Improving the Identification of Fractionated Atrial Electrograms Using Omnipolar Technology

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Abstract

The ablation strategy targeting regions with complex fractionated atrial electrograms (CFAEs) has been used for years as a treatment for atrial fibrillation (AF). Despite its initial success, recent research has failed to replicate the expected results in terminating this pathology. This study proposes using omnipolar electrograms (oEGMs) rather than traditional bipolar electrograms (bEGMs) to identify such regions. Unlike conventional bEGMs, oEGMs are not sensitive to the direction of wavefront propagation. Eight measurements of 16 unipolar electrograms were recorded using high-density sensors, both in healthy tissue and in tissue with fractionated electrograms. These data were preprocessed, windowed, and characterized using complexity (CI) and fractionation (FI) indices. The results show a reduction of more than 50% in the false positive rate when using the omnipolar configuration in healthy tissue, while maintaining a true positive rate of approximately 90% in fractionated tissue. In conclusion, the proposed omnipolar method optimizes the identification of CFAE regions, presenting itself as a technique for optimizing ablation-suitable regions in patients with AF.

1. Introduction

To date, atrial fibrillation (AF) remains a major concern that complicates healthcare delivery worldwide. An effective invasive treatment modality for this arrhythmia, developed in the previous decade, is the ablation of tissue regions characterized by complex fractionated atrial electrograms (CFAEs). The occurrence of these complexes may have multiple causes, which cannot be precisely determined. They are generally associated with heterogeneous tissue activation, arising from pathological factors such as fibrosis, collagen deposition, genetic conditions, or from functional factors such as anisotropy or the presence of structural barriers. Moreover, filter settings or other characteristics of the recording equipment used may contribute to the appearance of CFAEs [1].

The approach for identifying ablation targets was first introduced by Nademanee et al. [2] as a complement to pulmonary vein isolation (PVI), achieving an AF termination rate of 95%. However, the application of CFAE ablation did not yield the same clinical benefits in subsequent studies. Furthermore, due to the initially subjective approach to identifying these complexes, other studies focused on the characterization and development of quantitative methods for the automatic detection of CFAEs [3]. Despite the numerous definitions given to CFAEs, they are generally described as electrograms with high frequency and prolonged duration [1].

The bipolar electrograms (bEGMs) used in these studies are derived from the subtraction of adjacent unipolar electrograms. This local measurement provides an estimate of atrial electrical activity without the influence of far-field noise and other artifacts. However, it is a configuration dependent on interelectrode distance, propagation direction, and conduction velocity [4]. These drawbacks can be critical when defining bEGM morphology, potentially affecting characteristics such as temporal duration or the number of deflections [1], and consequently their similarity to CFAEs under healthy or homogeneous tissue conditions. This can be observed in cases where unipolar signals are subtracted with a bipole perpendicular to the propagation direction, resulting in a fractionated and lower-amplitude signal.

Given the limitations associated with the use of bEGMs, a new method was developed for estimating the electrical activity of the cardiac substrate. This configuration, denominated omnipolar, is robust to the propagation direction of the wavefront, making it independent of the bipole orientation [5]. Therefore, in the present study, omnipolar electrograms (oEGMs) are proposed as a methodology to optimize the identification of potential ablation sites, with the aim of revalidating the criterion for detecting CFAE regions.

2. Materials

The unipolar intracavitary electrograms used were acquired by the ICRC (Electrophysiology Laboratory of the International Clinical Research Center) in Brno, Czech Republic. A high-density catheter (Advisor™HD Grid Mapping Catheter, Abbott) was employed for the recording of the corresponding signals in a patient with recurrent atrial fibrillation (AF). This sensor is characterized by a 4 x 4 electrode structure with a 4 mm inter-electrode distance. Based on the identification of healthy and fragmented tissue by electrophysiologists, two data subsets were selected. A total of 16 measurements (8 for each tissue type), with their respective 16 unipolar electrograms per recording, were ultimately selected.

3. Methods

3.1. Omnipolar reconstruction

As a preliminary step for obtaining the bipolar and omnipolar configurations, preprocessing and windowing of the signals were performed, as detailed below. First, the unipolar signals were filtered with a 4th-order high-pass Butterworth filter, with a cutoff frequency of 5 Hz. This was implemented to remove baseline oscillation. Subsequently, the pulses were windowed using the Botteron filtering method. This filtering process follows these steps: a 40-250 Hz bandpass filter, rectification, and a 20 Hz low-pass filter. In this way, regardless of the degree of pulse fractionation, this process allowed for the detection of the temporal segment associated with atrial activity.

Given a 2 x 2 electrode cell, or clique, up to 6 distinct bipolar configurations can be computed: four corresponding to the lateral sides and two to the diagonals. The estimation of the bEGMs and the corresponding matrix comprising the orthogonal components $\mathbf{b}(t) = [b_x, b_y]$ is specified in [6].

The omnipolar configuration of each clique projects the vector $\mathbf{b}(t)$ in the direction of the wavefront propagation to estimate the maximum activation amplitude. The calculation of this maximum projection, along with its corresponding residual, is as follows:

$$\hat{\theta} = \underset{\theta}{\operatorname{argmax}} \left[\frac{\max([\cos\theta \ -\sin\theta]b(t))}{\max|[\sin\theta \ \cos\theta]b(t)|} \right] \tag{1}$$

$$\mathbf{o(t)} = \begin{bmatrix} \cos\hat{\theta} & -\sin\hat{\theta} \\ \sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \mathbf{b(t)} \tag{2}$$

Where $\mathbf{o}(t) = [o(t) \quad o_\perp(t)]$, with $o(t)$ being the estimated oEGM and $o_\perp(t)$ the residual resulting from the projection along the axis orthogonal to the propagation direction, defined as $\psi = -\hat{\theta}$.

For the subsequent characterization of fractionation, the corresponding triangular oEGMs and bEGMs were obtained for each of the 9 cliques of each measurement and tissue type.

3.2. Fractionation characterizacion

Given the short duration of the signals used (approximately one second), the CI (Complexity Index) and FI (Fractionation Index) parameters were considered suitable for characterizing fragmented tissue [1]. The CI quantifies the number of polarity changes or zero-crossings of the signal, while the FI quantifies the number of maxima and minima, or equivalently, the number of polarity changes of the signal's derivative. The amplitude threshold set for the FI was 0.05 mV [1]. An example of the characterization described can be seen in Figure 1.

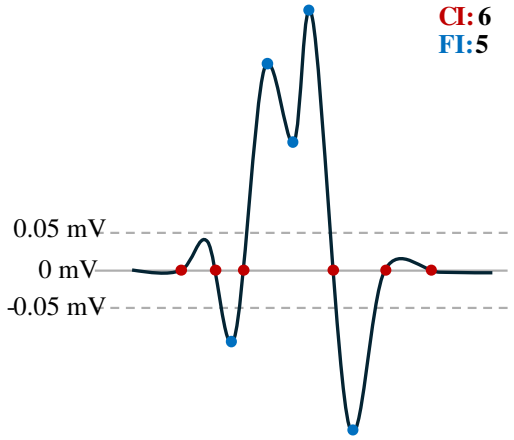

Figure 1. CI (red) and FI (blue) parameters for quantifying the degree of fractionation. The dashed lines indicate the threshold chosen for FI.

Complexes were identified as fragmented if they exhibited 4 or more polarity changes (CI) and/or 4 or more peaks (FI) above the established amplitude threshold [1].

4. Results

Table 1 shows the CI results for bEGM and oEGM in both tissue types. A significant reduction of approximately 13% in the false positive rate in healthy tissue is observed when characterizing omnipolar complexes. These false positives, in the bipolar case, are mostly concentrated in the *by* bipolar pair, with 21 false positives compared to 2 in the *bx* pair.

The true positive rate in fragmented tissue is higher than in healthy tissue, being slightly higher for oEGM, reaching 66.67%. In this case, the CFAE complexes are evenly distributed between the *bx* and *by* bipolar pairs.

	CI	Bipolar		Omnipolar
		bx	*by*	
Healthy tissue	≤ 2	68	35	65
	≤ 3	70	51	70
	> 3	2	21	2
	False positive rate	**15.97%**		**2.78%**
Fragmented tissue	≤ 2	10	19	12
	≤ 3	27	31	24
	> 3	45	41	48
	True positive rate	**59.72%**		**66.67%**

Table 1. Summary of the complexity index results.

In the case of the FI parameter, whose results are summarized in Table 2, the trends previously discussed for the CI are replicated. A 7% reduction in the false positive rate in healthy tissue is observed when characterizing the omnipolar configuration. These false positives are concentrated in the *by* bipolar pair in this case.

	FI	Bipolar		Omnipolar
		bx	*by*	
Healthy tissue	≤ 2	35	30	35
	≤ 3	66	58	67
	> 3	6	14	5
	False positive rate	**13.89%**		**6.94%**
Fragmented tissue	≤ 2	3	1	3
	≤ 3	10	5	9
	> 3	62	67	63
	True positive rate	**89.58%**		**87.50%**

Table 2. Summary of the fractionation index results.

The ability to detect CFAE in fragmented tissue using FI increases to values close to 90% for both configurations.

At first glance, and supported by the examples in Figure 2, the pulses from healthy tissue are easily distinguishable from those of fragmented tissue. This is primarily due to the increase in the number of deflections and the prolongation of the electrical pulse over time. In the case of healthy tissue, these characteristics are projected in a single direction (b_y), while in fragmented tissue, they are present in all obtained configurations, regardless of the parameter.

5. Discussion

As a result of the lack of knowledge about the electrophysiological origin of CFAEs, various definitions of fractionation and, therefore, of the characteristics for its measurement have been established [1]. Furthermore, in all of these studies, the characterization of this phenomenon has been carried out using bEGM signals, whose sensitivity to the propagation direction was not considered a potential source of additional fractionation. This increase in CFAE complexes in healthy regions was exacerbated by the type of filtering used in many of these studies, which involved subtracting low-frequency content and consequently modifying the morphology of these signals.

The results of the present study indicate an overall improvement in the reduction of false positives when using the metrics and thresholds defined in other studies [1], but applied to oEGM. The false positive and true positive rates do not fully align between the CI and FI parameters in both healthy and fragmented tissue, respectively, although this phenomenon has been described previously [7]. However, both parameters suggest that the proposed hypothesis is correct, and that the increase in CFAE detection capability between healthy and fragmented tissue is significant. If we examine the results obtained in the example in Figure 2, particularly in healthy tissue, we can observe how the omnipolar configuration provides an estimate that excludes the fractionation caused, in this case, by the bipole *by*. This bipolar pair dependence was detected in the false positive rates, with a reduction in this rate when using oEGM by at least 50%, which further supports the initial hypothesis.

The more uniform distribution of CFAEs between the two bipolar pairs (*bx* and *by*) observed in fragmented tissue, for both CI and FI, may be attributed to the morphological characteristics of the unipolar electrogram itself, which induces fractionation through electrophysiological mechanisms, unlike in healthy tissue.

It is important to note that the identification process of CFAEs during clinical practice was highly subjective [3]. Therefore, it is considered essential to complement this study with a *ground truth*, obtained from the classification of CFAEs in both bEGM and oEGM signals by an expert electrophysiologist. Additionally, replicating the study with a larger dataset and a higher number of subjects would be necessary to validate the results obtained.

Moreover, the study is limited by the short duration of the electrograms, as it only includes a single beat, which affects the resolution and reliability of the characterization performed [8].

6. Conclusion

This work analyzes the limitations of the bipolar configuration in the identification of CFAEs, which is affected during the classification of completely healthy pulses by the propagation direction. The omnipolar perspective is presented, significantly optimizing this identification, and it is proposed as a new robust measurement technique for the cardiac substrate, aimed at detecting suitable ablation regions in patients with AF.

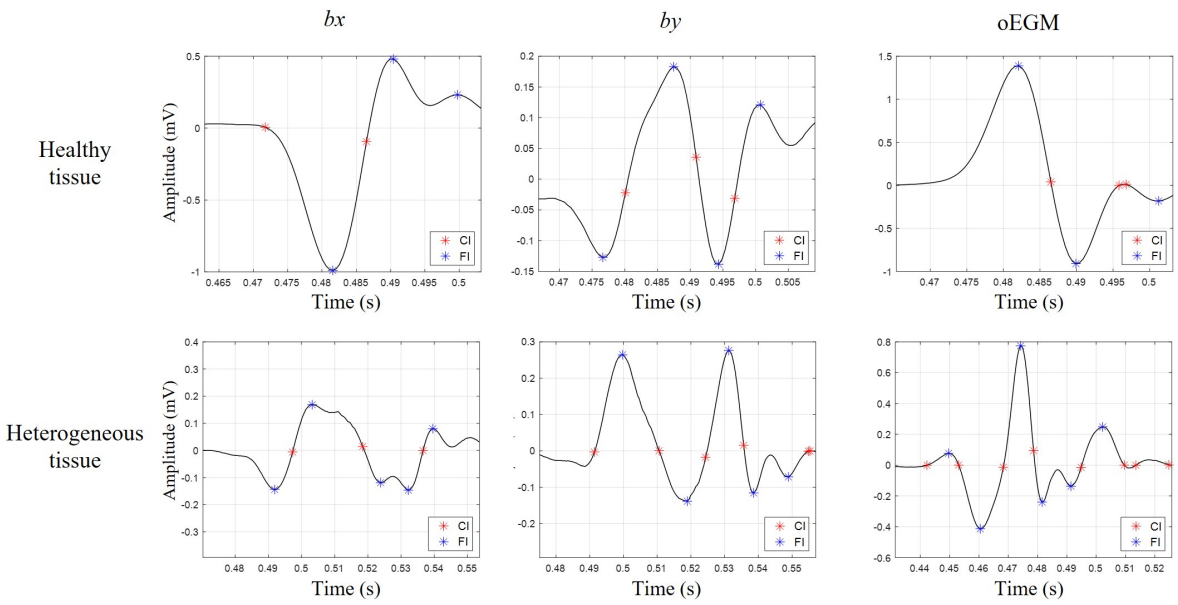

Figure 2. Example of fractionation quantification in bipolar complexes (*bx*, *by*) and omnipolar complexes in healthy and fragmented tissue using CI (red dots) and FI (blue dots).

Acknowledgments

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