Tracking Rotors With Minimal Electrodes
Modulation Index–Based Strategy

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Background—High-frequency periodic sources during cardiac fibrillation can be detected by phase mapping techniques. To enable practical therapeutic options for modulating periodic sources (existing techniques require high density multielectrode arrays and real time simultaneous mapping capability), a method to identify electrogram morphologies colocalizing to rotors that can be implemented on few electrograms needs to be devised.

Method and Results—Multichannel ventricular fibrillation electrogram data from 7 isolated human hearts using Langendorff setup and intraoperative clinical data from 2 human hearts were included in the analysis. The spatial locations of rotors were identified using phase maps constructed from 112 electrograms. Electrograms were analyzed for repeating patterns and discriminating signal morphologies around the locations of rotors and nonrotors were identified and quantified. Features were extracted from the unipolar electrogram patterns, which corroborated well with the spatial location of rotors. The results suggest that using the proposed modulation index feature, and as low as 1 sample point in the vicinity of the rotors, an accuracy as high as 86% (P<0.001) was obtained in separating rotor locations versus nonrotor locations. The analysis of bipolar electrogram signatures in the vicinity of the rotor locations suggest that 62.5% of the rotors occur at locations where the bipolar electrogram demonstrates continuous activities during ventricular fibrillation.

Conclusions—Unipolar electrogram extracted modulation index–based detection of rotors is feasible with few electrodes and has greater detection rate than bipolar approach. This strategy may be suitable for nonarray-based single mapping catheter enabled detection of rotors. (Circ Arrhythm Electrophysiol. 2015;8:447-455. DOI: 10.1161/CIRCEP.114.002306.)

Key Words: catheter ablation ■ entropy ■ modulation index ■ rotors ■ ventricular fibrillation

Ventricular fibrillation (VF) is a lethal cardiac arrhythmia and a major cause for sudden cardiac death. Catheter ablation of triggers of VF has been attempted, based on purkinje-like potentials that precede ectopic beats. However, targeting mechanisms and substrates that maintain early VF after the onset of VF has not been attempted and this strategy may have implications for reducing vulnerability to VF and incidence of multiple high voltage shocks from implantable defibrillators in structurally abnormal hearts. Previous studies in vivo and ex vivo human VF using multielectrode electric and optical mapping in myopathic human hearts have revealed organization of electric activity in the form of rotors and that these rotors are limited in number. In this journal, we previously presented the theory of a method based on phase mapping to identify the location of rotors that may provide clinicians a target to modulate rotors. In the existing methods using phase map and those methods that involve the deployment of an array catheter, the critical requirement of spatial resolution versus rotor detection accuracy is debatable.

If modulating rotors is to be tested and is to become a practical therapeutic strategy to be translated into the hands of practical electrophysiologist, then it is necessary to identify the unipolar and bipolar electrogram characteristics of rotor vicinity with a few electrodes on an ablating catheter. This strategy would be practical for clinician such that rotors can be detected using fewer electrograms acquired using mapping catheters as opposed to array catheters. However, the paradigm of identifying rotor core vicinity in human hearts, especially in relation to limited electrograms morphologies using nonarray-based approach that can be easily used by clinicians in the ablation arena, has not been explored in detail for human hearts.

The occurrence of rotors during the course of an arrhythmia may potentially create particular electrogram signatures with varying degree of electrogram organization. One signature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential nature that is commonly observed is the double potential
WHAT IS KNOWN

- Previous studies in in vivo and ex vivo human ventricular fibrillation using multielectrode electric and optical mapping in myopathic human hearts have revealed organization of electric activity in the form of rotors and that these rotors are limited in number.
- Contemporary multielectrode array and inverse solution-based tracking of rotors are limited by spatial resolution/interpolation issues, inappropriate phase transformation and filtering that hamper realistic mapping of cardiac fibrillation and tracking of true rotors for practical therapeutic options.

WHAT THE STUDY ADDS

- By analyzing commonly repeating electrogram patterns and identifying signal morphologies around the location of rotors and nonrotors, we have developed a modulation index–based method for detecting rotors using unipolar electrograms acquired during human ventricular fibrillation.
- The proposed modulation index–based method performed well in determining the proximity to rotors for the given human ventricular fibrillation database, demonstrating high potential for therapeutic options.
- This method was further validated by mathematical modeling in tissue thickness that was similar to the atria, and thus might be applicable to atrial fibrillation.

significance of the amplitude variation in the electrogram, and in particular its importance in the timing of the defibrillation shock. A recent study by our group had highlighted the occurrence of particular signatures in the surface ECG that could possibly be related to different levels of organization of ventricular arrhythmias. Therefore, in this article, we test the hypothesis that features extracted from single unipolar and bipolar electrogram morphologies can indicate the spatial locations of the rotors.

Methods

Human Heart-Simulated models
Computer simulations were performed to validate the hypothesis that signal morphologies in electrograms during VF could indicate spatial locations of the rotors. The Luo–Rudy 1 model was used to generate rotors with various levels of complexity by altering parameters as previously described. Four conditions were generated: a single stationary rotor, a single migratory rotor, 2 stationary rotors, and multiple rotors that broke down and randomly migrated. Simulations were performed on a 6x6 cm sheet with unipolar electrograms computed on a 10x10 array covering the sheet located 1.1 mm above the surface. Ten second long signals sampled at 1000 samples/s were generated. Since rotors formed within 1 s, only the last 9 s were analyzed.

Human Ex Vivo and In Vivo models
Electric mapping data from (n=9) patients were used in this study. Of these patients, 7 isolated human hearts, in which VF was induced, and 2 patients who had intraoperative ventricular tachycardia (VT) studies that degenerated to VF were used for the analysis of this study. Clinical characteristics of these patients are presented in the Results section of this article.

Ex Vivo VF Mapping
The experimental protocol for acquiring multichannel electrogram data from explanted human hearts using a Langendorff setup has been outlined previously in our works. Informed consent was obtained from each patient and was approved by University Health Network, Toronto, Canada. An electrode array with 112 unipolar and 112 bipolar silver bead electrodes was used for acquiring the electrograms. The arrangement of the electrodes on a two-dimensional surface is shown by black circles in the right bottom corner of Figure 1, where the center corresponds to the apex location of the heart. The multichannel

Figure 1. Top, Sample unipolar and bipolar electrograms acquired during human ventricular fibrillation. Bottom left, Sample phase map snapshot indicating the location of a phase singularity with a small rectangular box. Bottom right, Electrode placement (small circles, 13 arms with 8 electrodes in each arm) on the array.
electrograms were recorded in 10-s segments with a sampling rate of 1000 samples/s. The unipolar electrograms also had its filter settings between 0.5 and 200 Hz, whereas the bipolar electrograms were filtered between 28 and 700 Hz. More details on the acquisition and Langendorff setup are available in our previous work.4

In Vivo VF Mapping Intraoperatively
In addition to the ex vivo data set, we included clinical in vivo VF data from 2 patients in this study. These were patients who underwent intraoperative VT mapping. During the procedure of VT induction via rapid burst pacing, unintentionally the VT degenerated into disorganized VF. These unintentional VF episodes that were recorded were analyzed and segments that were after 1 s of the onset of VF were included in this study. We had analyzed electrograms for DF, scar maps, and published4 data from these 2 patients for another study; however, we had not analyzed data for unipolar and bipolar rotor signatures. Electrograms were acquired using the same 620 channel acquisition system as explained in the previous section (ex vivo VF mapping). More details on the acquisition are available in our previous work.4

New sock and balloon electrode arrays (consisting of an array of 112 unipolar and 112 bipolar electrode locations) were used for each of the patients. We included 2 independent VF segments (1 from both epicardium and endocardium and 1 from endocardium) from clinical data. The first independent VF segment was 2.24 s in length and the other independent VF segment was 3.76 s in length.

Phase Maps
In constructing all the above maps, data interpolation was used. Phase maps were generated for locating and tracking rotors as described previously.4 Briefly, at every time sample point we recorded 112 spatial points of electric activity, which were interpolated to create a much finer grid of spatially distributed pseudo electrogram data. These pseudo interpolated electrograms along with the 112 original electrograms were preprocessed and filtered to remove high- and low-frequency artifacts. The data were then used to extract phase information using the Hilbert Transform approach. The phase information over all these spatial points for each of the sample point in time served as a snapshot of the overall phase changes happening at that particular sample instant. When these snapshots for the sample points in time were played as a movie, they show the dynamic phase changes of the electric data

$MI = \frac{A_E}{A_C}$

where $A_E$ is the envelope amplitude and $A_C$ is the carrier amplitude.

Figure 2. Top, Modulation index using a synthetic signal example. Middle, Similar signal morphologies in an electrogram in the vicinity of a rotor during human ventricular fibrillation (VF). Bottom, An electrogram not in the vicinity of a rotor during human VF. MI indicates modulation index.

Figure 3. Left, Sample phase map snapshot with circles indicating the location of rotors. Right, Corresponding averaged modulation index map. Circles indicate the corresponding locations of rotors shown in left panel.
during the entire epicardium or endocardium. A rotor is then identified if the phase pattern rotates at least twice around a phase singularity point. These phase maps served as a ground truth to compare with the proposed methodology of identifying rotor locations.

Modulation Index

Analyzing the electrograms around the rotors locations, we observed few repeating signal patterns, of which one of the patterns demonstrated a strong amplitude modulation (AM) effects, which is reflected in the repeated and rhythmic amplitude variations of the electrogram amplitudes. AM is a well-known concept in radio frequency communication systems, where message data (e.g., speech, etc.) is used to modulate a high-frequency carrier signal to send it across long distances wirelessly. The amount of variation generated by the message signal to the carrier signal’s amplitude is quantified by the term called modulation index (MI), and it is given in the following equation:

$$\text{MI} = \frac{A_E}{A_C}$$  \hspace{1cm} (1)

From Equation 1, the term $A_E$ refers to the envelope amplitude and $A_C$ refers to the carrier amplitude. Similar to wireless communication, during VF, if rotors are considered to be few dominant but periodic sources that modulate the electric activity, then this rhythmic variation should be reflected in the amplitude of the electrograms acquired during VF. In Figure 2, the top panel shows a synthetic example of AM. The middle and bottom panels show patterns depicting AM both at the vicinity of rotor and nonrotor locations, respectively. As it could be seen, the locations closer to rotors exhibit stronger AM than the nonrotor locations. This is logical in the sense that if there is a rhythmic periodic rotational activity, it is supposed to influence the underlying electric activity rhythmically changing its amplitude. To quantify this, we use the average MI in Equation 3 for each envelope peak (pk).

$$\overline{\text{MI}}_{pk} = \frac{\sum_{x=1}^{N} \text{MI}_x}{N}$$  \hspace{1cm} (2)

$$\overline{\text{MI}} = \frac{1}{N} \sum_{x=1}^{N} \text{MI}_x$$  \hspace{1cm} (3)

Similar to capturing the phase information using the Hilbert Transform, the envelope is captured by taking the absolute of the complex-valued signal. The calculation of the MI at a given time instance (Equation 2) can highlight electrograms with stronger AM. Regions in the epicardium and endocardium having an AM throughout the electrogram will be correlated with a region having a high average MI. For validations of the occurrence of AM in the electrogram, a simulated set of rotors were generated, where 5 electrograms around the rotor location and 5 electrograms that were not in the vicinity of a rotor were extracted. Furthermore, to simulate a clinical setup, where we only have access to few electrograms at a given time, we computed the average MI using 5, 3, 2, and 1 spatial location(s) around the rotor and nonrotor locations in the phase maps generated using electrograms acquired from ex vivo and in vivo human hearts during VF. Figure 3 shows the distribution of the average MI over all the spatial locations for demonstration purpose (although only few will be used in the analysis later). As it could be observed, there are areas with high and low MI indicating the distribution of dynamic changes over the spatial locations.

Entropy

Although many existing studies (including our previous studies) did demonstrate strong correlation between spatial organization to

<table>
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<tr>
<th>Groups</th>
<th>MI</th>
<th>Entropy</th>
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<tbody>
<tr>
<td>Vicinity of Rotor</td>
<td>14*</td>
<td>11*</td>
</tr>
<tr>
<td>Away From Rotor</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>20</td>
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Table 1. Average MI and Entropy Features: Cross-Validated Results for Simulated Electrograms Using Luo–Rudy 1 Cardiac Model

Table: 

<table>
<thead>
<tr>
<th>Groups</th>
<th>MI</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>20</td>
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</table>

MI indicates modulation index. * indicates the number of correctly classified samples.
rotors, we also attempted to quantify this using another information theory measure: entropy. Entropy has been previously used by many existing works in cardiac fibrillation. Essentially, we try to quantify the randomness in the distribution of the data, in our case, the electrogram amplitude. Depending on the organization of the electrogram data, we could quantify this using entropy. To calculate the entropy of an electrogram, the distribution of the signal values was required. The histogram is used to approximate the probability density \( P \).\(^{19}\) To calculate the probability density, the amplitude of the electrogram was first sorted into 256 bins and then the counts in the bins were divided by the total count in all 256 bins. The Shannon entropy \( (\text{ShEn}) \) can be defined as given by Equation 4.

\[
\text{ShEn} = - \sum_{i=0}^{255} P_i \log_2(P_i) \tag{4}
\]

The Shannon entropy is expected to be low in electrograms that have a narrow distribution (ie, most of the signal’s amplitude is distributed over a few bins). Conversely, an electrogram that has a broad distribution of its amplitude will have higher Shannon entropy. For comparison purposes of this approach with the MI, we extracted this feature for the same set of simulated electrograms and the same 5, 3, 2, and 1 spatial location(s) in the phase maps generated using electrograms acquired from ex vivo and in vivo human hearts during VF as selected for the MI analysis.

Bipolar Signatures of Rotors

We also included specific signatures of bipolar electrograms in our analysis in the vicinity of the rotors. If we could also correlate bipolar pattern to rotors, then visually we will be able to locate rotors using bipolar electrograms in the clinical setting. We analyzed the bipolar electrograms of all the hearts under study over the 112 electrodes in epicardium/endocardium and chose 7 most common patterns that we observed frequently. We have presented the 7 patterns (normal, alternans, continuous activity, wide complex, multiple components, intermittent, and rapid) in Figure 4. Each of these patterns correlation was verified to the bipolar electrograms in the close vicinity of the rotors.

Pattern Classification

To evaluate if the identification of rotor and nonrotor locations can be automated, we tested the proposed features in a linear discriminant analysis-based classifier.\(^{20}\) In this classifier, a portion of the database is fed as a training set, where the classifier learns and arrives at a discriminative boundary and classifies the testing set (with no label) into groups. The accuracy is determined based on how many of the testing set is correctly grouped against the ground truth.

Results

Ex Vivo: The 7 isolated human hearts used in this study were explanted from patients undergoing heart transplant. Four of the hearts had a diagnosis of dilated cardiomyopathy and 3 had ischemic cardiomyopathy. The mean left ventricular ejection fraction was 25% before explanation. Five of the 7 patients were not on antiarrhythmic drugs at the time of cardiac transplantation other than \( \beta \)-blocker. Two of the patients were on amiodarone.

In Vivo: Two patients who underwent intraoperative VT mapping, whose VT degenerated into VF, were included in the study. All patients underwent VT mapping for ischemic cardiomyopathy with refractory ventricular arrhythmia.

Correlation of Rotors With MI and Entropy

Using the phase maps, sample points around rotor and nonrotor locations were randomly chosen for the analysis. From the simulated heart model, 5 electrograms in the vicinity of the

<table>
<thead>
<tr>
<th>Groups</th>
<th>MI—5 Sample Points</th>
<th>Entropy—5 Sample Points</th>
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<tbody>
<tr>
<td></td>
<td>VICINITY OF ROTOR</td>
<td>AWAY FROM ROTOR</td>
</tr>
<tr>
<td>VICINITY OF ROTOR</td>
<td>64*</td>
<td>16</td>
</tr>
<tr>
<td>AWAY FROM ROTOR</td>
<td>9</td>
<td>71*</td>
</tr>
<tr>
<td>OVERALL</td>
<td>84.4% of cross-validated grouped cases correctly classified</td>
<td>77.5% of cross-validated grouped cases correctly classified</td>
</tr>
</tbody>
</table>

MI indicates modulation index. * indicates the number of correctly classified samples.
Table 3. Average MI Feature: Cross-Validated Results for 3, 2, and 1 Locations in the Phase Map Generated Using Electrograms Acquired From Ex Vivo and In Vivo Human Hearts During Ventricular Fibrillation

<table>
<thead>
<tr>
<th></th>
<th>MI—3 Sample Points</th>
<th>MI—2 Sample Points</th>
<th>MI—1 Sample Point</th>
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<tbody>
<tr>
<td></td>
<td>Vicinity of Rotor</td>
<td>Away From Rotor</td>
<td>Total</td>
</tr>
<tr>
<td>Vicinity of Rotor</td>
<td>39*</td>
<td>9</td>
<td>48</td>
</tr>
<tr>
<td>Away from Rotor</td>
<td>5</td>
<td>43*</td>
<td>48</td>
</tr>
<tr>
<td>Overall</td>
<td>85.4% of cross-validated grouped cases correctly classified</td>
<td>84.4% of cross-validated grouped cases correctly classified</td>
<td>84.4% of cross-validated grouped cases correctly classified</td>
</tr>
</tbody>
</table>

* indicates modulation index. * indicates the number of correctly classified samples.

Table 4. Entropy Feature: Cross-Validated Results for 3, 2, and 1 Locations in the Phase Map Generated Using Electrograms Acquired From Ex Vivo and In Vivo Human Hearts During Ventricular Fibrillation

<table>
<thead>
<tr>
<th></th>
<th>Entropy—3 Sample Points</th>
<th>Entropy—2 Sample Points</th>
<th>Entropy—1 Sample Point</th>
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<tbody>
<tr>
<td></td>
<td>Vicinity of Rotor</td>
<td>Away From Rotor</td>
<td>Total</td>
</tr>
<tr>
<td>Vicinity of Rotor</td>
<td>36*</td>
<td>12</td>
<td>48</td>
</tr>
<tr>
<td>Away from Rotor</td>
<td>6</td>
<td>42*</td>
<td>48</td>
</tr>
<tr>
<td>Overall</td>
<td>81.3% of cross-validated grouped cases correctly classified</td>
<td>79.7% of cross-validated grouped cases correctly classified</td>
<td>81.3% of cross-validated grouped cases correctly classified</td>
</tr>
</tbody>
</table>

* indicates the number of correctly classified samples.

rotor and away from the rotor were analyzed. From the ex vivo and in vivo hearts, as only fewer electrograms are accessible in a clinical setup using catheters, we tested 5, 3, 2, and 1 location(s) randomly chosen around the core of the rotors (≈2 cm radius) and nonrotor locations. So, for example, for the 16 rotors used in this analysis, if each was sampled with 5 neighboring locations, it will result in 80 points spatially or 80 electrograms. Similarly, 80 points of nonrotor locations were chosen for comparative analysis. Each of the electrograms was preprocessed, filtered, and the MI and entropy features were computed, or testing the statistical difference in group means, we performed a 1-way ANOVA test and observed both features demonstrating significance. Following this, we performed automatic pattern classification to validate that these features could be used in an automated fashion to detect rotor locations. We used leave-one-out cross-validation method, which is a better approach to validate the results when the database is small. Table 1 and Figure 5 show the cross-validated results and box plot for the simulated electrograms (5 points in the simulated case). Tables 2–4 and Figures 6 and 7 show the cross-validated results and the box plot for the human heart electrograms (5, 3, 2, and 1 points in the ex vivo and in vivo case). Table 1 indicates that the MI feature has a classification accuracy of 72.5% and the entropy feature has a classification accuracy of 60% for the simulated electrograms. As could be seen from the Tables 2–4 for the ex vivo and in vivo electrograms, the MI feature achieved classification accuracies in the ranges of 84% to 86%, whereas the entropy resulted in classification accuracies in the ranges of 77% to 82% for the 5, 3, 2, and 1 sample point(s) around the rotor and nonrotor locations. These results have been summarized in Tables 5 and 6. The MI feature, in comparison with the entropy feature, was less influenced by changes in the number of sample points and also demonstrated balanced sensitivity and specificity.

**Bipolar Rotor Signatures**

We analyzed the rotors to identify bipolar patterns that can be associated with them. As explained in the Methods section of this article, we chose 7 most common bipolar patterns during VF (shown in Figure 4) and studied their correlation with the electrograms in the close vicinity of the rotors. We found that in most cases, the bipolar electrograms demonstrate continuous activity (10 instances) in the vicinity of the rotors followed by multiple components (6 instances) and wide complex patterns (4 instances). There were 4 instances of alternans and 1 instance of intermittent pattern that correlated with the rotor locations. It was also observed that a combination of these patterns had occurred in different electrograms that were in the vicinity of a rotor in some of the cases. There was no correlation observed with rapid bipolar pattern. Although the continuous activity can be considered to have high frequencies, it is sufficiently low in amplitude (like noise) and not periodic, and thus does not fall into the categorization of rapid bipolar activity and high-frequency periodic sources as suggested in the optical mapping literature.21

**Reverse Correlation: Bipolar Signatures and Phase Maps**

We also performed a reverse correlation to identify the relation between the bipolar electrogram signatures and the corresponding activity in the phase maps independent of rotors. We chose to compare the 3 patterns that physiological plausibility of rotor vicinity (multiple components, continuous activity, and rapid). The first 2 patterns are top scorers in the previous analysis with rotors, and we added the rapid pattern because there was no correlation with rotors and we were intrigued to identify what these rapid bipolar locations correspond to in the phase maps. We classified the corresponding...
locations in the phase map to the above 3 patterns into either rotor-like activity but not rotors (if there is a single phase singularity and a rotational component, however, not sufficient to be classified as rotors) or multiple-wavelet-like activity (if there were multiple phase singularities and collision of multiple wavefronts). In some of the episodes, both activities (in the phase map) were observed in different electrode locations of the same bipolar pattern. We found in 8 instances continuous activity bipolar patterns correspond to rotor-like activity in the phase maps and 3 correspond to multiple-wavelet activity; 8 instances of multiple component bipolar patterns correspond to rotor-like activity in the phase maps and 3 correspond to multiple-wavelet activity; 2 instances of rapid bipolar pattern correspond to rotor-like activity in the phase maps and 5 correspond to multiple-wavelet activity. These results again reiterate that the correlation of rapid bipolar patterns with rotor or rotor-like activities is poor, whereas the continuous activity and multiple components seem to support both rotor-like (mostly) and multiwavelet-like activities.21

Figure 6. Box plots of comparative analysis of the modulation index and entropy features near and far from rotors for 5 sample points for the ex vivo and in vivo data.

Figure 7. Box plots of comparative analysis of the modulation index (MI) and entropy features near and far from rotors for 3, 2, and 1 sample point(s) for the ex vivo and in vivo data.
Predicting Rotor Sites Without Induction of VF

Because a majority of the rotor locations exhibited continuous activity in the bipolar electrograms in comparison with other bipolar signatures, we used these locations of bipolar electrograms to analyze if there are any notable characteristics of these locations before the onset of VF. This exercise was performed to identify signal morphologies during paced rhythm, which could serve as a predictor for rotor preponderance such that locations of interest could be identified without subjecting the patient to mapping during VF. Out of the 16 rotor locations, we observed wide complex bipolar signature in 4 of the corresponding (and surrounding) sinus rhythm electrograms. Figure 8 shows a sample electrode location that exhibits continuous activity during VF and the same location in sinus rhythm exhibiting wide complex bipolar electrogram.

Discussion

In our study, we evaluated early human VF, to verify if there are quantifiable unipolar and bipolar electrogram characteristics that might assist in identifying rotor vicinity from limited number of electrograms. We identified that MI-based detection of rotors using features extracted from limited unipolar electrograms could be of potential value in providing insights and suggestions on target locations for substrate-based ablation for early human VF. More importantly, we demonstrate that this unipolar electrogram–based strategy was superior to bipolar electrogram patterns and may be suitable for single mapping catheter-based detection of rotor core vicinity.

MI and Entropy Markers for Rotor Localizations

The proposed MI-based marker demonstrates significant potential in tracking rotors using as low as 1 electrode location. This result was also validated by cardiac modeling simulations. In addition, the morphological signature of the MI will serve as a visual feedback to clinicians while tracking rotors. MI features are extracted per electrogram individually; hence this approach is more suitable for nonarray and single catheter mapping techniques than conventional spatial mapping approaches. Also, because MI computation is performed on selected spatial locations it could be implemented in near real time. This also allows the possibility of generating quick global maps and then narrowing the search on finer grids. MI markers are representative of amplitude and frequency signal modulation of electrograms during VF, and the dynamic variation of these patterns could be of interest for mechanistic insights or sub classifying events during VF. On the basis of the results presented, entropy markers did perform comparatively similar (although with unbalanced sensitivity and specificity) to MI markers. However, they lack meaningful morphological signature like MI markers, which could be vital to clinicians as visual feedback of pattern while tracking rotors in real time during an ablation procedure.

Bipolar Signature of Rotors

On the basis of the analysis we performed, we classified 7 different bipolar patterns that occurred more frequently in the electrograms during VF and correlated them to the vicinity of rotor locations. We observed a higher correlation with the bipolar pattern with continuous activity, which augments some of the findings of existing studies (including ours) on fractionated electrograms and atrial fibrillation. Interestingly, we did not observe a correlation of rotor locations with (rhythmic) rapid bipolar patterns. Our data show that in 62.5% of the cases, rotor occurs in locations where the bipolar electrogram exhibit continuous activities and the correlation between rotors and the location of rapid bipolar electrograms is poor. A reverse correlation of most frequently occurred bipolar patterns with corresponding phase patterns indicate that continuous activity and multiple components seem to support both rotor-like (mostly) and multiple-wavelet–like activities.

Limitation

The assumption made by the MI feature is that there are enough time samples accumulated (with sufficient time resolution) to identify the occurrence of an AM within the electrogram. The MI feature identifies possible rotor locations by analyzing the electrogram over time, therefore, requiring sufficient time resolution, which is easily accommodated by modern digital acquisition systems.

Conclusions

Human VF data obtained from patients in vivo and from isolated human hearts point to specific unipolar MI-based characteristic suggestive of rotor vicinity during VF. The proposed MI-based features indicate significant potential for tracking rotors and especially suitable for realistic nonarray and single catheter–based mapping approach that is not limited by interpolation and resolution errors that limit array-based methods. These findings form the basis of a mechanism-based strategy for architectural deduction of phase singularities in the clinical arena.

Table 5. MI Results Summary

<table>
<thead>
<tr>
<th>MI—Simulated Electrograms, %</th>
<th>MI—5 Electrograms, %</th>
<th>MI—3 Electrograms, %</th>
<th>MI—2 Electrograms, %</th>
<th>MI—1 Electrogram, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>72.50</td>
<td>84.40</td>
<td>85.40</td>
<td>84.40</td>
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</table>

MI indicates modulation index.

Table 6. Entropy Results Summary

<table>
<thead>
<tr>
<th>Entropy—Simulated Electrograms, %</th>
<th>Entropy—5 Electrograms, %</th>
<th>Entropy—3 Electrograms, %</th>
<th>Entropy—2 Electrograms, %</th>
<th>Entropy—1 Electrogram, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>60.00</td>
<td>77.50</td>
<td>81.30</td>
<td>79.70</td>
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</tbody>
</table>
Clinical Implications

Multielectrode array–based tracking of rotors are limited by interpolation errors and spatial resolution issues, and these issues hamper realistic tracking of rotors especially that migrate and are transient. More importantly, it is not feasible to deploy an array that can simultaneously map adequate area of a cardiac chamber with splines that are uniformly placed within that chamber for simultaneous mapping. In addition, the real-time computing power is feasible for isopotential mapping as opposed to true phase–based techniques. With the advent of MiniVADs (ventricular assist device), in the future patients with failing hearts with recurrent VF, will have hemodynamic support during VF for prolonged periods. This will allow for mapping approaches where one could envisage mapping to identify rotors and devise potential therapies. Thus, the novel strategy presented in this article that provides a limited electrode-based technique that can be implemented on a mapping/ablation catheter and may provide a practical solution for clinician seeking to localize phase singularities.

Sources of Funding

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Disclosures

None.

References


Figure 8. Top, Bipolar electrogram (continuous activity) during VF and (Bottom) the bipolar electrogram (wide complex) during pacing at the same electrode location.
Tracking Rotors With Minimal Electrodes: Modulation Index–Based Strategy
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