During radiofrequency catheter ablation, low electrode-tissue contact force (CF) is associated with ineffective lesion formation, whereas excessively high CF may result in an increased risk of steam pop and cardiac perforation.1–7 Because ablation systems have not had the ability to measure CF directly, other measures have been used as surrogates for CF, including the pattern of motion of the catheter tip under fluoroscopy, the amplitude of the unipolar and bipolar potentials, and impedance.3,6,7 The accuracy of these surrogate measures has not been effectively validated.

Two designs of ablation catheters using different technologies have recently 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 microdeformation of a deformable body in the catheter tip (TactiCath; Endosense SA).8–12 The other type of catheter uses a small spring connecting the ablation tip electrode to the catheter shaft with a magnetic transmitter and sensors to measure microdeflection of the spring (THERMOCOOL SMARTTOUCH; Biosense Webster, Inc).13–16 Both systems have CF resolution <1 g in bench testing.8,13–16

The purpose of this study was to test, in patients undergoing catheter ablation of paroxysmal atrial fibrillation (AF), the ability of the spring magnetic CF sensing catheter to: (1) identify the range and pattern of CF during mapping of the left atrium (LA) and pulmonary veins (PV); (2) determine the accuracy of electrogram amplitude and impedance in predicting CF; and (3) explore the feasibility of controlling radiofrequency power based on CF.

Background—During radiofrequency ablation, high electrode-tissue contact force (CF) is associated with increased risk of steam pop and perforation. The purpose of this study, in patients undergoing ablation of paroxysmal atrial fibrillation, was to: (1) identify factors producing high CF during left atrial (LA) and pulmonary vein mapping; (2) determine the ability of atrial potential amplitude and impedance to predict CF; and (3) explore the feasibility of controlling radiofrequency power based on CF.

Methods and Results—A high-density map of LA/pulmonary veins (median 328 sites) was obtained in 18 patients undergoing left atrial ablation using a 7.5-Fr irrigated mapping/ablation catheter to measure CF. Average CF was displayed on the 3D map. For 5682 mapped sites, CF ranged 1–144 g (median 8.2 g). High CF (≥35 g) was observed at only 118/5682 (2%) sites, clustering in 6 LA regions. The most common high CF site (48/113 sites in 17/18 patients) was located at the anterior/rightward LA roof, directly beneath the ascending aorta (confirmed by merging the CT image and map). Poor relationship between CF and either unipolar amplitude, bipolar amplitude, or impedance was observed. During ablation, radiofrequency power was modulated based on CF. All pulmonary veins were isolated without steam pop, impedance rise, or pericardial effusion.

Conclusions—High CF often occurs at anterior/rightward roof, where the ascending aorta provides resistance to the LA. Atrial potential amplitude and impedance are poor predictors of CF. Controlling radiofrequency power based on CF seems to prevent steam pop and impedance rise without loss of lesion effectiveness. (Circ Arrhythm Electrophysiol. 2013;6:746-753.)

Key Words: atrial fibrillation catheter ablation electrophysiology mapping radiofrequency
radiofrequency power based on CF (ie, lower power with high CF and higher power with low CF) and hence preventing steam pop and impedance rise while producing effective ablation lesions.

Methods
Eighteen (14 male and 4 female, aged 26–71 years, median age 56 years) patients with symptomatic, drug refractory paroxysmal AF were enrolled in this study. All patients provided written informed consent for the study, which was approved by the Institute for Clinical and Experimental Medicine (IKEM) institutional clinical research and ethics committee. A cardiac computed tomographic angiogram was obtained before the procedure to delineate LA and PV anatomy.

CF Sensing Catheter
The 7.5-Fr THERMOCOOL SMARTTOUCH CF sensing catheter has a 3.5-mm tip electrode with 6 small holes (0.4 mm diameter) around the circumference for saline irrigation. A tiny spring is located just proximal to the ablation tip electrode. A magnetic signal emitter is attached to the tip electrode (distal to the spring) and 3 magnetic sensors are located proximal to the spring to measure microdeflection of the spring. The microdeflection is computed to the magnitude and angle of CF every 25.6 ms (Figure 1). CF is displayed both continuously and as the average value (over 1 second) on an electroanatomical mapping system (CARTO XP; Biosense Webster, Inc). For each mapping point, the system stored the CF for the preceding 10 seconds, the average CF for the preceding 1 second, and the force angle (Figure 2). This catheter also has a magnetic location sensor for conventional electroanatomical mapping.

Electrophysiological Study
The electrophysiological study was performed under intravenous sedation with midazolam and fentanyl. A multielectrode catheter was inserted transvenously and positioned in the coronary sinus. After intravenous administration of heparin (maintaining activated clotting time >300 seconds), double transeptal puncture was performed under intracardiac ultrasound guidance (AcuNav, Acuson, Inc), placing 2 8.5-Fr sheaths (SL1; St Jude Medical, Inc) into the LA. A circular electrode catheter for recording PV potentials (Lasso; Biosense Webster, Inc) was inserted into the LA through one of the transseptal sheaths. The quadrupolar CF sensing mapping/ablation catheter was inserted through the second transseptal sheath. Under fluoroscopic guidance, the CF catheter was positioned centrally in the LA chamber without endocardial contact, confirmed by intracardiac echocardiography, to calibrate the CF sensor to 0 g (baseline noncontact value).

Electroanatomical Mapping of LA and PVs
An electroanatomical map of the LA and each PV was created during sinus rhythm (10 patients) or AF (8 patients) using the CF catheter guided by fluoroscopy and intracardiac echocardiography. Mapping was performed by 3 operators in different patients (#1, 12 patients; #2, 4 patients; and #3, 2 patients, respectively). During mapping, the transeptal sheath was positioned at the septum or in the right atrium for operator #1 and was located in the LA for operators #2 and #3. The physician maneuvering the catheter was blinded to the CF measurements, to identify the range of CF that occurs during routine mapping.

The electroanatomical maps were displayed in 5 separate formats: (1) map of activation time (sinus rhythm maps); (2) CF map, showing the average CF over 1 second (Figure 2); (3) unipolar voltage map, displaying the peak-to-peak amplitude of the unipolar electrogram filtered at 1 to 400 Hz; (4) bipolar voltage map, displaying the peak-to-peak amplitude of the bipolar electrogram filtered at 30 to 400 Hz; and (5) impedance map, measuring the impedance between the tip electrode and the skin patch.

PV Antrum Isolation
PV antrum isolation was performed in all 18 patients using the irrigated CF catheter. The catheter operator was not blinded to CF during ablation. During radiofrequency applications, the saline irrigation flow rate was increased from 2 mL/min to 30 mL/min. Radiofrequency power was adjusted based on CF: (1) power 35 to 45 watts at CF <10 g; (2) 25 to 34 watts at CF 11 to 30 g; (3) 15 to 24 watts at CF 31 to 50 g; and (4) 5 to 14 watts at CF >51g. The radiofrequency application time at each site was variable based on electrogram attenuation, but the usual duration was 20 to 30 seconds. PV antrum isolation was verified (absence of any PV potential and absence of any LA potential in the antral ablation area) using the circular catheter and/or the ablation catheter electrogams. Throughout the procedure, intracardiac echocardiography was used to monitor the mapping catheter tip position and its visual contact with the tissue (whenever possible). At the end of the procedure, intracardiac echocardiography was used to exclude the presence of PV stenosis, intracardiac thrombus, and pericardial effusion in all 18 patients. A transthoracic echocardiogram was performed on the day following the procedure to rule out pericardial effusion and other complications.

Follow-Up of Patients
The purpose of follow-up was to identify any procedure-related complications. All patients were seen in the IKEM arrhythmia clinic at 1, 3, and 6 months after ablation. A 24-hour Holter recording was obtained at the 6-month follow-up in all 18 patients. A repeat computed tomographic angiogram was obtained 3 months after ablation in all 18 patients, to identify the presence or absence of PV stenosis.

Statistical Analysis
The data were analyzed independent of Biosense Webster, Inc. The values are expressed as range and median or mean±SD. Due to the difference in the number of values measured between patients, a log transformation was performed on the variables of interest (ie, unipolar amplitude, bipolar amplitude, impedance, and average CF) to ensure the variables were normally distributed. A generalized estimating equation was applied on the log-transformed data to assess the
The most common site of high average CF was located at the rightward aspect of the anterior LA wall, accounting for 48 of the 118 (41%) high CF sites and occurring at that location in 17 of the 18 (94%) patients. The high CF occurred transiently during superior aspect of the anterior LA wall, ranging from 142 to 544 (median 328). For the 18 patients, a total of 5682 mapping sites were acquired for analysis (3213 sites during sinus rhythm and maximum CF for 1-second period at each of the 5682 sites ranged 1 to 144 g (median 8.2 g; Figure 3) and 2 to 170 g (median 12 g), respectively. There was only a small difference in average CF for the 3 operators (median 8.3 g, 7.3 g, and 9.3 g; Figure 3).

High average CF (≥35 g) was observed at only 118 of the 5682 (2%) sites, and at only 1 to 15 (median 5) sites per patient. The sites of high average CF were clustered in 6 regions (Figure 4). The most common site of high CF was located at the rightward superior aspect of the anterior LA wall, accounting for 48 of the 118 (41%) high CF sites and occurring at that location in 17 of the 18 (94%) patients. The high CF occurred transiently during the inspiratory phase of respiration when the roof of the LA is pressed against the catheter tip (Figure 5). Integrating the CF map with the preablation computed tomographic angiogram showed the highest CF site was located directly beneath the ascending aorta, which provides external support to the atrial wall in this region (Figure 6). Intracardiac echocardiography confirmed the catheter tip was pressed against the aortic wall with increased compression during inspiration. Importantly, a high CF at this site was observed even during pullback of the catheter from the left PVs to this region with the tip of the sheath in the right atrium.

The other sites of high CF were the antrum posterior to the right superior PV (23/118 sites [19%], present in 9/18 patients [50%]), inferior posterior LA wall (23/118 sites [19%], present in 7/18 patients [39%]), antrum posterior to the left superior PV (11/118 sites [9%], present in 6/18 patients [33%]), LA roof (11/118 sites [9%], present in 4/18 patients [22%]), and the anterior region of the proximal right PVs (3/118 sites [3%], present in 1/18 patients [6%]; Figure 4).

**Results**

**CF Mapping**

The average CF (over 1 second) ranged 2 to 70 g. Low average CF (≤10 g) is displayed in red. High average CF (>35 g) is displayed in purple. The CF at site #1 (base of the left atrial LA appendage) was low at 5 g. The CF at site #2 (anterior/rightward LA roof, beneath the ascending aorta) was high at 45 g. B, Ten-second continuous tracing of CF with the last 1 second recorded at site #1 (top; average CF 5 g, force angle 60°) and site #2 (bottom; average CF 45 g, force angle 45°). C, Atrial potentials recorded at sites #1 and #2. Although CF was low at site #1, the amplitude of the bipolar and unipolar potentials was greater than at site #2, recorded at high CF (2.63 mV vs 1.89 mV, respectively). The impedance was also greater at site #1 than site #2 (127 ohms vs 121 ohms). CS indicates coronary sinus; LIPV, left inferior pulmonary vein (PV); LSPV, left superior PV; RIPV, right inferior PV; and RSPV, right superior PV.

**Relationship Between CF and Electrogram Amplitude, Impedance**

Unipolar voltage, bipolar voltage, and impedance correlated poorly with average CF at the 2202 LA mapping sites during sinus rhythm in 10 patients and at the 1755 LA sites during AF in 8 patients (Figures 7 and 8). PV mapping sites were excluded from the correlation between electrogram amplitude,
impedance, and CF, due to the higher impedance and lower amplitude signals deep within the PV.

**CF During Radiofrequency Ablation**

The operators were not blinded to CF during ablation. The average CF during PV antrum isolation in 18 patients was a median of only 8 g (range 1–65 g). The range of CF during radiofrequency application was similar for the 3 operators (Figure 3B). The total radiofrequency time per patient ranged 28.3 to 70.8 (median 45) minutes, without the occurrence in any patient of either an audible steam pop, an impedance rise, or the presence of coagulum or char on the ablation electrode. Acute antrum isolation (>30 minutes) was achieved for all PVs in all 18 patients.

**Complications**

In 1 patient, hospitalization was extended due to the development of atrial tachycardia on the second day post-ablation. There were no other acute or late complications, including pericardial effusion, pericardial tamponade, stroke, phrenic nerve injury, LA-esophageal fistula, or PV stenosis. At 6 months, 14 (78%) of the 18 patients were free of symptoms, and Holter recording showed no AF or atrial tachycardia without antiarrhythmic medication.

**Figure 3.** Range of contact force (CF) during left atrial (LA)/pulmonary vein (PV) mapping and during ablation. A, Range of CF during LA/PV mapping for all 18 patients (5682 sites, median 8.2 g), and for operator #1 (12 patients, 3846 sites, median 8.3 g), operator #2 (4 patients, 1009 sites, median 7.3 g), operator #3 (2 patients, 827 sites, median 9.3 g). Box plot values are 10th percentile, 25th percentile, 50th percentile (median), 75th percentile, and 90th percentile of the range of CF. B, CF distribution during ablation for each of the 3 operators. CF was ≤20 g for >80% of ablation sites for all 3 operators. NS indicates not significant.

**Figure 4.** Locations of the 6 regions of high average contact force (CF; ≥35 g), shown in the posterior-anterior (PA) projection (left) and anterior-posterior (AP) projection (right). LA indicates left atrial; LIPV, left inferior pulmonary vein (PV); LSPV, left superior PV; RIPV, right inferior PV; and RSPV, right superior PV.
not dependent on the location of the transeptal sheath, because the ascending aorta exerts an external force against the directly beneath the ascending aorta. These observations suggest the ascending aorta exerts an external force against the LA wall and the catheter (Figure 6). High CF at this site was not dependent on the location of the transeptal sheath, because the sheath tip was positioned in the right atrium in 12 of the 17 patients.

The second most common region of high CF (present in 9 of the 18 patients) was located at the antrum, posterior to the right superior PV. Typically, this occurred as the catheter was moved across the superior posterior LA toward the right PVs with clockwise catheter torque. The catheter seemed to fall into this site, resulting in a transient high CF.

Respiratory movement (inspiration) contributed to transient high CF in the LA roof region. On the other hand, having only a short segment of the catheter exposed from the sheath was a factor for high CF in the infero-posterior LA region.

Although electrogram amplitude and impedance have been used to estimate CF, we found a poor relationship between CF and the unipolar or bipolar atrial potential amplitude or the impedance (Figures 7 and 8). In a previous study using a canine model with the catheter positioned at a single ventricular endocardial site, applying a progressive increase in CF was surprisingly not associated with a significant increase in either ventricular potential amplitude or ST elevation (injury current). Baseline impedance is also heavily influenced by the location of the electrode within the heart relative to high impedance extracardiac structures, such as lung. These observations support the importance of directly measuring electrode-tissue CF.

The relationship between CF and radiofrequency lesion depth has been examined in the canine thigh muscle preparation and canine right and left ventricles. Increasing CF (2, 10, 20, 30, and 40 g) in the canine thigh muscle produced a progressive increase in lesion depth for constant radiofrequency power (30 watts, median lesion depth 6.2–9.9 mm) and for high radiofrequency power (50 watts, median lesion depth 7.1–11.2 mm). Lesion depth was greater at 30 watts radiofrequency power at 40 g CF than at 50 watts and 10 g CF (median depth 9.9 mm versus 8.5 mm, P<0.01). The incidence of steam pop and thrombus formation also increased with increasing CF at both 30 and 50 watts.

In canine beating heart studies, increasing CF similarly increased radiofrequency lesion depth in the canine right ventricle (25 watts; median depth 4.6–7.4 mm) and left ventricle (40 watts; median depth 5.3–9.5 mm). Lesion depth was greater for radiofrequency applications at 25 watts at high CF (≥40 g) than at 40 watts at low CF (<10 g; median depth 7.4 mm and 5.3 mm, respectively). Based on these observations, the feasibility of modulating radiofrequency power based on CF to achieve desired lesion depth was explored in the canine right and left ventricles. Decreasing radiofrequency power from 40 Watts to 10 Watts with increasing CF from 10 g to 40 g in the right ventricle and 50 to 25 watts (when increasing CF from 10 to 40 g) in the left ventricle resulted in a similar range of lesion depth (median: 5.2–5.0 mm in the right ventricle; 8.6–8.0 mm in the left ventricle) with a decrease in steam pop at high CF and no thrombus on the electrode. In the present study, radiofrequency power was modulated for 4 ranges of CF. In addition, radiofrequency power was not delivered at average CF>65 g. Although the number of patients is small, there was no audible steam pop, thrombus, or pericardial effusion in any of the 18 patients. Acute PV antrum isolation was achieved in all patients with total radiofrequency application

**Discussion**

This study examined the spatial distribution of electrode-tissue CF during catheter mapping of the LA and PVs (with 3 operators blinded to the CF measurements) in 18 patients undergoing ablation of paroxysmal AF, and tested the ability of electrogram amplitude (unipolar and bipolar voltage) and impedance to predict CF. The results are summarized as follows: (1) there was a wide range of average CF (1–144 g) over 5682 sites during LA/PV mapping, but CF was relatively low over most sites for all 3 operators (median 8.2 g); (2) high average CF (≥35 g) was observed at only 2% of the mapping sites with the predominant site at the rightward superior aspect of the anterior LA, directly beneath the ascending aorta; (3) unipolar voltage, bipolar voltage, and impedance correlated poorly with average CF both during sinus rhythm and AF; and (4) modulating radiofrequency power based on CF allowed acute PV isolation without audible steam pop, thrombus, or pericardial effusion.

There was a wide range of CF for each operator, but unlike a previous study, the range and median values were similar between operators. The present study evaluated the spatial distribution of CF within the LA and PVs (with 3 operators blinded to the CF measurements) in 18 patients undergoing ablation of paroxysmal AF, and tested the ability of electrogram amplitude (unipolar and bipolar voltage) and impedance to predict CF. The results are summarized as follows: (1) there was a wide range of average CF (1–144 g) over 5682 sites during LA/PV mapping, but CF was relatively low over most sites for all 3 operators (median 8.2 g); (2) high average CF (≥35 g) was observed at only 2% of the mapping sites with the predominant site at the rightward superior aspect of the anterior LA, directly beneath the ascending aorta; (3) unipolar voltage, bipolar voltage, and impedance correlated poorly with average CF both during sinus rhythm and AF; and (4) modulating radiofrequency power based on CF allowed acute PV isolation without audible steam pop, thrombus, or pericardial effusion.
Figure 7. Comparison of maps of contact force (CF; A), unipolar atrial potential amplitude (Unipolar Voltage Map; B), bipolar atrial potential amplitude (Bipolar Voltage Map; C), and impedance (D) in the same patient. Note that a site of high CF (black arrow in the left) demonstrates a low unipolar amplitude, a moderate bipolar amplitude, and a low impedance. At a site of low CF (black arrow in the right), unipolar and bipolar amplitudes are high and an impedance is moderate (not low). AP indicates anterior-posterior; LIPV, left inferior pulmonary vein (PV); LSPV, left superior PV; PA, posterior-anterior; RIPV, right inferior PV; and RSPV, right superior PV.
times (median 45 minutes) similar to those expected by each of the 3 operators using conventional, non-CF sensing irrigated catheters, suggesting little or no loss of lesion effectiveness despite decrease in radiofrequency power at higher CF.

Limitations of the Study
There are 3 principal limitations for this study. First, the number of patients is too small to confirm a reduction in the incidence of steam pop and other complications by modulating radiofrequency power based on CF (i.e., reducing radiofrequency power with increasing CF). The second limitation relates to the inability to use acute PV isolation to measure lesion effectiveness during the titration of radiofrequency power. Acute PV isolation does not confirm transmural necrosis. In addition, adenosine testing was not performed to identify dormant PV conduction. Studies with larger numbers of patients and long-term follow-up will be required. The third limitation relates to the observation that more than 80% of radiofrequency applications were delivered at CF $\leq 20$ g. This limits the assessment of safety and efficacy of the power modulation algorithm at high CF.

Conclusions
There was a wide range of CF during catheter mapping and ablation of the LA and PVs. High average CF (≥35 g) occurred at 6 regions in the LA, most at anterior/rightward roof, where the ascending aorta provides resistance to the LA. Unipolar and bipolar atrial potential amplitude and impedance were found to be poor predictors of CF, suggesting there is no
present substitute for measuring catheter-tissue CF. Although the number of patients was small, controlling radiofrequency power based on CF seems to reduce or prevent steam pop, impedance rise, and pericardial effusion/tamponade without loss of lesion effectiveness.

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Disclosures
Drs Nakagawa, Kautzner, Natale, Di Biase, and Jackman are consultants for Biosense Webster, Inc. The other authors report no conflicts.

References

CLINICAL PERSPECTIVE
This study tested, in patients undergoing catheter ablation of paroxysmal atrial fibrillation, the ability of a contact force (CF) sensing catheter to: (1) identify the range and spatial distribution of CF during catheter mapping of the left atrium and pulmonary veins with 3 operators blinded to the CF measurements; (2) determine the accuracy of atrial potential amplitude and impedance in predicting CF; and (3) explore the feasibility of controlling radiofrequency power based on CF (ie, lower power with high CF and higher power with low CF) to achieve effective radiofrequency lesions while preventing steam pop and impedance rise. There was a wide range of CF during mapping and ablation within and between the 3 operators. High average CF (≥35 g) was observed at only 2% of mapped sites (118/5682 sites). The sites of high CF were clustered in 6 left atrium regions. The dominant high CF region (present in 17 of the 18 patients) was the rightward superior aspect of anterior left atrium, directly beneath the ascending aorta. High CF at this site was usually transient, present mainly during inspiration, suggesting the ascending aorta exerts an external force against the left atrium wall and the catheter. Unipolar and bipolar atrial potential amplitude and impedance were found to be poor predictors of CF, suggesting there is no present substitute for measuring catheter-tissue CF. Controlling radiofrequency power based on CF seems to reduce or prevent steam pop, impedance rise, and pericardial effusion/tamponade without loss of lesion effectiveness, measured as pulmonary vein isolation.
Locations of High Contact Force During Left Atrial Mapping in Atrial Fibrillation Patients: Electrogram Amplitude and Impedance Are Poor Predictors of Electrode-Tissue Contact Force for Ablation of Atrial Fibrillation
Hiroshi Nakagawa, Josef Kautzner, Andrea Natale, Petr Peichl, Robert Cihak, Dan Wichterle, Atsushi Ikeda, Pasquale Santangeli, Luigi Di Biase and Warren M. Jackman

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