In Vivo Contact Force Analysis and Correlation With Tissue Impedance During Left Atrial Mapping and Catheter Ablation of Atrial Fibrillation

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Background—The aim of this study was to evaluate in vivo contact force (CF) and the correlation of CF with impedance during left atrial 3-dimensional electroanatomical mapping and ablation.

Methods and Results—CF during point-by-point left atrial mapping was assessed in 30 patients undergoing atrial fibrillation ablation. Operators were blinded to the real-time CF data. Data were analyzed according to 11 predefined areas in the left atrial and 6 segments around the ipsilateral pulmonary veins. A total of 3475 mapping and 878 ablation points were analyzed. Median CF during mapping was 14.0 g (6.5–26.2; q1–q3), ranging from 5.1 g at the ridge to 29.8 g at the roof. Median CF at the ridge and mitral isthmus were 5.1 g and 6.9 g, respectively. Extremely high CF ≥100 g was noted in 24 points (0.7%). Median CFs during ablation around the right and left pulmonary veins were 22.8 g (12.6–37.9; q1–q3) and 12.3 g (6.9–30.2; q1–q3), respectively. The lowest median CFs were recorded at the anterior–superior and anterior–inferior segments of the left pulmonary veins (7.2 g and 7.9 g). Impedance values during mapping and impedance fall during ablation correlated with the applied CF (R²=0.16; P<0.001 and R²=0.04; P<0.001) although there was significant overlap.

Conclusions—Excessively high and low CF values can be observed during left atrial mapping and ablation. The low CF obtained at the mitral isthmus and anterior segments of the left pulmonary veins may explain why reconnection after ablation occurs more frequently at these sites. CF and impedance do correlate; however, the impedance for a given CF ranges widely, limiting its use in clinical practice. (Circ Arrhythm Electrophysiol. 2014;7:46-54.)

Key Words: atrial fibrillation catheter ablation contact force left atrial mapping pulmonary vein isolation

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In animal models, CF has been shown to correlate with tissue impedance, and impedance drop during radiofrequency (RF) application is associated with lesion formation. Antz et al reported previously that impedance correlates with catheter-to-tissue contact; however, the results from several other in vitro and in vivo studies are inconsistent. To the best of our knowledge, no systematic analysis of the relationship between in vivo CF and tissue impedance during point-by-point left atrial (LA) mapping and PVI have been performed.

Recently, the site- and operator-dependent differences when measuring CF have been reported; however, little is known about the detailed analysis of the distribution of CF and about catheter stability during point-by-point LA mapping and PVI using the Smart Touch catheter. To establish a baseline and evaluate the data in the setting of real clinical practice, operators in the present study were blinded to CF information.

The aims of this study were to (1) evaluate CF and catheter stability during LA mapping and ablation and (2) evaluate the correlation between CF and impedance during mapping and ablation of the PV antrum.

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Methods

Study Population
Thirty patients underwent catheter ablation for AF. Enrollment required ≥1 episode of sustained AF (>30 seconds) documented by 12-lead ECG, Holter monitoring, transtelephonic event monitor, telemetry strip, or pacemaker/implantable cardioverter defibrillator. All patients had symptomatic paroxysmal (n=22) or persistent AF, refractory or intolerant to ≥1 antiarrhythmic drug. Exclusion criterion was prior LA ablation. Patient characteristics are described in Table 1. All patients provided written informed consent for the procedure.

Mapping and PVI Procedure
All patients underwent transesophageal echocardiography before the procedure to exclude LA thrombus. The procedure was performed under deep sedation using midazolam, fentanyl, and continuous infusion of propofol. A 6-F catheter was placed inside the coronary sinus via the left subclavian vein or right femoral vein, and after transseptal punctures, 2 SL1 sheaths (St Jude Medical, St Paul, MN) were advanced into the LA. Three-dimensional (3D) electroanatomic mapping of the LA using the CF-sensing catheter (Thermocool SmartTouch, Biosense, Webster, CA) was performed.

Mapping was performed during sinus rhythm. All patients in AF before mapping underwent external cardioversion to restore sinus rhythm. Selective angiography of the PVs was performed in right anterior oblique 30° and left anterior oblique 40° to define the PV ostia. The catheter was maintained for ≥2 seconds at each mapping point before point acquisition. The LA was arbitrarily divided into 11 anatomic sites: posterior LA, roof, anterior roof, posterior septum, anterior LA, anterior septum, mitral isthmus, inferior LA, area above the posterior segment of the mitral valve (posterior to mitral valve), left atrial appendage (LAA), and ridge.

Circumferential PVI was performed in a power-controlled mode. RF energy was limited to 30 W along the posterior wall and roof and 40 W in the remaining areas. During the first 30 seconds of each application, the catheter was kept in a stable position and no dragging technique was used. Maximum duration of RF application was 60 seconds at each location. The circumferential lesions around the ipsilateral PVs were arbitrarily divided into the following segments: roof, antero-superior, antero-inferior, inferior, posterior-inferior, and postero-superior regions.

CF Measurement During Mapping and Ablation
The 7.5-Fr CF-sensing catheter uses a 3.5-mm irrigated tip electrode, connected by a tiny spring to the shaft. Catheter-tip CF and direction are measured with a resolution of <1 g every 50 ms by 3 location sensors within the shaft and the degree of spring bending via a magnetic transmitter at the catheter tip.

Table 1. Patient Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>N=30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>61.7±10.0</td>
</tr>
<tr>
<td>Men</td>
<td>23 (77%)</td>
</tr>
<tr>
<td>CHA2DS2-VASc score</td>
<td>1.8±1.3</td>
</tr>
<tr>
<td>History of heart failure</td>
<td>5 (17%)</td>
</tr>
<tr>
<td>History of stroke</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>21 (70%)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>3 (11%)</td>
</tr>
<tr>
<td>Paroxysmal AF</td>
<td>22 (73%)</td>
</tr>
<tr>
<td>Persistent AF</td>
<td>8 (27%)</td>
</tr>
<tr>
<td>Total duration of AF, mo</td>
<td>50.1±66.7</td>
</tr>
<tr>
<td>Left atrium size, mm</td>
<td>45.1±6.1</td>
</tr>
<tr>
<td>Ejection fraction, %</td>
<td>60.9±4.4</td>
</tr>
</tbody>
</table>

Continuous variables are shown as mean±SD. AF indicates atrial fibrillation.

Calibration of the CF catheter was performed before 3D electroanatomical mapping. CF data were not displayed to operators during the procedure but registered using the CARTO3 SMARTTOUCH Software Module (Figure 1). Mean CF was arbitrarily classified as low CF (<10 g), moderate CF (10–39 g), high CF (40–99 g), or excessively high CF (≥100 g). The following parameters were then recorded, extracted as raw data, and analyzed:

1. LA mapping points: mean CF, impedance, electrogram amplitude (unipolar, bipolar electrograms), CF values were measured every 50 ms. For each mapping point, CF data were analyzed for a 1.2-second period (24 serial measurements) to cover ≥1 atrial beat.
2. Ablation points: mean CF, impedance, electrogram amplitude (unipolar, bipolar electrograms), RF power, and temperature.

Before PVI, each predefined segment of the circumferential lesion around the ipsilateral PVs was tagged with a minimum of 2 mapping points. The first 30 seconds of each RF application was analyzed. Applications with durations <30 seconds were excluded. CF data were recorded continuously during ablation and analyzed in 50 ms intervals, then correlated with impedance data.

As a parameter of catheter stability during mapping, the relative SD (RSD) at each mapped point was calculated as follows: 100×SD/mean CF value. To evaluate catheter stability during ablation, the RSD of each RF application was calculated as follows: 100×SD of CF during the first 30 seconds/mean CF during the first 30 seconds.

Statistical Analysis
Differences between mapping and ablation sites were examined using mixed models to take into consideration repeated measurements for each patient. We assumed a compound symmetry structure for the mixed structure. The response variables were not normally distributed; therefore, we used a logarithmic transformation of the outcome variable to obtain normal distribution in the mixed models. For global test statistics, we used a significance level of 5%. If differences were shown, post hoc tests were applied to examine differences between subgroups. For the post hoc tests we presented Bonferroni-adjusted P values. Diagnostic performance of impedance for CF was evaluated by receiver operator characteristic (ROC) analysis. Continuous data were shown as means±SD for normally distributed data and as median values (first quartile–third quartile) otherwise. All analyses were performed using SAS version 9.3 TS Level 1M2 on a W32_7 PRO platform.

All authors had access to the data and have read and agreed to the article as written.

Results
LA Mapping
Mapping was performed during sinus rhythm in all 30 patients. No complications occurred during LA mapping or ablation. A total of 3475 LA mapping points were acquired and analyzed. The number of points acquired, median CF, and RSD at each predefined site are presented in Figure 2.

Median CF during LA mapping was 14.0 g (6.5–26.2). A high variability of CF was observed between different predefined sites, ranging from a median CF of 5.1 g (3.1–10.7) at the ridge to 29.8 g (16.1–48.2) at the roof (P<0.001; Figures 2 and 3A). CF applied at the roof and anterior roof (29.8 g [16.1–48.2] and 29.6 g [14.7–50.8]) was significantly higher compared with each of the other LA areas (P<0.001, respectively). CF at the ridge, LAA, and mitral isthmus (5.1 g [3.1–10.7], 6.1 g [3.2–10.1], and 6.9 g [3.6–12.0]) were significantly lower compared with each of the remaining LA areas except posterior to the mitral valve (P<0.001, respectively). CF within the
Figure 1. Contact force (CF) visualization on the CARTO3 screen. A, The system shows the CF value (red rectangles) and vector, which indicates the direction of catheter contact (yellow chain circle). The color-coded 3-dimensional (3D) map can be displayed according to CF value. In the real-time graph, force, impedance, temperature, and wattage can be shown (red rectangle, right inferior panel). B, During this study, operators were blinded to CF information. The CF window was hidden and the 3D map was displayed anatomically. The annotation window was narrowed to hide CF information. AP indicates anterior-posterior; LAO, left anterior oblique; LL, left lateral; PA, posterior-anterior; RAO, right anterior oblique; and RL, right lateral.
 Applications for the right-sided PVs and 436 (50%) for the left-sided PVs. In the 217 of 1095 (20%) excluded points, application was <30 seconds because of catheter movement (186/217 points; 86%) or impedance rise >100 $\Omega$. Impedance rise was recorded in 12 patients; these particular RF applications were associated with significantly higher CF (47.3g [34.6–64.7]) compared with the others (17.7g [8.8–34.9]; $P<0.001$). No audible pop was observed. CF and impedance data during PVI are presented in Table 3 and Figure 4A.

Median CFs during ablation at the right-sided PVs and left-sided PVs were 22.8g (12.6–37.9) and 12.3g (6.9–30.2), respectively ($P<0.001$). For right-sided PVs, CF at the postero-superior segment was significantly higher compared with each of the other segments except the roof. CF at LVPs was significantly higher at the roof and postero-superior segments compared with the remaining segments. Mean CF was <10g at the anterior segments of left-sided PVs.

For right-sided PVs, RSD at the antero-superior and antero-inferior segments was significantly lower (29.3% [17.7–38.3] and 27.7% [21.1–35.3], respectively ($P<0.001$). For left-sided PVs, RSD for the remaining segments compared with the remaining segments. Mean CF was <10g at the anterior segments of left-sided PVs.

Impedances before ablation for initial CF <10g, 10 to 39g, 40 to 99g, and ≥100g were 128 $\Omega$ (119–136), 135 $\Omega$ (126–146), 143 $\Omega$ (133–155), and 160 $\Omega$ (145–190), respectively ($P<0.001$). Correlation between overall impedance and applied CF, and in each of the 11 predefined left atrial areas (not shown), was statistically significant although there were large overlaps.

Diagnostic performance of impedance for high CF (CF≥40g) was evaluated by ROC analysis. Area under the ROC curve was 0.72. The sensitivity and specificity of impedance cutoff values are shown in Table 2.

When the cutoff value is defined as the nearest point to the top left corner of the ROC curve, the cutoff value of impedance $\Omega$ was 138. Using this cutoff value, specificity and sensitivity were 67%. At a cutoff value of 161 $\Omega$, specificity increased to 95%; however, sensitivity decreased to 20%.

### PVIs Isolation

PVI was performed successfully in all 30 patients. The total number of RF applications was 1095. A total of 878 RF applications (80%) were classified as valid for analysis: 442 (50%) applications for the right-sided PVs and 436 (50%) for the left-sided PVs. In the 217 of 1095 (20%) excluded points, application was <30 seconds because of catheter movement (186/217 points; 86%) or impedance rise >100 $\Omega$. Impedance rise was recorded in 12 patients; these particular RF applications were associated with significantly higher CF (47.3g [34.6–64.7]) compared with the others (17.7g [8.8–34.9]; $P<0.001$). No audible pop was observed. CF and impedance data during PVI are presented in Table 3 and Figure 4A.

Median CFs during ablation at the right-sided PVs and left-sided PVs were 22.8g (12.6–37.9) and 12.3g (6.9–30.2), respectively ($P<0.001$). For right-sided PVs, CF at the postero-superior segment was significantly higher compared with each of the other segments except the roof. CF at LVPs was significantly higher at the roof and postero-superior segments compared with the remaining segments. Mean CF was <10g at the anterior segments of left-sided PVs.

For right-sided PVs, RSD at the antero-superior and antero-inferior segments was significantly lower (29.3% [17.7–38.3] and 27.7% [21.1–35.3]), indicating that more stable catheter positions were obtained in these areas compared with the remaining segments (35.7% [24.0–51.0]; $P=0.001$ and $P=0.007$, respectively). In contrast, RSD for left-sided PVs was significantly higher at the antero-superior and antero-inferior segments (36.2% [24.9–58.2] and 31.5% [21.7–47.8]), indicating decreased catheter stability compared with the remaining segments (26.4% [18.9–35.7]; $P<0.001$ and $P=0.006$, respectively).

Impedances before ablation for initial CF <10g, 10 to 39g, 40 to 99g, and ≥100g were 128 $\Omega$ (117–133), 130 $\Omega$ (120–140), 137 $\Omega$ (125–146), and 147 $\Omega$ (125–182), respectively, indicating that CF correlates with impedance, although there was significant overlap ($R^2=0.076$; $P<0.001$).

Impedance drop for mean CF <10g, 10 to 39g, 40 to 99g, and ≥100g was −7 $\Omega$ (−4 to −11), −12 $\Omega$ (−6 to −17), −17 $\Omega$ (−10 to −20), and −9 $\Omega$ (−5 to −15), respectively ($P<0.001$).
Mean CF correlated with impedance drop during the first 30 seconds of RF application ($R^2=0.040$; $P<0.001$; Figure 4B and 4C), indicating that as mean CF increases, impedance drop becomes larger. This phenomenon is presented in Figure 4D, which shows serial impedance values according to applied CF.

**Operator-Related Differences**

The study was performed by 3 highly experienced operators (R.T., F.O., and A.R.), each having performed >200 PVI procedures in 2012. Operator-related CF differences according to LA sites and PV ostial segments are shown in Figure 5.

During LA mapping, there were no significant differences in median CF among the 3 operators (13.9 g [5.8–27.1], 13.7 g [7.4–24.8], and 14.5 g [6.8–25.8], respectively; $P=0.65$).

Median CF during PVI was different among the 3 operators; however, this did not reach statistical significance: CF of operator 1, 2, and 3 was 19.8 g (9.9–34.5), 14.4 g (7.7–32.7), and 18.9 g (8.0–39.4), respectively ($P=0.090$).

**Discussion**

Our study demonstrated that (1) low and excessively high CFs frequently occur during detailed point-by-point LA mapping; (2) CF and catheter stability during RF application have large site-specific variability; (3) higher CF was associated with higher tissue impedance and steeper impedance drop during RF application, although there was significant overlap.

In recent studies, evaluations of CF during mapping of different predefined right and left atrial sites and during PVI were performed. To the best of our knowledge, this was the
first systematic, detailed analysis of in vivo CF and catheter stability during LA point-by-point electroanatomical mapping and ablation in a clinical setting.

Impact of CF on Lesion Formation

RF lesion size is determined by multiple factors, including electrode–tissue contact, catheter tip size, and RF duration, power, and temperature. Okumura et al. evaluated the impact of CF on outcomes of mapping and ablation in dog hearts using the Sensei robotic system. They found that when irrigated RF ablation using 15 W for 30 seconds was performed, a CF of 10 to 20 g and ≥20 g generated transmural and significantly larger ablation lesions than those created with a CF <10 g. They also found that CF of 10 to 20 g produced 1.5× larger electroanatomical map volumes compared with those created using a CF of only 5 g. The authors concluded that ablation lesion size is optimized by applications of 10 to 20 g, and that mapping requires lower CF to avoid image distortion.

Di Biase et al. evaluated the relationship among lesion formation, pressure, and the development of complications in a dog model. When 30 W was applied, (1) no lesions using 10 g of CF were transmural, (2) lesions were more likely transmural with CF >40 g than with CF <30 g (75% versus 25%; P<0.001), and (3) steam pop and crater formation occurred significantly more often with CF >40 g compared with CF of 20 to 30 g (41% versus 15%; P=0.008). The majority of lesions placed using higher power (45 W) with higher pressures (>40 g) were associated with char and crater formation (66.7%). The authors concluded that CF of 20 to 30 g and power of 40 W were optimal in achieving transmural lesions with a favorable safety profile.

Shah et al. demonstrated that lesion size correlates linearly with measured CF-time integral. They also demonstrated that at constant RF power and identical peak CF, constant contact produces the largest lesions.

In our study, CF and RSD of CF varied widely depending on the mapped LA site (Figure 2). CF-sensing catheters may help avoid excessively high CFs >100 g and therefore complications such as cardiac perforation.

At the mitral isthmus and ridge, median CF was low (<10 g) and RSD of CF was high (35.3% and 33.8%, respectively). This indicates low catheter-to-tissue contact with unstable catheter position. This finding may explain why (1) conduction gaps in circumferential ablation lines around the PVs most frequently occur at the LAA ridge and (2) achieving bidirectional block along the mitral isthmus remains challenging in the majority of patients. CF-guided ablation has the potential to minimize ineffective RF application secondary to low CF.

Although previous in vitro and animal studies showed that excessively high CF results in risk of steam pops and cardiac perforation, no complications were observed during this study, despite obtaining excessively high CF at some sites. Therefore, although impedance rise was significantly associated with higher CF, the relationship between high CF and steam pop could not be evaluated as no audible pop occurred.

As described by Yokoyama et al., impedances during mapping and impedance drops during ablation correlated with CF in this study. However, as impedance is influenced by several factors including individual characteristics of the chest, indifferent electrode position, and hemodynamic conditions, correlation was weak. Our ROC analysis suggested that an impedance >161Ω has a high specificity, but low sensitivity for high CF. However, because of significant overlap

### Table 2. Performance Characteristics of Various Impedance Values for Predicting Contact Force ≥40g

<table>
<thead>
<tr>
<th>Min CF, g</th>
<th>Max CF, g</th>
<th>Sensitivity, %</th>
<th>Specificity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>170</td>
<td>12</td>
<td>97</td>
<td>20</td>
</tr>
<tr>
<td>160</td>
<td>22</td>
<td>94</td>
<td>20</td>
</tr>
<tr>
<td>150</td>
<td>37</td>
<td>86</td>
<td>20</td>
</tr>
<tr>
<td>140</td>
<td>61</td>
<td>71</td>
<td>20</td>
</tr>
<tr>
<td>138*</td>
<td>67</td>
<td>67</td>
<td>20</td>
</tr>
<tr>
<td>130</td>
<td>86</td>
<td>45</td>
<td>20</td>
</tr>
<tr>
<td>120</td>
<td>96</td>
<td>19</td>
<td>20</td>
</tr>
</tbody>
</table>

*Indicates optimal sensitivity and specificity.

### Table 3. CF, RSD, and Impedance Data During Pulmonary Vein Isolation

<table>
<thead>
<tr>
<th>PV Site</th>
<th>No. of Burns</th>
<th>Median CF, g</th>
<th>Max CF, g</th>
<th>Min CF, g</th>
<th>RSD, %</th>
<th>Initial Impedance, Ω</th>
<th>Impedance Fall, Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>Roof</td>
<td>68</td>
<td>32.9 (18.3 to 51.1)</td>
<td>71.2</td>
<td>10.4</td>
<td>39.6</td>
<td>136 (127 to 147)</td>
</tr>
<tr>
<td>Ant sup</td>
<td>79</td>
<td>20.8 (11.4 to 34.7)</td>
<td>46.9</td>
<td>8.8</td>
<td>29.3</td>
<td>130 (123 to 142)</td>
<td>−12 (−6 to −17)</td>
</tr>
<tr>
<td>Ant inf</td>
<td>62</td>
<td>22.6 (12.8 to 32.1)</td>
<td>35.6</td>
<td>7.1</td>
<td>27.7</td>
<td>131 (121 to 141)</td>
<td>−12 (−6 to −19)</td>
</tr>
<tr>
<td>Post sup</td>
<td>93</td>
<td>38.2 (22.8 to 53.1)</td>
<td>79.5</td>
<td>15.7</td>
<td>33.3</td>
<td>132 (124 to 143)</td>
<td>−11 (−11 to −25)</td>
</tr>
<tr>
<td>Post inf</td>
<td>69</td>
<td>14.7 (8.5 to 26.9)</td>
<td>44.9</td>
<td>3.3</td>
<td>40.6</td>
<td>131 (122 to 140)</td>
<td>−8 (−5 to −14)</td>
</tr>
<tr>
<td>Inferior</td>
<td>71</td>
<td>14.4 (8.4 to 22.2)</td>
<td>29.1</td>
<td>2.9</td>
<td>32.4</td>
<td>130 (119 to 140)</td>
<td>−11 (−6 to −18)</td>
</tr>
<tr>
<td>Left</td>
<td>Roof</td>
<td>75</td>
<td>35.2 (16.3 to 55.0)</td>
<td>71.2</td>
<td>19.1</td>
<td>25.8</td>
<td>138 (126 to 150)</td>
</tr>
<tr>
<td>Ant sup</td>
<td>87</td>
<td>7.2 (4.5 to 10.8)</td>
<td>18.2</td>
<td>1.9</td>
<td>36.2</td>
<td>125 (117 to 134)</td>
<td>−8 (−5 to −14)</td>
</tr>
<tr>
<td>Ant inf</td>
<td>93</td>
<td>7.9 (4.3 to 11.1)</td>
<td>17.4</td>
<td>3.1</td>
<td>31.5</td>
<td>121 (113 to 130)</td>
<td>−7 (−4 to −13)</td>
</tr>
<tr>
<td>Post sup</td>
<td>61</td>
<td>38.4 (26.6 to 50.0)</td>
<td>71.7</td>
<td>20.7</td>
<td>24.2</td>
<td>127 (116 to 137)</td>
<td>−14 (−9 to −21)</td>
</tr>
<tr>
<td>Post inf</td>
<td>50</td>
<td>19.5 (13.9 to 30.0)</td>
<td>45.9</td>
<td>7.8</td>
<td>29.7</td>
<td>126 (117 to 134)</td>
<td>−10 (−7 to −16)</td>
</tr>
<tr>
<td>Inferior</td>
<td>70</td>
<td>10.0 (6.1 to 17.7)</td>
<td>24.5</td>
<td>3.2</td>
<td>31.3</td>
<td>120 (114 to 127)</td>
<td>−9 (−5 to −13)</td>
</tr>
</tbody>
</table>

CF and impedance values are shown as median values (first quartile–third quartile). CF indicates contact force; PV, pulmonary vein; and RSD, relative SD.
between the predefined CF groups (Figure 3B), impedance may have limited value as a surrogate parameter for CF in clinical practice.

Clinical Implications and Perspective
Excessively high CF seen at the roof may explain some cases of perforation. Low CF and high RSD at the ridge and mitral isthmus may explain why durable PVI and mitral isthmus block can be difficult to obtain. Visualization of CF may help operators to improve efficacy and safety during mapping and ablation.

Consistent with previous studies,\(^4\) CF values in our study were dependent not only on the LA sites or PV ostial segments but also on the operators (Figure 5). Wide variations in median CF among operators during ablation are observed in the superior quadrant of both right and left superior PVs, but this difference is not statistically significant and may be secondary to the small sample size. Despite highly experienced operators, approximately half of the mapped points and RF applications had either high (≥40g) or low (<10g) CF. CF visualization may also reduce CF disparity between operators, resulting in averaged durable lesion formation. However, further trials are

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**Figure 4.** A. Predefined ostial segments are colored according to the median contact force (CF) during ablation. At the roof and postero-superior segments of both pulmonary veins (PVs), mean CF was higher compared with the remaining areas. At the antero-superior and antero-inferior segments of left PVs, CF was significantly lower than the other left ostial segments. B. Relationship between mean CF and impedance drop. Impedance drop during the first 30 seconds of ablation also showed significant differences among predefined groups according to mean CF. C. Although the correlation between mean CF and impedance drop was statistically significant, correlation coefficients were also low because of large overlaps. D. Serial impedance change during the first 30 seconds of ablation is shown. Impedance was higher with high CF (≥40g) as compared with that with low and moderate CF. LIPV indicates left inferior pulmonary vein; LPV, left-sided PV; LSPV, left superior pulmonary vein; RIPV, right inferior pulmonary vein; RPV, right-sided PV; and RSPV, right superior pulmonary vein.
necessary to confirm whether visualization of CF will alter the applied CF in clinical practice.

Limitations
This study has several limitations. First, although we adopted the RSD of CF to assess catheter stability, there are no data at this stage validating RSD as a true reflection of catheter stability. Second, the mapping data were recorded during LA mapping, not during catheter ablation. Although no difference in CF on the left atrial ridge was observed during mapping and ablation in our study, CF may be different at other predefined areas (eg, mitral isthmus) during ablation. Third, the aim of this study was to evaluate only stable CF during PVI, hence ≈20% of RF applications were excluded from the analysis because of short RF duration. Fourth, this study was intended as a pilot study to analyze CF in clinical practice; hence, sample size was small and may have affected the statistical result. Finally, force-time-integral and force-time-power-integral are considered important indices for lesion creation. However, as our aim was to evaluate the real CF value in clinical practice and we analyzed solely the first 30 seconds of each RF application.

Conclusions
Excessively high and low CF values can be observed during LA mapping and ablation. Low CF and poor catheter stability at the anterior–superior and anterior–inferior segments of the left PVs and the mitral isthmus may explain why these ostial sites are the most common sites of recovered PV conduction after circumferential PVI, and why blocking conduction across the mitral isthmus can be difficult. CF and tissue impedance do correlate; however, impedance values have considerable overlap, which limits its use in clinical practice.

Disclosures
Dr Makimoto received travel grants from Biosense Webster. Dr Tilz received travel grants, research grants, and speaker honoraria from Biosense Webster and St Jude Medical. Dr Lin received a fellowship grant from St Jude Medical. Dr Antz received speaker honoraria from Biosense Webster. Dr Rillig received travel grants from St Jude Medical and Biosense Webster. Dr Kuck received research grants from Biosense Webster, Stereotaxis, ProRhythm, Medtronic, Edwards, Cryocath, and Biotronik, and he is consultant to St Jude Medical, Biosense Webster, ProRhythm, and Stereotaxis, and he is scientific advisor and shareholder of Endosense.
References

   


CLINICAL PERSPECTIVE

Recently, contact force (CF)–sensing catheters have been introduced to measure real-time CF, aiming at improvement of catheter-to-tissue CF as well as improved safety during mapping and ablation procedures. The aim of this study was to evaluate in vivo CF and the correlation of CF with impedance value during left atrial mapping and pulmonary vein isolation for treatment of atrial fibrillation. We found that when the operator had no access to the CF data, excessive low and excessive high CF can frequently be observed during both left atrial mapping and ablation. Particularly, the low CF obtained at the mitral isthmus and anterior segments of left pulmonary veins may explain why reconnection after prior ablation procedures occurs more frequently at these sites. In this study, CF and impedance did correlate statistically, but because of large overlaps the clinical use of impedance as a surrogate parameter for CF seems to be of limited value. Wide variations in CF among operators should also be noted. To the best of our knowledge, this is the first report evaluating the systematical and detailed data of CF during point-by-point electroanatomical mapping and left atrial ablation. Although further trials are necessary to confirm whether visualization of CF will alter the applied CF in clinical practice, the data of the present study imply that CF-guided ablation may improve clinical success by avoiding ineffective lesion formation because of low CF and reduce the complication rate by avoiding excessive high CF.
In Vivo Contact Force Analysis and Correlation With Tissue Impedance During Left Atrial Mapping and Catheter Ablation of Atrial Fibrillation

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