Several experimental studies have shown that electrode-tissue contact force (CF) is a major determinant of lesion size during radiofrequency ablation.1–7 Until recently, CF could not be measured directly by ablation catheters. As a result, surrogate measures of CF have been proposed, including electrogram amplitude, preablation impedance, and changes during ablation in electrode temperature and impedance.1,3,4 The accuracy of these surrogate measures has not been extensively validated.

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Recently, two designs of ablation catheters have been developed to measure real-time catheter-tissue CF during catheter mapping and radiofrequency ablation. One type of catheter uses 3 optical fibers to measure CF as the microdeformation of a deformable body in the catheter tip (TactiCath, St. Jude Medical).8–12 The other catheter incorporates a small spring connecting the ablation tip electrode to the catheter shaft and uses a magnetic transmitter and location sensors to measure CF as the microdeflection of the spring (THERMOCOOL SMARTTOUCH, Biosense Webster, Inc).13,14 In bench testing, both systems have a CF resolution of <1 g.8–14 Although clinical practice is suggesting that increasing CF improves radiofrequency lesion formation,11,12 there are no studies correlating radiofrequency lesion size to CF in the beating heart. The purpose of this study was to determine, in the canine beating heart: (1) the relationship between CF and radiofrequency lesion size, as well as the incidence of steam pop; and (2) the accuracy of predicting CF and radiofrequency lesion size by the surrogate measures of CF, ie, intracardiac electrogram amplitude and downstroke slope, preablation impedance, and the change in electrode temperature and impedance during radiofrequency delivery.

**Background**—Electrode-tissue contact force (CF) is believed to be a major factor in radiofrequency lesion size. The purpose of this study was to determine, in the beating canine heart, the relationship between CF and radiofrequency lesion size and the accuracy of predicting CF and lesion size by measuring electrogram amplitude, impedance, and electrode temperature.

**Methods and Results**—Eight dogs were studied closed chest. Using a 7F catheter with a 3.5 mm irrigated electrode and CF sensor (TactiCath, St. Jude Medical), radiofrequency applications were delivered to 3 separate sites in the right ventricle (30 W, 60 seconds, 17 mL/min irrigation) and 3 sites in the left ventricle (40 W, 60 seconds, 30 mL/min irrigation) at (1) low CF (median 8 g); (2) moderate CF (median 21 g); and (3) high CF (median 60 g). Dogs were euthanized and lesion size was measured. At constant radiofrequency and time, lesion size increased significantly with increasing CF (P<0.01). The incidence of a steam pop increased with both increasing CF and higher power. Peak electrode temperature correlated poorly with lesion size. The decrease in impedance during the radiofrequency application correlated well with lesion size for lesions in the left ventricle but less well for lesions in the right ventricle. There was a poor relationship between CF and the amplitude of the bipolar or unipolar ventricular electrogram, unipolar injury current, and impedance.

**Conclusions**—Radiofrequency lesion size and the incidence of steam pop increase strikingly with increasing CF. Electrogram parameters and initial impedance are poor predictors of CF for radiofrequency ablation. (Circ Arrhythm Electrophysiol. 2014;7:1174-1180.)

**Key Words:** atrial fibrillation ■ catheter ablation ■ radiofrequency ■ ventricular tachycardia

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Methods

CF Sensing Ablation Catheter

The 7F quadripoal ablation catheter with a CF sensor (TactiCath, St. Jude Medical, Geneva, Switzerland) has a 3.5-mm tip electrode with 6 small irrigation holes (0.4 mm diameter) around the circumference, located 1.2 mm from the tip for saline irrigation during radiofrequency delivery (Figure 1). The ablation electrode contains a thermocouple to measure the electrode temperature.

The CF sensor consists of a deformable body (elastic polymer) and 3 optical fibers (0.125 mm diameter, Figure 1) attached circumferentially around the deformable body. Force on the deformable body changes the reflected wavelength of light in the 3 optical fibers. By monitoring the reflected wavelength, the system is able to calculate the amplitude and display the vector of the CF at 100 ms intervals.

Experimental Model

The experimental protocol was approved by the University of Oklahoma Committee on the Use and Care of Animals. Eight

![Figure 1. Schematic representation of the distal end of the 7F contact force (CF) sensing ablation catheter. The CF sensor includes 3 optical fibers attached circumferentially with Fiber Bragg Gratings (FBG) to a deformable body. CF on the deformable body changes the FBG refractive index pattern which changes the reflected wavelength of light in the 3 optical fibers. The change in reflected wavelength is proportional to CF (magnitude and angle), measured at intervals of 100 ms.](image)

![Figure 2. Examples of measurements of electrogram parameters on a bipolar ventricular potential (top) and unipolar ventricular potential (bottom). Electrogram amplitude was measured from peak-to-peak. The mean negative dV/dt was measured as the amplitude of the downstroke divided by its duration. The amplitude of injury current was measured on the unfiltered unipolar electrogram from the baseline to the peak of ST elevation. By monitoring the reflected wavelength, the system is able to calculate the amplitude and display the vector of the CF at 100 ms intervals.](image)

![Figure 3. Radiofrequency (RF) ablation lesion size as function of low contact force (CF), moderate CF, and high CF. A. Examples of RF lesions (30 Watts, 60 seconds) in the right ventricle (RV). Increasing from low to high CF, increased the lesion depth from 4.8 mm to 8.7 mm, and increased lesion diameter from 5.9 mm to 9.4 mm. B. Examples of RF lesions (40 Watts, 60 seconds) in the left ventricle (LV). Increasing from low to high CF, doubled the lesion depth from 5.0 mm to 10.5 mm, and almost tripled lesion diameter from 5.7 mm to 15.0 mm. The crater in the high CF lesion resulted from a steam pop. C. Lesion measurements (mean±SD) at low, moderate, and high CF for the RV (top) and LV (bottom). Measurements include maximum depth, maximum diameter, depth at maximum diameter, and surface lesion diameter. Increasing from low to high CF, increased lesion depth in the RV from 5.0±0.7 mm to 8.5±1.3 mm, and increased lesion depth in the LV from 5.9±1.2 mm to 11.2±0.9 mm. Lesion measurements were not used in the 4 transmural lesions observed in the RV (1 at moderate CF and 3 at high CF).](image)
mongrel dogs weighing 31 to 39 kg were anesthetized with sodium pentobarbital (30 mg/kg) and ventilated mechanically with room air. The right carotid artery was cannulated for monitoring arterial pressure. A 7F, 20-electrode catheter was inserted into the right jugular vein and advanced into the coronary sinus under fluoroscopic guidance. A 10F ultrasound catheter (AcuNav, Acuson) was inserted into the left femoral vein and advanced into the right atrium to be used for intracardiac echocardiography. Heparin (5000 IU) was administered intravenously, with additional doses, as necessary to maintain the activated clotting time >250 seconds. Transseptal puncture was performed under intracardiac echocardiography and fluoroscopic guidance. The CF ablation catheter was inserted into the left atrium through the transseptal sheath. The CF catheter was initially positioned centrally within the left atrium, without endocardial contact (confirmed by intracardiac echocardiography), to calibrate the CF sensor to 0 g (baseline noncontact value). The CF ablation catheter was advanced into the left ventricle (LV) for ablation. After LV ablation was complete, the transseptal sheath was withdrawn into the right atrium and the CF ablation catheter was positioned into the right ventricle (RV). Ablation was then performed in the RV as described below.

Ablation Protocol

Radiofrequency applications were performed at 3 separate sites in the LV (septum, lateral free-wall, and apical region) and 3 separate sites in the RV (basal free-wall, medial wall of the outflow tract, and apical region). These 6 locations were sufficiently far apart to identify accurately during lesion assessment. The 3 radiofrequency applications in the LV and the 3 radiofrequency applications in the RV were delivered at 3 different levels of CF (one each, randomized): (1) low CF (range 2–10 g, median 8 g); (2) moderate CF (range 20–30 g, median 21 g); and (3) high CF (range 50–100 g, median 60 g. Figure 2), CF was stabilized and averaged over the 5 seconds before the onset of the radiofrequency application. Data for radiofrequency applications were not included if the catheter position or movement had changed during ablation or if the CF measured immediately after ablation had changed (>5–10 g). To examine selectively the effect of CF on lesion size, radiofrequency applications were delivered at constant radiofrequency power and application time. In the LV, radiofrequency applications were delivered at 40 Watts for 60 seconds, using a saline irrigation flow rate of 30 mL/min. Radiofrequency applications in the RV were delivered at 30 Watts for 60 seconds, using an irrigation flow rate of 17 mL/min. In the event of a steam pop (abrupt small increase of impedance, audible or not, confirmed by histology with small cavitation or crater formation) or impedance rise (>10 Ohms), the radiofrequency application was continued for the full 60 seconds to allow the comparison of lesion size. Lidocaine (100 mg) was administered intravenously just before ablation to prevent radiofrequency-induced ventricular fibrillation. Additional doses of lidocaine were administered as needed.

A custom radiofrequency generator (Radionics, model RFG-3DJ) was used to allow the recording of power, impedance, and electrode temperature at 20 ms intervals. Intracardiac electrograms (bipolar and unipolar signals), CF, radiofrequency power, impedance, and electrode temperature were monitored continuously and recorded (LabSystem Duo, CR Bard, Inc).

The dogs were euthanized 30 minutes after the final radiofrequency application. The hearts were excised and stained with triphenyl tetrazolium chloride, which stains intracellular dehydrogenase a deep red color, distinguishing viable (red), and necrotic (pale) tissue. The hearts were fixed in 10% formalin and sectioned from transmural to surface diameters. (A) Graphs of lesion depth as a function of CF in the right ventricle (RV, left) and left ventricle (LV, right), showing a highly significant relationship. B, Graphs of lesion diameter as a function of CF in the RV (left) and LV (right), also showing a significant relationship. CI indicates confidence interval.

Figure 5. Nonsignificant relationship between peak electrode temperature during the radiofrequency (RF) application and RF lesion depth (A) and diameter (B). CI indicates confidence interval; LV, left ventricle; and RV, right ventricle.
Measurement of Electrogram Parameters

Bipolar electrograms were recorded between the tip electrode and second electrode and filtered at 30 to 500 Hz. Unipolar electrograms were recorded between the tip electrode and a needle skin electrode, filtered at 1 to 500 Hz. The following electrogram measurements were obtained at each ablation site before the onset of the radio-frequency application: (1) bipolar ventricular potential amplitude (peak-to-peak); (2) bipolar ventricular potential mean negative dV/dt (amplitude/duration, downstroke slope); (3) unipolar ventricular potential amplitude (peak-to-peak); (4) unipolar ventricular potential mean negative dV/dt (amplitude/duration, downstroke slope); and (5) unipolar injury current amplitude (Figure 2).

Statistical Analysis

Statistical analyses were performed using SAS software (version 9.2). The relationships between average CF, peak electrode temperature, and decrease in impedance (the onset of radiofrequency application minus the minimum impedance during the radiofrequency application) versus lesion depth and lesion diameter were assessed by a mixed effects model using Proc Gennmod, providing β-coefficients for x variables and their corresponding 95% confidence intervals (CIs). Chi square test and Fisher exact test were used to test the overall association between CF category and the incidence of steam pop and impedance rise. The relationships between average CF, electrogram amplitude, mean negative dV/dt (downstroke slope), injury current amplitude, impedance at the onset of radiofrequency application, and impedance decrease were assessed by a mixed effects model using Proc Gennod. The relationship between the degree of impedance decrease and the occurrence of steam pop was assessed by Mann–Whitney U test. A probability value of <0.05 was considered to be statistically significant.

Results

Relationship Between CF and Lesion Size and Incidence of Steam Pop

A total of 48 lesions were created in the 8 dogs: 24 lesions in the RV (30 Watts, 60 seconds) at low CF (n=8), moderate CF (n=8), and high CF (n=8); and 24 lesions in the LV (40 Watts, 60 seconds) at low CF (n=8), moderate CF (n=8), and high CF (n=8). Lesion measurements were not used in the 4 transmural lesions observed in the RV (1 at moderate CF and 3 at high CF) because these values would be artificially low. Lesion size was independent of the 3 locations in the RV and the 3 locations in the LV.

At constant radiofrequency power and application time, lesion depth and diameter increased significantly with increasing CF (Figures 3 and 4). Lesions at lower power (30 Watts) and moderate CF were significantly deeper (6.7±0.8 mm versus 5.9±1.2 mm) and wider (9.6±1.1 mm versus 8.0±1.9 mm) than lesions at higher power (40 Watts) at low CF (Figure 3C). Lesions at lower power (30 Watts) and high CF were similar in depth and diameter to lesions at higher power (40 Watts) at moderate CF (Figure 3C). Lesion depth and diameter correlated well with average CF for both RV and LV (Figure 4).

Peak electrode temperature during the radiofrequency application correlated poorly with lesion depth and diameter (Figure 5). The decrease in impedance during the radiofrequency application relatively correlated well with lesion depth and diameter for lesions in the LV: 95% CI=0.13–0.28 and 95% CI=0.20–0.33, respectively, and in the RV: 95% CI=0.03, 0.14 and 95% CI=0.06, 0.19, respectively, Figure 6A and 6B.

The incidence of a steam pop increased significantly with increasing CF at 40 Watts (P=0.03) and with higher power (40 Watts versus 30 Watts, P=0.02, Figure 7). At 30 Watts in the RV, a steam pop occurred during 0/8 radiofrequency applications at low CF, 1/8 radiofrequency applications at moderate CF, and 1/8 radiofrequency applications at high CF. At 40 Watts in the LV, a steam pop occurred during 0/8 radiofrequency applications at low CF, 4/8 radiofrequency applications at moderate CF, and 5/8 radiofrequency applications at high CF.
Figure 8. Weak relationships between surrogate parameters and contact force (CF). Graphs of bipolar electrogram amplitude vs CF (A), mean negative dV/dt of the bipolar electrogram vs CF (B), unipolar electrogram amplitude vs CF (C), mean negative dV/dt of the unipolar electrogram vs CF (D), amplitude of the unipolar injury current vs CF (E), initial impedance (impedance at the onset radiofrequency [RF] application) vs CF (F) and impedance decrease vs CF (G). The deference of the degree of impedance decease between RF applications with and without steam pop (H), and the relationship between the degree of impedance decrease and the time of occurrence of the steam pop (I).
An impedance rise ($\geq 10$ Ohms increase from the minimum value during radiofrequency) occurred only in 3/8 radiofrequency applications at high CF and high power (40 Watts). An impedance rise did not occur at lower CF or at 30 Watts.

**Relationship Between Surrogate Parameters and CF and Lesion Size**

The peak-to-peak amplitude and downstroke slope of the bipolar and unipolar ventricular potentials correlated poorly with CF (Figure 8A–BD). The amplitude of unipolar injury current correlated better with CF but still had a wide overlap in values (Figure 8E). The ratio of injury current/unipolar ventricular potential amplitude correlated less well with CF than injury current amplitude, $Y=0.34+0.01*X$, 95% CI=0.002–0.02, $R=0.022$ and $Y=4.19+0.14*X$, 95% CI=0.06–0.22, $P=0.006$, respectively. Impedance at the onset of radiofrequency application (initial impedance) also correlated poorly with CF (Figure 8F). The degree of decrease in impedance during the radiofrequency application correlated only slightly better with CF (Figure 8G). At higher radiofrequency power (40 Watts), the occurrence of a steam pop correlated with the degree of impedance decrease (Figure 8H), but there was no significant relationship between the time of steam pop and the degree of impedance decrease (Figure 8I).

**Discussion**

To our knowledge, this is a first study to examine the relationship between radiofrequency lesion size and CF in the beating heart. We found a wide range of lesion size (depth and diameter) for radiofrequency applications with varying CF but same power and application time. Under these conditions (constant radiofrequency power and time), lesion size correlated well with CF (Figures 3 and 4). Increasing from low CF to high CF increased lesion depth by 70% at 30 Watts and by 90% at 40 Watts (Figure 3C). Lesions produced at 30 Watts and moderate CF were larger than lesions produced at 40 Watts and low CF, and lesions at 30 Watts and high CF were similar to lesions at 40 Watts and moderate CF (Figure 3). These data indicate that increasing CF is comparable to increasing radiofrequency power.

By measuring CF before the onset of an radiofrequency application, an appropriate radiofrequency power and time can be selected to achieve efficacy (lesion depth) and minimize the risk of steam pop. Low CF may be compensated by delivering higher radiofrequency power. The incidence of steam pop may be decreased while maintaining similar radiofrequency lesion size by using lower radiofrequency power and maintaining good CF.

Peak electrode temperature during radiofrequency applications was not predictive of lesion depth or diameter (Figure 5). The decrease in impedance during the radiofrequency application (initial impedance minus minimum impedance) correlated relatively well with lesion size (especially in the LV at 40 Watts, Figure 6). The degree of impedance decrease correlated with the occurrence of a steam pop at higher radiofrequency power (40 Watts) but did not correlate with the time of occurrence of the steam pop (Figure 8H and 8I). One limitation of the impedance decrease is that this measure is not available before the onset of the radiofrequency application.

This study also demonstrates that the surrogate parameters of CF have limited or no value. Electrogram amplitude (unipolar and bipolar) and downstroke slope correlated poorly with CF. Even the amplitude of the injury current is a weak predictor of CF, although the presence of an injury current indicates some contact. Impedance is also not predictive of the magnitude of CF. These findings indicate the surrogate measures are poor predictors of CF and confirm the importance of directly measuring CF.

**Study Limitation**

A principal limitation of the study was that all radiofrequency applications were delivered for a relatively long interval (60 seconds). The impact of CF on lesion size may be even greater during shorter radiofrequency application times. The role of CF may also be greater or lesser at higher or lower radiofrequency power than the 30 Watts and 40 Watts used in this study. Further studies are required to compare the importance of CF to different radiofrequency power and application time.

**Clinical Implications**

Incorporating real-time CF measurement in an irrigated radiofrequency ablation catheter should help optimize the selection of radiofrequency power and application time to maximize radiofrequency lesion formation and reduce the risk of steam pop in clinical application.

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**Disclosures**

Drs Nakagawa, Shah, and Jackman were consultants for Endosense SA. Drs Lambert, Fonck, and Yulzari were employees of Endosense SA (currently St. Jude Medical GVA). The other authors report no conflicts.

**References**

This study tested a saline irrigated radiofrequency ablation catheter with 3 optical fibers to measure real-time contact force (CF) as the microdeformation of a deformable body in the catheter tip in canine beating hearts. Radiofrequency applications were delivered to 3 separate sites in the right ventricle (30 W, 60 seconds) and 3 sites in the left ventricle (40 W, 60 seconds) at (1) low CF (median 8 g); (2) moderate CF (median 21 g); and (3) high CF (median 60g). Compared with the peak electrode temperature and the decrease in impedance during the radiofrequency application, radiofrequency lesion size (depth and diameter) correlated best with CF. The incidence of a steam pop increased significantly with both increasing CF and higher power. Increasing CF from low to high level increased lesion depth by 70% at 30 Watts and by 90% at 40 Watts. Lesions produced at 30 Watts and moderate CF were larger than lesions produced at 40 Watts and low CF, and lesions at 30 Watts and high CF were similar to lesions at 40 Watts and moderate CF, indicating that increasing CF is comparable to increasing radiofrequency power. The surrogate measures of CF by intracardiac electrogram amplitude (including unipolar injury current amplitude) and downstroke slope and preablation impedance had limited or no value. Incorporating real-time CF measurement in an irrigated radiofrequency ablation catheter may help optimize the selection of radiofrequency power and application time to maximize radiofrequency lesion formation and reduce or prevent steam pop in clinical application.
Relationship Between Catheter Contact Force and Radiofrequency Lesion Size and Incidence of Steam Pop in the Beating Canine Heart: Electrogram Amplitude, Impedance, and Electrode Temperature Are Poor Predictors of Electrode-Tissue Contact Force and Lesion Size

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