Incidence and Anatomical Locations of Catheter Instability During Circumferential Pulmonary Vein Isolation Using Contact Force

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Summary

In addition to contact force (CF), catheter stability is considered to be an important factor in creating radiofrequency lesions.

To evaluate the catheter stability during pulmonary vein isolation (PVI) using CF-sensing catheter.

PVI was performed in 32 patients using a CF-sensing catheter. Operators were blinded to CF. The application was arbitrarily defined as a “visually unstable” point if the catheter moved ≥ 4 mm. Data were analyzed according to 6 pre-defined segments for the ipsilateral PVs. As a parameter of catheter stability, the standard deviation (SD) of CF and relative standard deviation (RSD = 100 × SD of CF /average CF) were introduced.

A total of 932 RF applications with 426 visually unstable points (UP; 45.7%) and 506 stable points (SP; 54.3%) were analyzed. SD was significantly higher at UP (8.0g versus 5.7g, P < 0.001), and RSD was significantly higher at UP (43.7% versus 26.5%, P < 0.001). Higher RSD was associated with visual instability in all the segments of both PVs, however, higher SD of CF was not in all segments. At the antero-superior segment of the LPV, and the roof and postero-inferior segments of the RPV, the RSD values were over 50%, suggesting catheter instability.

Catheter instability occurred in 45% of ablations during PVI and was predominantly located in the antero-superior segment of the LPV and postero-inferior segment of the RPV, which may result in incomplete lesion formation. RSD had significant correlation with visual catheter stability. (Int Heart J 2014; 55: 249-255)

Key words: Atrial fibrillation, Catheter ablation, Catheter stability

Pulmonary vein isolation (PVI) has now become a mainstay therapy for atrial fibrillation (AF).1,2 However, at reprocedure for recurrent AF, the predominant cause identified is electrical reconnection between the pulmonary veins (PV) and left atrium (LA).3,4 Durable lesion formation is therefore considered to be essential in preventing recurrences of AF, thereby avoiding repeat procedures. To improve the durability of lesions, various 3D-mapping systems and irrigation catheters have been developed. Recently, a contact force (CF) sensing catheter that measures the CF between the catheter tip and cardiac tissue has become clinically available.5

Visualization of the direction and force of the contact between the catheter tip and cardiac tissue can help to avoid 1) excessively high CF, which may potentially lead to complications such as perforation and cardiac tamponade, and 2) excessively low CF, which may result in ineffective lesion formation and prolong procedure time. With the currently available CF catheter, the average or maximum CF between the catheter tip and cardiac tissue is displayed. It provides limited information regarding catheter stability during ablation due to the smooth structure of the left atrium. Previous studies have demonstrated that the CF between the catheter tip and myocardial tissue is an important parameter in determining radiofrequency lesion formation, however, catheter stability is also thought to be an important parameter.6 In this study, we attempted to evaluate the catheter stability at predefined anatomical locations during PVI using the CF sensing catheter with the CARTO3 system. We analyzed the variability of CF values as parameters for catheter stability and compared the difference between visually stable and unstable points during circumferential PVI. We hypothesized that the standard deviation (SD) of CF could be an index of catheter stability, however, the SD of CF can be larger in areas with higher CF, because the SD should be proportional to the value of the original data. In line with this, we have also

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adopted the relative standard deviation (RSD) of CF (RSD = \(\frac{SD \times 100}{\text{average CF}}\)) and compared the usability of these two indices.

**METHODS**

**Study population:** The study population consisted of 32 patients who underwent catheter ablation of recurrent AF. At least one episode of sustained (> 30 seconds) AF must have been documented by 12-lead ECG, Holter monitoring, transtelephonic event monitor, telemetry strip, or pacemaker/ICD. All patients had symptomatic paroxysmal (n = 24) or persistent AF refractory or intolerant to at least one antiarrhythmic drug. Exclusion criterion was prior left atrial ablation. Patient characteristics are described in Table I. All patients provided written informed consent prior to the procedure.

**Procedures and definition of instability:** All patients underwent a transesophageal echocardiogram (TEE) to rule out LA thrombus prior to the procedure. Three experienced operators performed the procedures (15 patients, 11 patients, and 6 patients for each operator). The procedure was performed under deep sedation utilizing midazolam, fentanyl, and continuous infusion of propofol. A 6F catheter was placed inside the coronary sinus (CS) via the left subclavian vein or right femoral vein, and following double transseptal punctures, two 8.5F SL1 sheaths (St. Jude Medical, MN, USA) were advanced to the LA. 3D-electroanatomical mapping of the LA using the CF sensing catheter (Thermocool® Smart Touch™, Biosense Webster, Inc., CA, USA) was performed. Mapping was performed only during stable sinus rhythm. If the patient was in AF at the start or during the procedure, external cardioversion was performed to restore sinus rhythm. Selective angiography of the PVs was performed in RAO 30° and LAO 40° to enable definition of the PV ostia. Only circumferential PVI around the ipsilateral PVs was performed in these patients. The circumferential lesions around the ipsilateral PVs were arbitrarily divided into the following segments: roof, antero-superior, antero-inferior, inferior, postero-inferior, and postero-superior segments.

In this study, circumferential PVI was performed in a power-controlled mode. RF energy was limited to 25-30 W along the posterior wall and roof, and to 30-40 W in the remaining areas. During the first 30 seconds of ablation, the catheter was maintained in a stable position and no dragging technique was used. The application was arbitrarily defined as a “visually unstable” point if the catheter moved ≥ 4 mm. The maximum duration of RF application was 60 seconds at each location.

**CF measurement during mapping and ablation:** The CF sensing catheter (Thermocool® Smart Touch™, Biosense Webster, Inc., CA, USA) is a commercially available 7.5 French RF ablation catheter. This catheter uses a 3.5 mm irrigated tip electrode, which is connected by a tiny spring to the shaft. Catheter tip CF and direction is measured with a resolution of < 1g every 50 ms by 3 location sensors in the shaft and the degree of spring bending via a magnetic transmitter at the catheter tip.

Calibration of the CF sensing catheter in the LA was performed prior to 3D electroanatomical mapping. The CF information was blinded to the operators during the procedure, but was registered using the 3D electroanatomical system (CAR-TO®, Biosense Webster Inc, CA, USA) with the CARTO® SMARTTOUCH® Software Module.

Before circumferential PVI, each segment along the circumferential lesion around the ipsilateral PVs was tagged with a minimum of two mapping points. Solely the first 30 seconds of data during each application were analyzed. Applications with RF duration less than 30 seconds were excluded from the analysis. The following parameters were recorded during PVI and analyzed in this study: average CF, impedance, electrogram amplitude (unipolar, bipolar electrogram), RF power and temperature. CF data was continuously recorded during ablation, analyzed in 50 ms intervals and correlated with impedance data. For the analysis of impedance, mean CF was arbitrarily classified as low CF (< 10g), low-intermediate CF (10-19g), intermediate CF (20-29g), high-intermediate CF (30-39g), or high CF (≥ 40g).

As a parameter of catheter stability during mapping, standard deviation (SD) and the relative standard deviation (RSD) were used. To evaluate catheter stability during ablation, the RSD was calculated as follows: SD of CF during the first 30 seconds divided by the mean CF during the first 30 seconds of each RF application.

**Statistical analysis:** The chi-square test, Student t test, 1-way analysis of variance, or multiple regression analysis was performed when appropriate to test for statistical differences. A \(P\) value of < 0.05 was considered statistically significant. In case of multiple comparisons, the Bonferroni adjusted \(P\) value was used. Diagnostic performance of the SD and the RSD for visual catheter stability was evaluated by receiver operator characteristic (ROC) analysis.

All authors had full access to the data and have read and agreed to the manuscript as written. Statistical analysis was performed using JMP 9.0 software package (SAS Institute, Inc, Cary, NC).

**RESULTS**

**Pulmonary vein isolation:** PVI was successfully performed in all 32 patients. The total number of RF applications was 1154. Of those, 932 RF applications (81%) were classified as valid for CF analysis, including 473 (51%) RF applications for the right-sided PVs (RPV) and 459 (49%) for the left-sided PVs (LPV). The CF and impedance data during PVI are presented in Table II and Figure 1.
CATHETER STABILITY DURING PULMONARY VEIN ISOLATION

Table II. CF, RSD, and Impedance Data PVI

<table>
<thead>
<tr>
<th>PV Site</th>
<th>Number of Burns</th>
<th>Mean CF (g)</th>
<th>SD (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>71</td>
<td>33.7 ± 25.8</td>
<td>10.9 ± 6.2</td>
<td>41.7 ± 19.4</td>
<td>135.4 ± 14.7</td>
</tr>
<tr>
<td></td>
<td>Ant Sup</td>
<td>86</td>
<td>24.0 ± 17.9</td>
<td>6.1 ± 4.3</td>
<td>30.5 ± 17.2</td>
<td>132.3 ± 14.2</td>
</tr>
<tr>
<td></td>
<td>Ant Inf</td>
<td>67</td>
<td>23.2 ± 11.7</td>
<td>6.0 ± 2.9</td>
<td>28.9 ± 12.2</td>
<td>130.8 ± 13.0</td>
</tr>
<tr>
<td></td>
<td>Post Sup</td>
<td>96</td>
<td>40.7 ± 24.4</td>
<td>12.1 ± 8.5</td>
<td>35.5 ± 19.9</td>
<td>133.4 ± 14.7</td>
</tr>
<tr>
<td></td>
<td>Post Inf</td>
<td>75</td>
<td>22.1 ± 18.5</td>
<td>7.2 ± 5.8</td>
<td>40.2 ± 21.8</td>
<td>129.4 ± 11.9</td>
</tr>
<tr>
<td></td>
<td>Inferior</td>
<td>78</td>
<td>18.0 ± 13.2</td>
<td>5.4 ± 3.5</td>
<td>34.9 ± 15.3</td>
<td>129.7 ± 13.8</td>
</tr>
<tr>
<td>Left</td>
<td>Roof</td>
<td>86</td>
<td>39.8 ± 32.0</td>
<td>8.2 ± 5.3</td>
<td>27.2 ± 15.8</td>
<td>139.3 ± 15.6</td>
</tr>
<tr>
<td></td>
<td>Ant Sup</td>
<td>87</td>
<td>8.2 ± 5.4</td>
<td>3.1 ± 3.0</td>
<td>40.4 ± 22.0</td>
<td>125.5 ± 12.0</td>
</tr>
<tr>
<td></td>
<td>Ant Inf</td>
<td>94</td>
<td>9.6 ± 8.5</td>
<td>3.3 ± 3.3</td>
<td>36.9 ± 19.2</td>
<td>122.3 ± 12.0</td>
</tr>
<tr>
<td></td>
<td>Post Sup</td>
<td>63</td>
<td>36.0 ± 15.7</td>
<td>9.1 ± 5.6</td>
<td>26.5 ± 11.7</td>
<td>127.6 ± 14.0</td>
</tr>
<tr>
<td></td>
<td>Post Inf</td>
<td>57</td>
<td>22.8 ± 14.4</td>
<td>6.5 ± 5.0</td>
<td>29.2 ± 11.7</td>
<td>124.3 ± 11.3</td>
</tr>
<tr>
<td></td>
<td>Inferior</td>
<td>72</td>
<td>14.3 ± 11.2</td>
<td>4.1 ± 2.8</td>
<td>34.1 ± 15.7</td>
<td>121.2 ± 12.7</td>
</tr>
</tbody>
</table>

CF indicates contact force; PVI, pulmonary vein isolation; and RSD, relative standard deviation (%).

Mean CF during ablation of the RPV and LPV were 27.5 ± 21.1g and 21.0 ± 21.2g, respectively (P < 0.001). The mean CF at the RPVs was significantly higher at the postero-superior and roof segments (40.7 ± 24.4g, 33.7 ± 25.8g, respectively) as compared to the remaining segments (21.8 ± 15.9g (P < 0.001). The mean CF at the LPVs was significantly higher at the roof and postero-superior segments (39.8 ± 32.0g, 36.0 ± 15.7g, respectively) as compared to the other segments (12.7 ± 11.2g (P < 0.001). Of note, mean CF was less than 10g at the anterior segments of the LPVs in 127 out of 181 points (70%).

The mean CF according to the operators showed no significant differences (24.7 ± 19.5g, 24.5 ± 24.3g, and 22.8 ± 19.0g, respectively). In addition, there were no significant differences in the mean CF in each predefined segment between the 3 operators.

Of the 932 RF applications, 426 points (46%) were classified as visually unstable RF points. The mean CF of the visually stable RF points was significantly higher than that of the visually unstable RF points (27.1 ± 25.1g versus 20.9 ± 15.3g, P < 0.001). Along the right-sided circumferential lesions, the incidence of visually unstable points was significantly higher at the posterior segment compared to the other segments (Figure 1A, P < 0.001). Along the left-sided circumferential lesions, the incidence of visually unstable points was significantly higher at the inferior segment as compared to the other segments (P = 0.021).

Standard deviation and relative standard deviation during pulmonary vein isolation: At the RPV, SD at the postero-superior and roof segments was significantly higher (12.1 ± 8.5g, 10.9 ± 6.2g, respectively) as compared to the remaining segments (Table II). At the LPV, SD at the postero-superior and roof segments was also significantly higher (9.1 ± 5.6g, 8.2 ± 5.3g, respectively) as compared to the remaining segments.

The average value of RSD was 34.1 ± 18.2% (RPV: 35.3 ± 18.5%, LPV: 32.9 ± 17.7%). The RSD data are presented in Table II and Figure 2. For the right-sided circumferential lesions, RSD at the roof and postero-inferior segments were significantly higher (41.7 ± 19.4g, 40.2 ± 21.8g, respectively) as compared to the remaining RPV segments (P = 0.003, P = 0.033, respectively). In contrast, the RSD at the antero-inferior segment was significantly lower (28.9 ± 12.2%, P = 0.003). For the left-sided circumferential lesions, RSD at the antero-superior and antero-inferior segments were significantly higher (40.4 ± 22.0%, 36.9 ± 19.2%, respectively) as compared to the

Figure 1. Mean contact force (CF) and relative standard deviation (RSD) in the predefined ostial segments during ablation. A: Predefined ostial segments are colored according to mean CF during ablation. At the roof and postero-superior segments of both pulmonary veins (PVs), mean CF was higher as compared to the remaining segments. At the anterior segments of the left PVs, mean CF was < 10g and significantly lower than the other left ostial segments. The number of visually unstable points is also shown at each segment. The incidence of visually unstable points was high at the inferior segment of the left PVs and the postero-inferior segment of both PVs. B: Predefined ostial segments are colored according to the RSD. At the roof and postero-inferior segments of the right PVs and the antero-superior segment of the left PVs, RSD was significantly higher as compared to the other segments.
remaining segments ($P < 0.001$). In comparison, the RSD at the postero-superior and roof segments of the LPV were significantly lower (26.5 ± 15.8%, respectively, $P < 0.001$).

**Comparison of SD and RSD between visually stable and unstable points:** The comparisons of SD values between the visually stable and visually unstable RF points are presented in Table III and Figure 2. For the right-sided circumferential lesions, SD of unstable points was significantly higher than that of stable points at the postero-inferior and antero-inferior segments. There was no significant difference in SD between stable and unstable points at all other segments of the RPV. For the left-sided circumferential lesions, SD of unstable points was significantly higher than that of stable points in all segments except at the roof.

The comparison of RSD between visually stable and visually unstable RF points is also shown in Table III. For the right-sided and left-sided circumferential lesions, the RSD of unstable points was significantly higher than that of stable points at all the segments of both PVs.

The receiver-operator curves between the visual catheter stability and SD or RSD are presented in Figure 4. The area under the ROC curve (AUC) of SD was 0.63, and the AUC of RSD was 0.79. Moreover, an RSD value of > 39.8% was associated with a high specificity of 0.89 for visual instability.

**Impedance data during pulmonary vein isolation:** The relationship between the applied CF value and the impedance value at the beginning of RF applications is shown in Figure 3A. The initial impedance values corresponding to initial CF < 10g, 10-19g, 20-29g, 30-39g, and ≥ 40g were 125 ± 12Ω, 129 ± 14Ω, 129 ± 14Ω, 134 ± 15Ω, and 137 ± 16Ω ($P < 0.001$), respectively, indicating that applied CF correlates with impedance values.

The relationship between the applied CF value and the impedance drop during RF application is presented in Figure 3B. Average CF was correlated with tissue impedance drop during the first 30 seconds of RF application. Impedance drop for a mean CF < 10g, 10-19g, 20-29g, 30-39g, and ≥ 40g were 8.0 ± 5.7Ω, 11.9 ± 8.1Ω, 13.2 ± 9.1Ω, 14.3 ± 10.0Ω, and 16.4 ± 8.9Ω ($P < 0.001$). This data indicates that as average CF increases the impedance drop becomes larger.

The impedance drop of visually stable RF points was significantly larger as compared to that of visually unstable RF points (-12.7 ± 8.9Ω versus -11.5 ± 8.2Ω, $P = 0.032$), however, there was a significant overlap.

**Discussion**

The major findings of the present study during circumferential lesions of the PV were significantly lower. The comparisons of SD values between the visually stable and visually unstable RF points are presented in Table III and Figure 2. For the right-sided circumferential lesions, SD of unstable points was significantly higher than that of stable points at the postero-inferior and antero-inferior segments. There was no significant difference in SD between stable and unstable points at all other segments of the RPV. For the left-sided circumferential lesions, SD of unstable points was significantly higher than that of stable points in all segments except at the roof.

The comparison of RSD between visually stable and visually unstable RF points is also shown in Table III. For the right-sided and left-sided circumferential lesions, the RSD of unstable points was significantly higher than that of stable points at all the segments of both PVs.

The receiver-operator curves between the visual catheter stability and SD or RSD are presented in Figure 4. The area under the ROC curve (AUC) of SD was 0.63, and the AUC of RSD was 0.79. Moreover, an RSD value of > 39.8% was associated with a high specificity of 0.89 for visual instability.

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The relationship between the applied CF value and the impedance drop during RF application is presented in Figure 3B. Average CF was correlated with tissue impedance drop during the first 30 seconds of RF application. Impedance drop for a mean CF < 10g, 10-19g, 20-29g, 30-39g, and ≥ 40g were 8.0 ± 5.7Ω, 11.9 ± 8.1Ω, 13.2 ± 9.1Ω, 14.3 ± 10.0Ω, and 16.4 ± 8.9Ω ($P < 0.001$). This data indicates that as average CF increases the impedance drop becomes larger.

The impedance drop of visually stable RF points was significantly larger as compared to that of visually unstable RF points (-12.7 ± 8.9Ω versus -11.5 ± 8.2Ω, $P = 0.032$), however, there was a significant overlap.

**Table III. CF, SD, and RSD Data During PVI**

<table>
<thead>
<tr>
<th>PV Site</th>
<th>No. of Burns</th>
<th>No. of UP</th>
<th>SP Mean CF</th>
<th>UP Mean CF</th>
<th>P</th>
<th>SP SD</th>
<th>UP SD</th>
<th>P</th>
<th>SP RSD</th>
<th>UP RSD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Roof</td>
<td>71 (49%)</td>
<td>35 (49%)</td>
<td>43.6 ± 30.1</td>
<td>23.6 ± 15.2</td>
<td>&lt; 0.001</td>
<td>10.0 ± 4.4</td>
<td>11.9 ± 7.7</td>
<td>0.22</td>
<td>29.2 ± 13.6</td>
<td>54.6 ± 15.7</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Ant Sup</td>
<td>86 (15%)</td>
<td>13 (15%)</td>
<td>25.0 ± 18.7</td>
<td>18.7 ± 11.9</td>
<td>0.24</td>
<td>5.8 ± 4.4</td>
<td>7.7 ± 3.5</td>
<td>0.14</td>
<td>26.5 ± 11.7</td>
<td>53.0 ± 25.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Ant Inf</td>
<td>67 (31%)</td>
<td>21 (31%)</td>
<td>24.2 ± 11.3</td>
<td>21.1 ± 12.6</td>
<td>0.31</td>
<td>5.5 ± 2.6</td>
<td>7.1 ± 3.3</td>
<td>0.033</td>
<td>24.4 ± 8.7</td>
<td>38.9 ± 13.1</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Post Sup</td>
<td>96 (55%)</td>
<td>53 (55%)</td>
<td>53.5 ± 26.5</td>
<td>30.3 ± 16.7</td>
<td>&lt; 0.001</td>
<td>11.3 ± 6.2</td>
<td>12.8 ± 10.0</td>
<td>0.4</td>
<td>23.8 ± 10.9</td>
<td>44.9 ± 20.6</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Post Inf</td>
<td>75 (63%)</td>
<td>47 (63%)</td>
<td>23.1 ± 22.6</td>
<td>21.5 ± 15.8</td>
<td>0.71</td>
<td>5.1 ± 5.3</td>
<td>8.4 ± 5.7</td>
<td>0.013</td>
<td>27.6 ± 12.5</td>
<td>47.7 ± 22.8</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Inferior</td>
<td>78 (44%)</td>
<td>34 (44%)</td>
<td>20.0 ± 15.7</td>
<td>15.4 ± 8.5</td>
<td>0.13</td>
<td>5.0 ± 3.7</td>
<td>6.0 ± 3.1</td>
<td>0.22</td>
<td>28.3 ± 11.9</td>
<td>43.5 ± 15.2</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Left Roof</td>
<td>86 (50%)</td>
<td>43 (50%)</td>
<td>53.1 ± 37.9</td>
<td>26.4 ± 16.6</td>
<td>&lt; 0.001</td>
<td>8.6 ± 6.0</td>
<td>7.9 ± 4.5</td>
<td>0.56</td>
<td>19.2 ± 10.1</td>
<td>35.1 ± 16.6</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Ant Sup</td>
<td>87 (59%)</td>
<td>40 (59%)</td>
<td>8.4 ± 5.3</td>
<td>7.8 ± 5.5</td>
<td>0.58</td>
<td>2.4 ± 2.4</td>
<td>4.0 ± 3.6</td>
<td>0.019</td>
<td>31.3 ± 13.6</td>
<td>54.7 ± 25.0</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Ant Inf</td>
<td>94 (43%)</td>
<td>40 (43%)</td>
<td>9.6 ± 9.1</td>
<td>9.5 ± 7.7</td>
<td>0.99</td>
<td>2.3 ± 2.6</td>
<td>4.6 ± 3.8</td>
<td>&lt; 0.001</td>
<td>25.7 ± 10.2</td>
<td>51.9 ± 18.3</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Post Sup</td>
<td>63 (48%)</td>
<td>30 (48%)</td>
<td>36.6 ± 17.1</td>
<td>35.3 ± 14.2</td>
<td>0.73</td>
<td>7.3 ± 4.0</td>
<td>11.1 ± 6.4</td>
<td>0.0058</td>
<td>20.4 ± 7.0</td>
<td>33.1 ± 12.3</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Post Inf</td>
<td>57 (56%)</td>
<td>32 (56%)</td>
<td>20.8 ± 16.1</td>
<td>24.3 ± 12.9</td>
<td>0.37</td>
<td>4.3 ± 3.2</td>
<td>8.2 ± 5.5</td>
<td>0.0025</td>
<td>22.2 ± 7.3</td>
<td>34.6 ± 11.5</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Inferior</td>
<td>72 (61%)</td>
<td>44 (61%)</td>
<td>14.0 ± 11.7</td>
<td>14.5 ± 11.0</td>
<td>0.85</td>
<td>3.1 ± 2.2</td>
<td>4.7 ± 3.0</td>
<td>0.016</td>
<td>27.3 ± 11.1</td>
<td>38.5 ± 16.8</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

CF indicates contact force; PVI, pulmonary vein isolation; RSD, relative standard deviation (%); SD, standard deviation; SP, stable point; and UP, unstable point.
However, excessively high CF may cause thrombus formation with a CF which exceeds a certain value should be attempted. Catheter stability analysis using CF data: was more specifically associated with visual stability compared with higher SD and RSD values during PVI, and 3) RSD the RPV, 2) visually unstable sites were significantly associated with higher tissue impedance (\(Z\)), and higher CF was significantly associated with larger impedance drop (\(\Delta Z\)). Both the initial impedance and impedance drop showed no significant differences between RF with low-intermediate CF (10-19g) and intermediate CF (20-29g).

![Figure 3](image)

**Figure 3.** Relationship between the applied CF and the tissue impedance or impedance drop during the first 30 seconds of ablation. Higher CF was significantly associated with higher tissue impedance (A), and higher CF was significantly associated with larger impedance drop (B). Both the initial impedance and impedance drop showed no significant differences between RF with low-intermediate CF (10-19g) and intermediate CF (20-29g).

Comparison of SD and RSD: It is widely known that the SD value becomes larger in proportion to the average value of the original data. In the present study, in the segments where SD was not associated with visual catheter stability, the mean CF of visually stable points was higher as compared to that of visually unstable points (Table III). This explains why the SD of visually stable points became larger in these segments, resulting in nonsignificance of the SD between the visually stable and unstable points. As shown in Figure 4, RSD was a better parameter for evaluating catheter stability in the present study.

![Figure 4](image)

**Figure 4.** Receiver-operator characteristics curves (ROC) of standard deviation (SD) and relative standard deviation (RSD) for predicting visual instability. The area under the curve (AUC) was 0.63 in the ROC curve of the SD (A). The AUC was 0.79 in the ROC curve of the RSD (B). The nearest point to the left top corner indicated the RSD value of 39.8\%, where the specificity was 0.89 and the sensitivity was 0.54.

Catheter stability and impedance value: Previous in-vitro studies have shown that the stronger the contact, or higher CF between the catheter tip and cardiac tissue, the deeper the RF lesions.\(^6\)\(^-\)\(^9\) Therefore, RF applications with a CF which exceeds a certain value should be attempted. However, excessively high CF may cause thrombus formation and myocardial damage due to steam pops, resulting in cardiac perforation.\(^10\)\(^,\)\(^11\)

The introduction of CF sensing catheters may potentially assist in avoiding ineffective lesion formation secondary to excessively low CF, and complications because of excessively high CF. However, even if the mean CF applied is within the target range, a large variability of the actual CF value during an RF application suggests catheter instability. There has been no systematic analysis of catheter stability using the CF sensing catheter during PVI. The present study demonstrated that visual catheter stability on the electroanatomic mapping system correlated with the RSD of CF.

Moreover, the data analysis based on this result demonstrated that the catheter stability during PVI had large variability, dependent on the ostial segments around the PVs. In particular, the RSD was significantly higher at the anterior segments of the LPV and the roof and postero-inferior segments of the RPV as compared to the other segments, which may influence lesion formation during circumferential PVI in clinical practice.

We have previously reported that the residual conduction after a single continuous circular lesion for ipsilateral PVI was often seen at the anterior segments of the LPVs and the posterior segments of the RPVs.\(^12\) Rajappan, \textit{et al} have also reported similar results on the acute and chronic reconnection sites after PVI.\(^13\) In this study, we observed higher RSD during ablation at the roof and posterior segments of the RPV, suggesting catheter instability at these locations. This may explain why conduction gaps are often seen in these segments, even though the CF value itself was not excessively low. At the anterior segments of the LPV, where the most frequent reconnection gaps are seen, not only was the RSD value high, but the CF value was also excessively low.

Instability of the catheter during RF application may be mainly due to the natural respiratory movement of patients and the distance from the septal puncture site. Kumar, \textit{et al} have recently reported that RF applications under apnea could achieve higher CF as compared to those under ventilation.\(^14\) Therefore, jet ventilation with lower volume and higher frequency can improve catheter stability, resulting in more effective lesion creation and may shorten procedure duration.

**Comparison of SD and RSD:** It is widely known that the SD value becomes larger in proportion to the average value of the original data. In the present study, in the segments where SD was not associated with visual catheter stability, the mean CF of visually stable points was higher as compared to that of visually unstable points (Table III). This explains why the SD of visually stable points became larger in these segments, resulting in nonsignificance of the SD between the visually stable and unstable points. As shown in Figure 4, RSD was a better parameter for evaluating catheter stability in the present study.

Catheter stability during PVI isolation were the following: 1) The most common sites for catheter instability during ablation are the antero-superior segment of the LPV and postero-inferior segments of the RPV, 2) visually unstable sites were significantly associated with higher SD and RSD values during PVI, and 3) RSD was more specifically associated with visual stability compared to SD.

**Catheter stability analysis using CF data:** Recently, PVI by way of catheter ablation has been established as a standard therapy for AF, and the most frequent finding in redo procedures after AF recurrence is reported to be electrical reconduction between the LA and PV. In an attempt to reduce this reconduction, advances in the development of 3D-mapping methods and irrigation catheters have been made, and recently the CF sensing catheter has become available.

Previous in-vitro studies have shown that the stronger the contact, or higher CF between the catheter tip and cardiac tissue, the deeper the RF lesions.\(^6\)\(^-\)\(^9\) Therefore, RF applications with a CF which exceeds a certain value should be attempted. However, excessively high CF may cause thrombus formation and myocardial damage due to steam pops, resulting in cardiac perforation.\(^10\)\(^,\)\(^11\)
number of RF applications (100 in total). In the present study, we analyzed the data from 932 RF applications. This difference could be due to the number of applications analyzed.

The statistically significant, but clinically poor relationship between CF and impedance may be ascribed to adjacent tissues such as the lungs and ascending aorta. Our results are in accordance with the recent report by Nakagawa, et al. 46

We showed that the impedance drop of visually stable RF points was significantly larger as compared to that of visually unstable RF points. As mentioned above, the applied CF of stable points was higher than that of unstable points. Hence, we performed multiple regression analysis to identify the possible causes for the difference in impedance drop between the stable and unstable points. What we found is that the mean CF applied was associated with the value of impedance drop ($P < 0.001$), however, catheter stability was not associated with impedance drop ($P = 0.28$). This suggested that impedance drop is not a good index in determining catheter stability.

**Limitations:** We defined visual catheter instability as move of the catheter that exceeded 4 mm on the 3D-electroanatomical mapping system. This movement on the CARTO system may have resulted from multiple factors, such as physician experience and deep respiration under deep sedation without intubation. Intubation was not performed in any patients, it was unknown if catheter instability was dominantly due to the deep respiration with current sedation approaches. Secondly, recovered PV conduction was not systematically re-evaluated in all patients, it was also unknown whether the catheter instability was associated with recovered PV conduction. Operator-related CF differences were not demonstrated in the present study. This may be due to the large variation of CF and the number of patients. In addition, we exclusively used nonsteerable sheaths. A steerable sheath may improve catheter to cardiac tissue contact. Future studies should further analyze this variable.

**Conclusion:** The relative standard deviation of contact force during pulmonary vein isolation had significant correlation with visual catheter stability, although the standard deviation of contact force did not always have significant correlation. Our data demonstrated that catheter stability during PVI differs enormously depending on the ostial sites and may explain why conduction gaps in the roof and postero-inferior segments of the pulmonary veins are often observed, even when adequate or high CF is applied.

**DISCLOSURE**

**Conflicts of Interest:** H Makimoto received travel grants from Biosense Webster. RR Tilz received travel grants, research grants and speaker honoraria from Biosense Webster and St. Jude Medical. T Lin received a fellowship grant from St. Jude Medical. A Rillig received travel grants from St. Jude Medical and Biosense Webster. KH Kuck received research grants from Biosense Webster, Stereotaxis, Prorhythm, Medtronic, Edwards, Cryocath and Biotronik, he is consultant to St. Jude Medical, Biosense Webster, Prorhythm and Stereotaxis, and he is a scientific advisor and shareholder of Endosense.

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