Impact of Catheter Contact Force on Human Left Atrial Electrogram Characteristics in Sinus Rhythm and Atrial Fibrillation

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Background—During left atrial mapping, optimal contact parameters minimizing variation secondary to catheter contact are not established.

Methods and Results—Across 30 patients undergoing first-time atrial fibrillation ablation, 1965 stable mapping points (1409 atrial fibrillation, 556 sinus rhythm), comprising 8-s contact force (CF) and bipolar electrogram data were analyzed. Points were taken in groups at locations with CF or catheter orientation actively changed between acquisitions. Complexes were less positive at higher CF (Spearman $\rho = −0.2$; $P<0.005$, both rhythms). Increasing CF at a location significantly increased complex size, but only where initial CF was $<10$ g, and if the change was $≥4.5$ g in sinus rhythm and $≥8$ g in atrial fibrillation ($P<0.0005$, both rhythms): if initial CF was $≥10$ g, no change was observed, regardless of CF change ($P>0.05$, both). Atrial ectopics during sinus rhythm were observed more frequently when CF was $≥10$ g ($P<0.0005$). Increasing CF at a location was associated with an increase in the complex fractionated atrial electrogram interval confidence level score, but only if initial CF was $<10$ g and CF increased $≥8$ g ($P=0.003$). The dominant frequency and organization index were unaffected by CF ($P>0.1$ for both). Changing catheter orientation from perpendicular to parallel in atrial fibrillation was associated with smaller, more positive complexes ($P=0.001$ for both), but no changes in complex fractionated atrial electrogram scores, dominant frequency or organization index ($P>0.08$ for each).

Conclusions—During left atrial electrogram mapping, including complex fractionated atrial electrogram but not spectral parameter mapping, CF and catheter orientation influence results: consequently, mapping CFs should be $≥10$ g to negate the influence of CF.


Key Words: atrial electrogram ■ atrial fibrillation ■ human ■ left atrium ■ myocardium

Global atrial stretch alters the electric properties of the human atrium, and human ventricular myocytes in vitro demonstrate stretch-induced depolarizations and extrasystoles. During atrial mapping, the contact force (CF) applied by the mapping catheter may affect the measured electric properties of the left atrium (LA) by affecting the physical relationship between the electrodes and tissue (affecting electrogram measurement) and by applying a local stretch stimulus to the myocardium (affecting the underlying substrate). In this context, the optimal contact characteristics minimizing such effects, if apparent, are undetermined.

As part of the ablation procedure for persistent atrial fibrillation (AF), complex fractionated atrial electrograms (CFAEs) have been targeted with varying success. CFAE are fragmented complexes considered involved in maintaining AF, and identified using visual or automated assessment using fractionation scores. Assessment of the electrogram is a pivotal part of CFAE ablation but, until recently, data on CF has not been available and hence the impact of this on CFAE parameters unexplored. Data from spectral analysis of electrograms to guide ablation may also be of use, but the effect of catheter contact on these measurements is similarly unknown. In man, a higher CF is weakly correlated with increasing electrogram amplitude in the LA and left ventricle. In porcine studies, the orientation of the catheter also impacts on the bipolar electrogram morphology observed. The effect of changing catheter contact on electrogram parameters at a fixed location has not been previously investigated.

In this study, we investigated the relationship between a change in CF and catheter orientation on LA electrogram...
WHAT IS KNOWN

- Atrial stretch can alter the electrical properties of the human atrium: the mapping catheter offers a localised stretch stimulus through its contact with the atrial myocardium.
- Electrogram mapping has been used to assess the efficacy of ablation based on electrogram attenuation and morphology changes.
- There is a known variability in complex fractionated electrogram and spectral parameters maps.
- The effect of changes in catheter contact on the human left atrial electrogram, including spectral and fractionation parameters, is unknown.

WHAT THE STUDY ADDS

- Increasing contact force significantly increases electrogram complex size in AF and sinus rhythm and this effect is dependent on the initial contact force and the magnitude of change: ≥10 g of initial force, no change in complex size with changes in contact force are observed. Complex fractionated electrogram scores are similarly affected, while spectral parameters are unaffected by changes in contact force.
- Atrial ectopics in sinus rhythm are more frequently observed at ≥10 g of contact force and this may have a bearing on activation mapping.
- During electrogram mapping, including fractionated electrogram but not spectral parameter mapping, a contact force ≥10 g negates the influence of contact force on these measurements.

characteristics, atrial ectopic burden, CFAE, and spectral analysis parameters in sinus rhythm (SR) and AF, to determine if there is an optimal CF for mapping to minimize any evident changes.

Methods

All participants gave informed consent to participate in the study. The study had ethical approval from the UK National Research Ethics Service. Consecutive patients with persistent or paroxysmal AF undergoing their first ablation were enrolled. Procedures were performed with patients under moderate (conscious) sedation. CF was measured at 20 Hz using a Thermocool SmartTouch catheter ( Biosense Webster Inc, Diamond Bar, CA). Before CF data collection, with the catheter not in contact with the myocardium (judged based on the absence of a recorded electrogram, the location of the catheter and catheter motion), CF sensing was zeroed. This process was repeated if the catheter’s internal diagnostics suggested CF measurement errors.

Mapping points were prospectively taken at evenly spaced LA locations. No ablation was performed in these regions until mapping was completed. At each location, three to four 8-s recording of CF and electrograms were taken with the catheter in a stable location, with a minimum CF of 1 g. At alternate locations, CF was changed by the operator for the second 2 readings (data being collected once the catheter was stable at the new CF). In a subset of locations in the patients in AF, the orientation of the catheter was changed from perpendicular to parallel and a further two 8-s reading taken.

The Carto3 electroanatomic mapping system ( Biosense Webster Inc) recorded CF and location data. Electrograms were recorded simultaneously using LabSystem Pro ( Bard Electrophysiology Division, Lowell, MA). Synchronicity between CF and electrogram measurements was ensured by manually taking points at the same time or the LabLink module ( Bard Electrophysiology Division), which synchronizes the 2 systems.

Catheter tip and electrode location data were recorded over a 2.5-s window for each point, sampled at 60 Hz. Catheter tip displacement was referenced to the averaged location of the 20 electrode poles of a circular pulmonary vein (PV) catheter, positioned in a PV (to account for movement secondary to respiration).

Electrograms analyzed were bipolar, filtered at 30 to 250 Hz. In SR, the incidence of atrial ectopics was determined for each 8-s electrogram on visual review of the surface ECG and intracardiac bipolar and unipolar (referred to an indifferent electrode in the inferior vena cava) signals.

Electrogram data were processed and analyzed using custom-written Matlab scripts (MathWorks, Natick, MA).

Peaks and troughs in the signal were identified using a 70-ms cut off to prevent double counting of complexes.6 Electrogram complex size was measured from the dominant peak to trough of a complex using previously described methods,14 and averaged for the signal, Figure 1. Complexes <0.05 mV (peak to trough) were assigned as noise.15 The angles of the rising and falling signal were determined for the dominant deflection in a complex, from a point at one third of the complex size from the dominant peak or trough. A correction factor for angle measurements was used to make the signal equivalent to that displayed on LabSystem Pro at a sweep speed of 100 mm/s at 32× scale. In total 89 105 complexes were identified based on the complex size and 70-ms double counting cut off. Histograms constructed demonstrated the majority of complexes had a rising or falling angle ≤15° (with the difference more pronounced in the SR signals), Figure 2A. For the data as a whole 60% of the rising or falling angles in the complexes were ≤15°. This value was taken as the field cut off: complexes with a rising or falling angle >15° were, therefore, excluded. Points with no identifiable complexes based on the above criteria were excluded from further analysis (other than automated CFAE score analysis).

The polarity ratio was determined by the ratio of the positive deflection in a complex to the total complex size. These values were averaged for a signal to give the mean polarity ratio. To determine the non-noise level in the signal, the proportion of the total waveform outside a 0.05-mV window centered at 0mV was determined.

Dominant frequency (DF) analysis was performed for the AF points using previously described methods to preprocess electrograms6,17; the signal was bandpass filtered at 40 Hz to 250 Hz, rectified and lowpass filtered at 20 Hz. A Hanning window was then applied to the signal. After this, an 8192 point fast Fourier transform was performed on the signal and the DF determined as the largest peak from 3 Hz to 15 Hz.6 The organization index (OI) was determined from the ratio of the area under the DF peak and its (≤3) harmonic peaks compared with the area under the frequency spectrum.16,18 A 4096 point fast Fourier transform was performed over a 4-s sliding window every second on the processed 8-s signal.19 The OI for each 8-s signal was then derived from the mean of the values for each window. High-DF points were taken as those where the DF was ≥20% the mean DF for that patient.6 To assess if changes in CF affected the frequencies observed in the frequency spectrum, the area under the spectrum, including for frequencies above and below the upper and lower quantiles of the 3 to 15 Hz range respectively, were assessed.

Automated CFAE analysis was performed at each point for persistent AF patients using Carto3 with intervals of interest between deflections specified as a minimum of 70 ms, maximum of 120 ms, and voltage thresholds left at factory settings (0.05 mV–0.15 mV).4 In this analysis, the shortest complex interval (SCI) is the shortest interval between electrogram deflections falling within this range, the average complex interval (ACI) is the average duration of all intervals falling within this range, and the interval confidence level (ICL) is the number of intervals within this range. High-grade CFAE were designated.
as those with an ICL ≥ 7 based on previous validation work comparing automated CFAE measurements with visually assessed electrogram fractionation. As the CFAE analysis was conducted over a 2.5-s window, where CF was compared with CFAE scores, CF data for the same 2.5-s period (rather than the whole 8 s of data collected at a point) were used.

Statistics
Statistical analysis was performed using SPSS (IBM SPSS Statistics, version 20 IBM Corp, Armonk, NY) and Matlab V7.12 with Statistics Toolbox v7.5. P < 0.05 was taken to indicate statistical significance. Data are presented as mean±SD or median (interquartile range). Correlations were assessed using Pearson correlation where the relationship appeared linear and Spearman rank correlation otherwise. Point-Biserial correlation was used to correlate continuous with binary variables. Electrogram complex size data taken as a group at a point were analyzed using a split-plot ANOVA incorporating the starting CF (as a dichotomous variable split at 10 g) and atrial rhythm as between subject factors. Points were excluded from the group if >7 mm displaced from the first point, if no complexes were present or if in SR >1 atrial ectopic was present. Further testing was performed using the Wilcoxon signed-rank test on pairs of points taken at a location to explore the magnitude of any effect observed and further define CF thresholds affecting the electrogram. For the paired analysis, displacement was compared between the pair of points and if this exceeded the above threshold, or if any of the other criteria above were met, the pair was excluded from the paired analysis. In the case of the analysis in pairs, where 4 points had been taken at a location, this would result in 6 pairs for analysis. For this analysis, the pairs were subdivided based on the atrial rhythm, initial CF in a pair and the change in CF between points in a pair. These thresholds were then used to perform analysis in pairs for CFAE and spectral parameter data.

Results
The study patients’ baseline characteristics are presented in Table 1.

CF and the Electrogram
One thousand nine hundred forty-five data points were collected (1396 in AF, 549 in SR, and 59 [37–107] per patient at 19 [10–25] locations), and the spread of CFs is shown in Figure 2B.
There was a significant difference by location for both AF and SR points in complex size (P<0.005 for each; Figure 3). There was a correlation between the polarity ratio of the complexes observed and CF in AF and SR (Pearson correlation, −0.2; P<0.005 for both), such that the complexes became proportionately less positive at higher CF.

To assess whether changing CF at a location was associated with a change in electrogram complex size, the data were analyzed in groups for points taken at the same location. On the basis of the exclusion criteria, this left 471 groups for comparison (340 in AF and 131 in SR). A split-plot ANOVA suggested a significant multivariate effect on the electrogram size with repeated measures by the interaction between the atrial rhythm and initial CF in a group (P<0.005; partial η², 0.126). To further explore the CF thresholds affecting electrogram size, a paired analysis was, therefore, conducted using pairs of points taken at the same location. There were 2518 pairs of CF/electrogram readings (2120 in AF and 398 in SR).

As shown in Table 2, if the starting CF was <10 g, the difference between a pair of electrograms was only significant if the increase in CF between measurements was >4.5 g in SR, but not if the change in CF was below this. If the starting CF was ≥10 g, there was no significant change between pairs, even if the change in CF was >4.5 g. In AF, a similar relationship was found, although in this case, the electrogram only changed significantly at a location when the initial CF was <10 g and the change in CF was ≥8 g and not if the change in CF was below this. For both rhythms, the difference in the response to an increase in CF when the initial CF was <10 g rather than ≥10 g was not explained by a lesser overall increase in the CF in the latter group between measurements as the increase in CF was not significantly different between groups—in other words, there was a similar increment in the CF between measurements in the <10-g and ≥10-g initial CF groups.

The polarity ratio was also subjected to a similar paired analysis. In SR, if CF increased <10 g, there was no difference in the polarity ratio (P=0.23), whereas if there was a 10- to 20-g increase, there was a significant decrease (P=0.016; median change, −7[−23 to 15]%). In AF, if CF changed <10 g, there was a small significant decrease (median change, −1[−15 to 13]%; P=0.002) with a greater decrease if CF increased 10 g to 20 g (median change, −6[−23 to 15]%; P<0.0005). The likelihood of observing at least 1 atrial ectopic in SR during the 8-s electrogram window significantly increased with mean CF, as the increase in CF was not significantly different between groups—in other words, there was a similar increment in the CF between measurements in the <10-g and ≥10-g initial CF groups.

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On subanalysis by location, the correlation between the CF and observation of at least 1 atrial ectopic was strongest at the inferior LA (Point-Biserial correlation, 0.35; P<0.006).

There was a weak positive correlation between the change in CF between points at a location and the change in the number of complexes observed in AF, but only if starting CF was <10 g (Spearman ρ, 0.11; P=0.003), and not if ≥10 g (Spearman ρ P=0.05).

### Contact Force and CFAE

One thousand five hundred forty-nine AF points had automated CFAE parameters recorded. There was a weak negative

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**Table 1. Study Population Baseline Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>No. of patients</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, mean±SD</td>
<td>61±8 y</td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>21 Males (70%)</td>
<td></td>
</tr>
<tr>
<td>Persistent AF</td>
<td>15 (50%)</td>
<td></td>
</tr>
<tr>
<td>Duration of persistent AF</td>
<td>20±12 mo</td>
<td></td>
</tr>
<tr>
<td>CHA₂DS₂-VASc score, mean±SD</td>
<td>1.4±1.0</td>
<td></td>
</tr>
<tr>
<td>Left atrial diameter, mean±SD</td>
<td>4.4±0.6 cm</td>
<td></td>
</tr>
<tr>
<td>Severe left ventricular impairment (ejection fraction &lt;35%)</td>
<td>2 (7%)</td>
<td></td>
</tr>
</tbody>
</table>

AF indicates atrial fibrillation.
The correlation between the CF at a point and the SCI (Spearman ρ, −0.08; P=0.002) and ACI (Spearman ρ, −0.07; P=0.01), and a weak positive correlation with the ICL (Spearman ρ, 0.05; P=0.034). The proportion of high-grade CFAE was 420 of 1549 (27%). High-grade CFAE points had a statistically significant slightly higher CF than non–high-grade CFAE points: high-grade 16.7(10.2–26.2) g, non–high-grade 15.3(9.3–24) g, P=0.034.

The effect of changing CF at a location on CFAE scores was assessed in 2262 pairs of points, Table 3. There was a significant (though small) increase in the ICL score at points where the starting CF was <10 g and change in CF was >8 g (Figure 5). If the change in CF was ≤8 g, there was no significant difference. Conversely, if the starting CF was ≥10 g, there was no significant change in ICL score, even if the CF change was >8 g. There was no significant change in ACI or SCI between pairs of measurements regardless of the initial CF or CF change between pairs of measurements.

**Table 2. Change in Median Complex Size by Atrial Rhythm, Initial CF, and Increase in CF Between Pairs of Measurements at a Location**

<table>
<thead>
<tr>
<th>Rhythm</th>
<th>Initial CF in a Pair, g</th>
<th>&lt;4.5 g SR and &lt;8 g AF</th>
<th>≥4.5 g SR and ≥8 g AF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Change in Mean CF, g</td>
<td>Median Change in Complex Size, %</td>
<td>P Value</td>
</tr>
<tr>
<td>SR</td>
<td>1–10</td>
<td>0.8 (0.4–3.1)</td>
<td>6 (–8 to 34)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>1.7 (0.8–3.1)</td>
<td>3 (–8 to 22)</td>
</tr>
<tr>
<td>AF</td>
<td>1–10</td>
<td>1.8 (0.7–4.4)</td>
<td>0 (–12 to 16)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>2.1 (0.9–4.5)</td>
<td>2 (–13 to 18)</td>
</tr>
</tbody>
</table>

AF indicates atrial fibrillation; CF, contact force; and SR, sinus rhythm.

*P=0.77 and †P=0.08 for comparison of change in CF between pairs in the initial CF <10 g versus ≥10 g groups for each rhythm.
CF and DF

Across all the AF points, the DF was 5.9(5.4–6.6) Hz. There was a significant correlation between DF and ICL (Spearman \( \rho \), 0.14; \( P < 0.0005 \)), and weaker correlations with the SCI and ACI (Spearman \( \rho \), −0.06; \( P =0.04 \), both), as well as between ICL and OI (Spearman \( \rho \), 0.07; \( P =0.02 \)), and the OI with the SCI and ACI (Spearman \( \rho \), 0.12 [SCI], 0.21 [ACI]; \( P <0.0005 \), both). Compared with non–high-grade CFAE points, high-grade ones had a significantly higher DF, although the difference was negligible (high-grade CFAE: 6.1 [5.6–6.8] Hz, non–high-grade: 5.9 [5.2–6.6] Hz; \( P <0.0005 \)), but there was no difference in the OI between CFAE grades (\( P =0.08 \)).

Forty-four points in 10 patients qualified as high-DF points. Median DF for these points was 8.9 (7.8–10.5) Hz. High-DF points were not more likely to be high-grade CFAE points (24% high-DF points were high-grade CFAE, whereas 27% low-DF points were high-grade CFAE points; \( P =0.7 \)).

There was no significant difference in the CF of high-DF points compared with low-DF points (high-DF, 16.4 [11.7–27.4] g; low DF, 16.8 [10.2–24.8] g; \( P =0.6 \)).

There was no correlation between DF or OI with CF (Spearman correlation \( P >0.05 \) for each). There was a negative correlation between CF and the total area under the frequency spectrum (Spearman \( \rho \), −0.1; \( P <0.0005 \)), but a weak positive correlation between the CF and proportion of the spectrum below the lower quartile of the 3 to 15 Hz range (Spearman \( \rho \), 0.06; \( P =0.02 \)). There was no relationship between CF and proportion of the frequency spectrum above the upper quartile of the 3 to 15 Hz range (Spearman correlation \( P =0.2 \)).

A change in CF between pairs of measurements at a location in the 2120 AF point pairs assessed was not associated with a change in the DF or OI, even where initial CF was <10 g and CF change was >8 g, Table 3. In the paired analysis, the proportions of the frequency spectrum above or below the upper and lower quartile respectively were not significantly different, regardless of initial CF or CF change (\( P >0.2 \) for all points).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Initial CF in a Pair, g</th>
<th>Increase in CF Between Paired Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;8 g (Median Change, %)</td>
<td>( P ) Value</td>
</tr>
<tr>
<td>ICL</td>
<td>1–10</td>
<td>0 (−38 to 50)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>0 (−33 to 50)</td>
</tr>
<tr>
<td>SCI</td>
<td>1–10</td>
<td>0 (−10 to 9)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>0 (−8 to 8)</td>
</tr>
<tr>
<td>ACI</td>
<td>1–10</td>
<td>0 (−9 to 9)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>0 (−8 to 9)</td>
</tr>
<tr>
<td>DF</td>
<td>1–10</td>
<td>0 (−4 to 6)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>0 (−6 to 5)</td>
</tr>
<tr>
<td>OI</td>
<td>1–10</td>
<td>1 (−12 to 16)</td>
</tr>
<tr>
<td></td>
<td>≥10</td>
<td>0 (−14 to 16)</td>
</tr>
</tbody>
</table>

ACI indicates average complex interval; CF, contact force; CFAE, complex fractionated atrial electrogram; DF, dominant frequency; ICL, interval confidence level; OI, organization index; and SCI, shortest complex interval.

Table 3. Change in CFAE and Spectral Analysis Measurements at a Location by Initial CF and Increase in CF Between Pairs of Measurements at a Location
Comparisons). The total area under the frequency spectrum was lower when the initial CF was <10 g and change in CF was >8 g (0.003 ± 0.002 mV/s versus 0.005 ± 0.004 mV/s; \( P = 0.003 \)). There was no significant difference for any other starting CF or change in CF (\( P > 0.07 \)).

Catheter Orientation

The effect of catheter orientation was assessed by observing the difference in the electrogram, CFAE, and spectral analysis parameters on changing the catheter from a perpendicular to parallel orientation in a subset of AF points (Table 4). In the case of the electrogram and CFAE pairs, only those where the difference in CF between orientations was <8 g were used to minimize differences secondary to CF for the electrogram analysis because of the influence of CF on these measurements. On changing orientation from perpendicular to parallel, complexes became smaller and more positive but without any change in CFAE or spectral measures.

Discussion

This study examined the relationship between CF and catheter orientation with electrogram parameters. The main findings were:

1. An increase in CF at a location was associated with an increase in the complex size in both AF and SR, but this difference was only apparent if the initial CF was <10 g and for changes in CF >4.5 g in SR and >8 g in AF.
2. Increasing CF at a location was associated with a small increase in ICL scores, although only if the initial CF was <10 g and change in CF was >8 g.
3. Changing the CF at a location did not affect spectral measurements.
4. Changing from a perpendicular to parallel orientation was associated with a reduction in the electrogram complex size and more positive complexes in AF but no change in CFAE or spectral measures.

Catheter Contact and the Electrogram

A previous study used manual assessment of the SR electrogram around the PV antra, averaging 5 complexes per location and found a modest relationship between CF and electrogram amplitude.10 In another study, a weak relationship was found between these parameters throughout the LA in paroxysmal AF patients, around half of whom were in AF, although the authors did not give details of how the electrogram parameters were measured.11 This study examined this relationship in both AF and SR throughout the LA, using automated analysis of 8 s of electrogram data at each location. No relationship between electrogram complex size and CF was observed, probably because of the much larger effect of LA location on complex size.

Table 4. The Change in Electrogram Properties With a Change in Catheter Orientation Between Measurements Taken at the Same Location

<table>
<thead>
<tr>
<th>Group (Measure)</th>
<th>Catheter Orientation</th>
<th>Median Change</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrogram (70 pairs)**</td>
<td>Perpendicular</td>
<td>0.026 (0.019–0.03)</td>
<td>–13.4%</td>
</tr>
<tr>
<td></td>
<td>Parallel</td>
<td>0.023 (0.017–0.027)</td>
<td></td>
</tr>
<tr>
<td>Proportion of signal &gt;0.05-mV noise window (%)</td>
<td>Perpendicular</td>
<td>37.2 (24.4–42.8)</td>
<td>–12.5%</td>
</tr>
<tr>
<td></td>
<td>Parallel</td>
<td>32.6 (19.4–39.8)</td>
<td></td>
</tr>
<tr>
<td>Median complex size (mV)</td>
<td>Perpendicular</td>
<td>0.144 (0.111–0.206)</td>
<td>–5.1%</td>
</tr>
<tr>
<td></td>
<td>Parallel</td>
<td>0.137 (0.095–0.19)</td>
<td></td>
</tr>
<tr>
<td>No. of complexes</td>
<td>Perpendicular</td>
<td>36 (15–45)</td>
<td>–32.4%</td>
</tr>
<tr>
<td></td>
<td>Parallel</td>
<td>24 (17–38)</td>
<td></td>
</tr>
<tr>
<td>Polarity ratio</td>
<td>Perpendicular</td>
<td>0.48 (0.4–0.59)</td>
<td>17.3%</td>
</tr>
<tr>
<td></td>
<td>Parallel</td>
<td>0.57 (0.45–0.63)</td>
<td></td>
</tr>
<tr>
<td>Dominant deflection angle (°)</td>
<td>Perpendicular</td>
<td>12.5 (8.4–15.6)</td>
<td>13.2%</td>
</tr>
<tr>
<td></td>
<td>Parallel</td>
<td>14.1 (11.3–15.7)</td>
<td></td>
</tr>
<tr>
<td>CFAE (98 pairs)**</td>
<td>SCI</td>
<td>75 (71–84)</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>ACI</td>
<td>93 (87–98)</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>ICL</td>
<td>5.5 (4–7)</td>
<td>3%</td>
</tr>
<tr>
<td>Spectral analysis (140 pairs)</td>
<td>DF (Hz)</td>
<td>5.7 (5.2–6.3)</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>OI</td>
<td>0.18 (0.16–0.2)</td>
<td>6%</td>
</tr>
</tbody>
</table>

ACI indicates average complex interval; CF, contact force; CFAE, complex fractionated atrial electrogram; DF, dominant frequency; ICL, interval confidence level; OI, organization index; and SCI, shortest complex interval.

*Difference in CF for a pair ≤8 g, resulting in no significant difference in CF between measurements at the 2 orientations (Electrogram group: perpendicular 16.8(13.4–24.1) g, parallel: 15.7(10.6–25.5) g; \( P = 0.2 \) and CFAE group: perpendicular 15.9(11.6–23.8) g, parallel: 15(10.8–23.3) g, \( P = 0.5 \).
One would expect that the thickness of the tissue under the catheter and its compliance affect the size of the electrogram; a larger mass of tissue produces a larger electrogram, and a more compliant area would deform around the catheter tip to contact the bipoles more effectively. The thickness of the tissue around the LA and the compliance of different parts of the LA are known to differ. During an ablation procedure, the whole of the atrium is potentially mapped and ablated and, therefore, our data conforms with previous work suggesting electrogram size cannot be used as a reliable surrogate for real-time CF measurement in either AF or SR. One reason being the difference in the electrogram based purely on location as reported here. This study developed the electrogram analysis further although by studying repeated measures of electrogram parameters at constant locations, allowing greater understanding of the impact of changes in CF (controlling for baseline differences in parameters).

The morphology of the bipolar electrogram was affected by CF, with complexes becoming more negative at higher CF. This may be a function of the proximal bipole having increased contact with the tissue at higher CF (study points were generally taken in a perpendicular orientation). Interestingly, when the catheter was changed from a perpendicular to parallel orientation (whereby the proximal pole would have a similar degree of contact to the distal), complexes became more positive: at the same time, there was also a reduction in electrogram complex size (including when changes in CF between measurements were minimized to address any confounding from this). This suggests that for a bipole, it is not just the degree of contact that affects both the size and morphology of the observed complexes but also its orientation.

The influence of CF changes on the electrogram is an important consideration, especially where mapping studies are conducted with electrodes at a stable position for a prolonged period of time within the LA, such as recent work with rotor mapping where electrograms are collected for >10 minutes. Moreover, the effect of a change in CF and catheter orientation on the electrogram is an important consideration when comparing pre-and postablation electrograms to judge ablation efficacy based on electrogram morphology changes (criteria which have been used to guide clinical ablation). Data from this study suggest mapping with a CF ≥10 g of force would minimize CF-related electrogram changes, as would ensuring the difference in CF between apical regions of the electrogram are ≤4.5 g in SR and ≤8 g in AF. The higher threshold in the case of AF signals is likely secondary to the higher intrinsic variance in the AF electrogram making CF-related changes harder to appreciate.

The observation of increased atrial ectopy in SR at higher CF is consistent with findings of increased excitability of atrial tissue from global atrial stretch in animal models and humans, as well as the observation of stretch-induced depolarizations of human myocytes. It is also consistent with the increased susceptibility to AF in those with hypertension. The differential locational vulnerability to stretch induced ectopy suggested by this study is interesting and may reflect the electromechanical sensitivity of the tissues themselves: the inferior wall demonstrated the strongest correlations between CF and ectopic incidence. It may also be that nearby structures are being affected by the stretch stimulus from the catheter, for example the inferior right and left ganglionated plexi are in proximity to the inferior wall. One would expect points taken within PVs would demonstrate even higher ectopic vulnerability in view of these being common trigger sites for paroxysmal AF (in this study, points were taken at the antra rather than deep within the PVs, hence this was not assessed).

Interestingly, at the 10-g CF level, there was a change in the tissue behavior—ectopics were more frequently observed >10 g of CF than below this threshold. This also seems to be a threshold for observing an effect on the electrogram from a change in CF, and may relate to the electric or compliance properties of the tissue changing above this threshold. At a CF below 10 g, the tissue may not be particularly stretched and, therefore, exhibits less ectopics and incompletely envelops the catheter bipole. The tissue has capacity for stretching and, therefore, if from this point CF increases, more stretch-related activations manifest and the tissue becomes more closely apposed to the bipole. If the starting CF is ≥10 g, the tissue is likely already enveloping the bipole to an extent that further increases in CF make little difference to this and so the electrogram. Moreover, the excitability threshold for stretch-related activations has already been exceeded, so further CF increases have little effect on further increasing the frequency of ectopy.

Catheter Contact and CFAE Parameters

There was a weak relationship between automated CFAE scores and CF, with the scores suggesting higher CF was associated with greater fractionation. Increasing CF at a location may be associated with an increase in the detection of low amplitude deflections by the automated CFAE algorithms—an increase in CF was associated with an increase in mean electrogram waveform size with more of the electrogram outside of the noise window. In this sense, the initial CFAE recorded with low CF represents an artificial distortion because of poor contact (with less of the signal appreciated by the automated analysis than is actually present). Alternatively, it may be that increasing CF is associated with increasing tissue stretch and is directly causing an increase in activations and, therefore, influencing CFAE measurements in this manner. Importantly, the relationship between CFAE score and CF was no longer apparent if the starting CF was ≥10 g. It is, therefore, possible that a proportion of the variation previously observed in CFAE maps is contributed to by changes in catheter CF during mapping.

Catheter Contact and Spectral Analysis Parameters

A relationship between DF measurements and CFAE scores has previously been observed. As observed here, regions harboring CFAE have also previously been noted to be more extensive than those with high DF. Previous investigators have noted that fractionated electrograms tend to occur adjacent to high-DF areas rather than directly superimposed on them. The latter is the probable explanation for high-DF points not being significantly more likely to be high-grade CFAE points in this study.
The area under the frequency spectrum reduced with increasing CF, suggesting a less noisy signal. Increasing CF was not correlated with any other general changes in the frequency spectrum and neither did changing CF (or catheter orientation) affect DF or OI measurements. The changes in complex morphology and size secondary to changes in CF would not be expected to affect a frequency-based analysis. An increase in the number of activations observed in a time period as observed here with increasing CF (and having a small effect on CFAE measurements) evidently does not affect spectral analysis parameters. This may be because such extra activations are not consistent enough to have a significant effect in the frequency domain. The lack of change in the LA electric substrate as measured by spectral analysis suggests the increase in CFAE scores with an increase in CF may be more related to improvements in the measurement of the electrogram rather than changes in the electric properties of the substrate. Therefore, the temporal instability observed in DF maps is not explained by differences in mapping CF.

Conclusions
Changes in catheter CF and orientation affect electrogram complex size and morphology, and this most probably reflects changes in the physical relationship between the catheter bipoles and atrial tissue. Complex size is not affected by increases in CF if the starting CF is ≥10 g or if the change in CF is ≤8 g in AF. Higher CF is also associated with atrial ectopy, likely thorough stretch-sensitive depolarizations, and this has a greater effect for CF ≥10 g (potentially of importance for activation mapping). CFAE parameters are affected by CF (again, if the initial CF is ≤10 g), whereas spectral analysis parameters are unaffected by this or catheter orientation. This suggests that in AF, the measurement of the electrogram is predominantly being affected by CF, through greater contact between the bipole and the tissue, without greatly affecting the underlying substrate (based on the lack of impact on spectral parameters). Therefore, during mapping of the LA (and electrogram-guided ablation), it is important to be aware of the effects of CF and catheter orientation as these influence the results: conversely, substrate-based ablation targeting spectral parameters is unaffected by catheter contact and orientation. On the basis of these results, an optimal CF during electrogram mapping of ≥10 g is suggested, as below this value the CF has a significant influence on the electrogram and CFAE scores.

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