistently reached a depth of ≥3 mm after 30 s of ablation and 4 mm after 60 s of ablation regardless of the degree of catheter sliding motion. In comparison, using conventional ablations none
of the lesions achieved these depths by 30 and 60 s when sliding distances were ≥6 mm.

Ablation Movies in the Thermochromic Myocardial Phantom
Movies of conventional and gated ablations at each of the 4 catheter lateral sliding distances are available in the Data Supplement.

Discussion
Cardiac contractions may cause lateral sliding movements of the ablation catheter tip across the surface of an electrode–tissue interface during radiofrequency ablations. The distance and velocity of lateral sliding movements occurring during an ablation are generally unknown and depend on the anatomic location within a cardiac chamber during a cardiac cycle. This can translate to poor catheter contact force, nontransmural lesions, longer ablation times, and higher reconnection rates because of gaps between ablation lesions. This study simulated the catheter lateral sliding movements in a previously validated thermochromic liquid crystal myocardial phantom model to demonstrate that conventional (ie, nonelectrogram gated) radiofrequency ablations produced significantly shallower lesions as the degree of catheter surface sliding distance progressively lengthened. In addition, it was shown that lesion length (in the

Figure 2. The thermodynamic effects of conventional (nongated) and cardiac cycle gated radiofrequency (RF) ablation in a gel myocardial phantom model during variable catheter related surface sliding distances of 0 to 9 mm. High spatiotemporal resolution measurement of temperature gradients in response to RF energy was achieved by colorimetric analysis of the thermochromic liquid crystal substrate. Delivery of RF energy during electrogram gating resulted in consistent lesion dimensions based on the 53°C isotherm indicated by the thermochromic liquid crystal substrate independent of catheter sliding distance. In contrast, increased lateral catheter sliding distance during conventional ablation resulted in lower maximum temperature, reduced lesion depth, and increased lesion width.
plane of catheter movement) increased (increased length:depth ratio) progressively with greater catheter sliding distances during conventional ablations. However, a gated, 20% duty cycle, pulsed power ablation delivering the same average power as a standard 30 W conventional ablation was able to negate the effects of catheter lateral motion by consistently creating deeper lesions (with preserved lesion length:depth ratio) irrespective of the degree of catheter lateral sliding distances during an ablation.

### Table 3. Lesion Length mean±SD (mm) for 60-S Radiofrequency Ablations by Catheter Lateral Sliding Distance (mm) for Conventional and EGM-Gated Ablations

<table>
<thead>
<tr>
<th>Catheter Lateral Sliding Distance, mm</th>
<th>Lesion Length After 60 S Mean±SD, mm</th>
<th>Estimated Mean Change in Length From 0-mm Lateral Sliding With 95% CI, mm</th>
<th>Estimated Mean Change in Length From 3-mm Lateral Sliding With 95% CI, mm</th>
<th>Estimated Mean Change in Length From 6-mm Lateral Sliding With 95% CI, mm</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (non–EGM-gated ablations)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (n=6)</td>
<td>7.63±0.28</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td></td>
</tr>
<tr>
<td>3 (n=6)</td>
<td>7.88±0.15</td>
<td>0.24 (0.04 to 0.45)</td>
<td>0.023</td>
<td>…</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>6 (n=6)</td>
<td>9.12±0.13</td>
<td>1.48 (1.27 to 1.69)</td>
<td>&lt;0.001</td>
<td>1.24 (1.03 to 1.45)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>9 (n=6)</td>
<td>9.84±0.07</td>
<td>2.21 (2.00 to 2.42)</td>
<td>&lt;0.001</td>
<td>1.97 (1.76 to 2.17)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EGM-gated ablations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (n=6)</td>
<td>8.02±0.18</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td></td>
</tr>
<tr>
<td>3 (n=6)</td>
<td>8.01±0.11</td>
<td>−0.01 (−0.15 to 0.13)</td>
<td>0.861</td>
<td>…</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>6 (n=6)</td>
<td>8.13±0.10</td>
<td>0.11 (−0.03 to 0.25)</td>
<td>0.109</td>
<td>0.12 (−0.02 to 0.26)</td>
<td>0.079</td>
</tr>
<tr>
<td>9 (n=6)</td>
<td>8.14±0.08</td>
<td>0.12 (−0.02 to 0.25)</td>
<td>0.107</td>
<td>0.13 (−0.01 to 0.27)</td>
<td>0.056</td>
</tr>
</tbody>
</table>

There was a significant 2-way interaction between the fixed effects of catheter sliding distance and gating status in the linear mixed-effect model for lesion length (P<0.001). Appropriate model parameterization and linear contrasts provided the estimated mean change in length and 95% CI associated with increasing lateral sliding distances by gating status. In conventional ablations, significant increases in lesion length were observed as sliding distance increased. In gated ablations, no significant changes in lesion length were observed as sliding distance increased. CI indicates confidence interval; and EGM, electrogram.
The principal result of catheter lateral sliding movement is that the same energy is delivered for a larger area, which implies less heating per unit area of tissue.9,10 In areas of increased lateral sliding movements, this translates to reduced lesion depth. Our results confirmed that ablation depth was reduced by \( \approx 20\% \) (from a mean of 4.2 to \( \leq 3.4 \) mm) at lateral sliding distance of \( \geq 6 \) mm. Importantly, for minimal or no lateral sliding distance, that is, \( \leq 3 \) mm, this adverse effect on lesion depth during conventional ablations was not as prominent. Progressive reductions in lesion depths were most notable once lateral sliding movements exceeded 3 mm in our model. This may be explained by the length of the standard open-irrigated catheter’s 3.5-mm electrode tip, which compensated for sliding distances of \( \leq 3 \) mm. This was the rationale behind the decision to choose the parallel catheter orientation because a nonparallel (eg, \( 45^\circ -90^\circ \)) orientation will present significantly less electrode-surface area to the substrate. It is likely that the portion of the target substrate that is not in continuous contact with the ablation tip in an acute orientation will lose more heat than the part of the substrate in continuous contact, such as would be expected to occur in a parallel orientation. Therefore, it is considered that the parallel catheter orientation is the least favorable for the experimental hypotheses. However, the core problem remains the inability to predict the presence and degree of catheter motion at any given time during radiofrequency energy delivery.

Our results demonstrated that gated ablation lesion dimensions remained consistent irrespective of the degree of lateral sliding movement. This is likely to have resulted from power delivery to a limited target area. This is important because we cannot accurately anticipate how much actual catheter sliding movement may occur.

The thermochromic liquid crystal myocardial phantom allowed lesion growth to be measured with high temporal resolution. Nongated ablations showed significantly slower growth with increased catheter sliding. This effect was negated by gated ablation, suggesting that gated ablation may be particularly beneficial when short duration ablations are being used. The recent development of contact force sensing catheters had been shown to improve radiofrequency lesion efficacy by improving contact force delivered at the electrode–tissue interface, but variability in catheter stability and the associated

### Table 4. Lesion Depth Means±SD (mm) After 30 and 60 S of Radiofrequency Ablation by Catheter Lateral Sliding Distance (mm) for Conventional and Electrogram-Gated Ablations

<table>
<thead>
<tr>
<th>Catheter Lateral Sliding Distance, mm</th>
<th>Lesion Depth After 30 S Mean±SD, mm</th>
<th>Lesion Depth After 60 S Mean±SD, mm</th>
<th>Estimated Mean Increase in Depth From 30 to 60 S With 95% CI, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional (non-EGM gated ablations)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (n=6)</td>
<td>3.30±0.07</td>
<td>4.17±0.15</td>
<td>0.87 (0.75–0.99)</td>
</tr>
<tr>
<td>3 (n=6)</td>
<td>3.22±0.15</td>
<td>4.05±0.17</td>
<td>0.84 (0.80–0.88)</td>
</tr>
<tr>
<td>6 (n=6)</td>
<td>2.62±0.18</td>
<td>3.44±0.15</td>
<td>0.82 (0.78–0.88)</td>
</tr>
<tr>
<td>9 (n=6)</td>
<td>2.16±0.17</td>
<td>2.94±0.16</td>
<td>0.78 (0.74–0.81)</td>
</tr>
<tr>
<td>EGM-gated ablations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (n=6)</td>
<td>3.24±0.07</td>
<td>4.34±0.11</td>
<td>1.10 (1.00–1.20)</td>
</tr>
<tr>
<td>3 (n=6)</td>
<td>3.30±0.06</td>
<td>4.36±0.08</td>
<td>1.06 (1.02–1.10)</td>
</tr>
<tr>
<td>6 (n=6)</td>
<td>3.32±0.09</td>
<td>4.39±0.10</td>
<td>1.08 (1.04–1.11)</td>
</tr>
<tr>
<td>9 (n=6)</td>
<td>3.34±0.08</td>
<td>4.41±0.06</td>
<td>1.08 (1.01–1.15)</td>
</tr>
</tbody>
</table>

*Estimated mean increases in lesion depth (mm) between 30- and 60-s ablation with 95% CI (mm) by sliding distance were obtained using appropriate linear mixed-effect model parameterization and linear contrasts. CI indicates confidence interval; and EGM, electrogram.*

### Figure 4. These plots show the evolution of lesion depth over time for each catheter lateral sliding distance under conventional (left) and electrogram-gated (right) ablation conditions. For conventional ablations, the slopes or rate of growth at 6 and 9 mm were significantly less steep, corresponding to a shallower lesion for a given ablation duration. In comparison, the 4 slopes representing the rate of lesion depth growth at each catheter sliding distances were not different and achieved significantly deeper lesions when compared with conventional ablations at 6 and 9 mm for both 30 and 60 s. All gated ablations consistently reached a depth of \( \geq 3 \) mm (average depth for atrial tissue) after 30 s of ablation and 4 mm after 60 s of ablation regardless of the degree of catheter motion as opposed to none of the lesions using conventional ablations when sliding distances exceeded 6 mm.
effect on suboptimal lesion morphology caused by cardiac and respiratory movements remain.

Although a higher contact force should be associated with improved stability, this needs to be balanced against the potential for serious complications, such as cardiac perforation and tamponade, especially at thin target tissues that are not structurally well supported (such as the posterior left atrial wall). In addition, anatomic locations, such as the left anterior superior ridge and the right septal superior position during pulmonary vein isolation, have shown to be associated with lower achievable contact force during ablation performed by experienced proceduralists. Therefore, in situations where catheter sliding is inevitable, gated ablations offer a method to alleviate the unwelcome sequelae.

Radiofrequency ablations are associated with significant morbidity and mortality arising from collateral complications during energy delivery. Therefore, there is an increasing demand to create consistent lesion size and morphology as shown with gated duty cycle energy delivery from the perspective of patient safety. In addition, once a lesion of presumed transmurality is created, it is important to be able to estimate how far along the line of ablation the next lesion should be targeted. Without being able to predict a consistent lesion length as seen in gated ablations, it is extremely difficult to achieve a contiguous line of radiofrequency ablation lesions with no gaps in between lesions that are transmural. For a given duration and power of ablations, lesion length created was highly variable and because we often have no means of quantifying or predicting the amount of catheter sliding motion occurring at any time point, lesion length is, therefore, unpredictable depending on the catheter sliding distance occurring at the time of lesion creation. Wider than expected lesions could potentially lead to unwanted radiofrequency energy delivery to structures, such as the AV node, conversely, thinner lesions may be more conducive to interlesion gaps leading to reconstructions. It is worthwhile noting that although the lesions in conventional ablations are wider at greater catheter sliding distances, the corresponding effective depth (represented by the 53°C isotherms) at the periphery of these lesions are shallower and thus lead to an increased propensity to nontransmural lesions and reconnections across ablation lines.

**Limitations**

Although this study modeled the electrical impedance of myocardium, blood, and endocardial blood flow, the effect of blood and myocardial vascular perfusion was not modeled; thus, the potential for thrombus and steam pop formation was not studied. The effect on distance and directionality of catheter sliding movements caused by respiratory motion was not considered. Indeed physicians consider performing high-frequency JET ventilated or even apnoeic ablations to provide a steadier ablation platform. The present study chose to exclude respiratory motion in the in vitro ablations because the apnoeic option exists in vivo. In our laboratory 10-g contact force had been previously validated in vitro as a surrogate for presumed contact force. However, application of a greater contact force was limited because of the composition of the gel substrate surface, which was less resilient against breakage with a moving catheter.

The hue change of the thermochromic film used in this experiment was sensitive to temperatures between 50°C and 78°C. Higher temperatures were not assessed. In most cases, the chief interest was in determining areas of ablation target where the catheter resides but ablation temperatures were not reached because of catheter motion. High power ablations during shorter times may cause surface coagulation and steam pops. Studies that focus on maximal temperatures would benefit more from in vivo models, such as the thigh model where the effects of thrombus and steam pops could also be assessed.

The radiofrequency generator’s output power in response to changes during switching (from the load resistor to the catheter) may vary between specific generators, leading to variations in lesion size in the gated condition. Once assessed, this should be constant for a given generator. Alternatively, a purpose-built generator, designed to implement the gated algorithm, would be able to avoid this problem.

The issue of tachyarrhythmia was not addressed in the present gating schema. Heart motion (eg, during atrial or ventricular arrhythmias) may not be regular, and the benefits of gating under these conditions are presently unknown but should be minor.

The present study used a sinusoid pattern as the character of catheter sliding motion. This was done because it is the simplest model of cyclic motion, and any more complex description could not be justified in the absence of a known surface velocity and vector profile of the catheter.

**Clinical Implications**

The clinical implications of this present model include the ability to deliver deeper and more consistent ablation lesions irrespective of the degree of catheter surface movement in a cardiac cycle within any one specific anatomic location within a cardiac chamber. This should facilitate more consistent transmural ablations and contiguous linear lesions.

**Conclusions**

Ablation catheter-related lateral sliding movements relative to the cardiac tissue surface occur to varying degrees during radiofrequency ablation therapy. The present study demonstrates a novel method that overcomes the effects of catheter tip sliding motion because of cardiac contractions to create consistently deeper and more predictable lesions.

**Disclosures**

None.

**References**


Radiofrequency energy is delivered by direct tissue contact with the catheter electrode resulting in coagulative necrosis by resistive heating. However, cardiac and respiratory movements cause catheter instability translating to poor catheter contact force, nontransmural lesions, longer ablation times, and higher reconnection rates because of gaps between ablation lesions. This study simulated the catheter lateral sliding movements in a previously validated thermochromic liquid crystal myocardial phantom. J Cardiovasc Electrophysiol. 2013;24:1278–1286.


Electrogram-Gated Radiofrequency Ablations With Duty Cycle Power Delivery Negate Effects of Ablation Catheter Motion
William W.B. Chik, Michael Anthony Barry, Jim Pouliopoulos, Karen Byth, Christine Midekin, Abhishek Bhaskaran, Gopal Sivagangabalan, Stuart P. Thomas, David L. Ross, Alistair McEwan, Pramesh Kooroo and Aravinda Thiagalingam

Circ Arrhythm Electrophysiol. 2014;7:920-928; originally published online August 11, 2014; doi: 10.1161/CIRCEP.113.001112

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circep.ahajournals.org/content/7/5/920

Data Supplement (unedited) at:
http://circep.ahajournals.org/content/suppl/2014/08/11/CIRCEP.113.001112.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation: Arrhythmia and Electrophysiology can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation: Arrhythmia and Electrophysiology is online at:
http://circep.ahajournals.org//subscriptions/
SUPPLEMENTAL MATERIAL

Movie/Video Legend

This composite movie panel consists of four simultaneous ablation videos in the Thermochromic Liquid Crystal Gel Myocardial Phantom under Conventional and Gated Ablation conditions using a standard 3.5 external irrigated tip ablation catheter. The top panels illustrate the lesion growth on the thermochromic film over time during a Conventional RF ablation when subjected to 3mm (top left) versus 9mm of lateral catheter sliding motion using 30W, 30mls/min saline irrigation for 60 seconds.

The bottom panels consist of corresponding RF ablation movies under Gated conditions using 20% duty cycle (30W average power) at the same lateral catheter sliding distances of 3mm (bottom left) and 9mm (bottom right) respectively for 60 seconds. A scale in mm is shown.

The visualized color bandwidth on the Thermochromic film starts from 50°C (red – lethal isotherm) to 78°C (black). Forty-eight RF ablations were performed. Deeper lesions were created in EGM-Gated vs. Conventional ablations at 3mm (4.36 ± 0.08mm vs. 4.05 ± 0.17mm, p=0.009), 6mm (4.39 ± 0.10mm vs. 3.44 ± 0.15mm, p<0.001) and 9mm (4.41 ± 0.06mm vs. 2.94 ± 0.16mm, p<<0.001) sliding distances. EGM-Gated ablations created consistent lesions at a quicker rate of growth in depth compared to Conventional ablations (p<0.001).
**RF Generator Behaviour during Conventional versus Gated Ablations**

With the series of gated ablations performed, it became evident that the RF generator has characteristics which interact with the gated switching regime to produce slight differences in delivered power when compared with the conventional ablations. These characteristics may reasonably be expected to differ between different RF generators and should be assessed on a case by case basis.

With short gated delivery of energy, the maximum energy delivered in one second of steady state into 100Ω was 36J (gated) and 31.4J (conventional). The total energy delivered in 60 seconds were similar 1962J (gated average power 32.7W) and 1871J (conventional average power 31.2W). Ramp-up for the gated condition was longer (11 sec) than for conventional (2.7 sec). This is graphically illustrated by the scope output of the gated ramp-up shown in the graph below.

The second diagram is a zoomed in look at the peak of a steady-state pulse, showing the generator trying to drop voltage after the switch.
There was a disparity between actual power delivered to the catheter in gated and conventional modes at steady state. The disparity was due to the difference in impedance between the load resistor ($R_L = 110\ \Omega$) and the catheter circuit impedance (100$\ \Omega$). The generator has a load sensing circuit to estimate the load impedance of the resistors, but sometimes when the switching is on/off, the impedance and circuit being measured is alternating. The RF generator was not able to track the impedance change as quickly. Consequently, it sensed a higher than actual catheter impedance more often, and therefore delivered slightly more power to the catheter. This would nominally be overcome by building a generator which would account for that, but we wanted to use a conventional RF generator for the purpose of this study.

The generator logged output during a 60-second Gated ablation using a 100$\ \Omega$ catheter load is shown in the following graph.
The generator sensing circuit recorded impedance slightly over 110Ω (114Ω average at steady state) and current for gated marginally less than conventional ablations. The generator took approximately 11 seconds to reach steady state.

At steady state, the generator output still fluctuated, due to the internal impedance sensing circuit of the generator trying to track the switched nature of the load, which oscillated between the catheter and the dummy load.

The following graphs show measurement of the generator output using a Rigol MSO 4014 oscilloscope with a LeCroy SI-9000 differential high voltage probe into a measured 100Ω catheter circuit load, with the standard dummy load of 110Ω. These graphs show that the generator try to track an impedance load that oscillates rapidly, as seen in the gated only situation.

The first graph (a) is the output from startup to ~14 seconds;
and the second graph (b) represents a zoomed-in portion at steady state.

The voltage to the catheter at midpoint of a 160 msec gate-on is 185V. Quantization of the signal limits the measurement to ~3V steps.

Power is calculated as \([(185V \times 0.7071)^2 / R] \times \text{duty cycle} = 36W\) at steady state. However, the generator takes ~11 seconds to ramp up, which drops the average for the whole 60 second period to ~34W.
The disparity between target and delivered power may therefore be ascribed to the RF generator’s attempt to track a load whose impedance changed faster than the tracking was designed to follow. The generator circuit perceived a higher than true impedance (114Ω perceived versus 100Ω actual), and output at higher voltage to compensate, leading to a situation where slightly more power was delivered than target.

In conclusion, gated ablations can provide advantages over conventional ablations, but the RF generator behavior in this mode must be taken into account to deliver the set power.