Far-Field Intracardiac Electrograms Removal Enables Highly Reliable Automatic Cycle Length Estimation During Atrial Arrhythmia

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Abstract

Electrograms (EGMs) from the intracardiac reference catheter placed in the coronary sinus (CS) vein are susceptible to ventricular noise. Most atrial tachycardia (AT) or fibrillation (AF) catheter ablation procedures use this location. Because of its proximity to ventricles, electrograms tend to include waves similar to the QRS complex (far-field activity) as seen on the electrocardiogram (ECG). These ventricular activities can, for instance, disturb the atrial cycle length estimation from those electrograms, or could fail its estimation.

This study aims to determine whether the electrograms with ventricular far field (VFF) removed allow for higher cycle length estimation performance and reliable real-time diagnostic assistance. A method proposed in this paper separates and adaptively removes VFF while preserving useful atrial activity even when the two activities are superposed. This is achieved through generating a VFF blueprint from the time-frequency analysis using wavelet decomposition. Suppressing this blueprint in the wavelet domain and reconstructing the signal permits us to achieve artifact-free EGMs.

1. Introduction

Atrial electrograms (EGMs) nearby the ventricles can be altered by the ventricular activity. It generates waveforms on intracardiac electrograms called ventricular far-field (VFF). Such distortion by ventricles makes signal analysis of atrial EGMs more difficult and misleads data analysis (e.g. cycle length estimations).

In this study, we introduce an algorithm to remove VFF that takes the noisy intracardiac signals as input, the location of ventricular far-field, and outputs the signals with canceled VFF and reconstructed atrial activity in case of superposition.

To quantify the performance of our algorithm, we monitor signal to noise ratio (see section 3.1 for a definition) and improvement in automatic atrial cycle length estimation.

Cycle length (CL) is a well-known measure aiming to characterizes the electrical activity within the atria, serving to guide catheter ablation. CL measurement unit is milliseconds and generally reflects the time during which a full cycle of relaxation and contraction of the atria occurs. Tracking CL value of a stable reference catheter is essential for physicians. Indeed, it indicates the evolution of the pathology during the procedure and can be a valuable indicator of a correct ablation strategy. For instance the relative CL difference between two intracardiac dipoles is crucial to make a judgment on the mapped area.

To our knowledge, there is no comparable method used by existing recording systems in the operating room except for completely suppressing portion of EGMs where the VFF have been detected (which we will refer as blanking), even in superposition. That approach may reduce or erase useful information.

Previous works use source separation methods [1–3], template matching and subtraction [4], as well as adaptive ventricular cancellation [5] on either bipolar or unipolar electrograms with multiple leads or only one lead. Inspired by [4], we implemented a new approach trying to leverage wavelet decomposition and different methods to combine and produce a blueprint to be subtracted. Noteworthy, in our method, every EGM is treated independently in a streaming manner, making it suitable for real-time analysis.

2. Material and methods

2.1. Dataset description and annotations

The data used to validate and test the proposed algorithm were extracted from a General Electric Cardiolab recording system from Saint-Joseph Hospital, Marseille, France. For each extraction, 5 CS dipoles (longitudinal catheter) and the 12 ECG leads were available with a sampling rate of 977 Hz. It was annotated via an inner annotation tool of Volta Medical by 7 expert annotators. The instruction was to measure and label the mean cycle length (common for the 5 CS tracks) of electrograms of patients in sinus

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rhythm (SR), AT or AF. Each recording contains 3 or 4 labeled segments lasting for around 10 seconds or alternatively containing 10 cycles.

Intracardiac leads were filtered with a 50 Hz notch filter and a band-pass (30-125 Hz) filter and down-sampled at 250 Hz.

Overall, the dataset includes 119 different atrial catheter ablation procedure segments capitalizing approximately 75 minutes of annotated signal duration (6 minutes of annotated AF from 18 different segments, 35 minutes from 80 different AT segments, and 32 minutes from 21 different SR segments).

2.2. Input data

The algorithm needs as input noisy intracardiac leads and the location of the ventricular far-field component. If the VFF locations are not available, we may use ECG leads and an algorithm to detect the location of the QRS complexes in it as those ventricular activities in ECG are synchronous with far-field noise in CS. This algorithm can be, for instance, Pan-Tompkins algorithm [6].

2.3. Ventricular far-field removal method

The underlying idea is that atrial and ventricular activities, especially in atrial tachycardia or fibrillation, can be considered statistically independent from two distinct sources with different cycle lengths. In that case, the intracardiac leads contain the mixture of both atrial and ventricular contents. Meaning that, if we stream the intracardiac signals as in the operating room, we may see two independent events occurring, with a different pace, overlapping sometimes and then separating (see figures 1, 2, 3).

We hypothesize that, if we process the signal in a moving window manner (bufferizing enough VFF potentials), we would have a majority of non-overlapping atrial near-field VFF activities with consistent morphology, hence the possibility to recover a blueprint of the VFF automatically with an agglomeration method such as principal component analysis (PCA), independent component analysis (ICA) or a geometric median, which favored the most common pattern of those buffered activities.

The implemented method combines wavelet decomposition [7] and the independence of atrial near-field and VFF.

First, we compute every level of the stationary wavelet transform [7,8] until the wavelet (Daubechies 3) dimension is twice as large as VFF dimension fixed at 120 ms.

Subsequently we collect and store each ventricular far-field activity, specific to each lead, in buffers. The length of the buffer is a parameter of the method, in our experimental setting we chose the length to be 10 patterns. At first, the buffers of ventricular far-field activities is empty. Then, it is quickly filled up or has enough ventricular far-field activities per-lead to compute blueprints of those activities to be canceled.

Next, we combine these activities into blueprints of the far-field for each lead and time-frequency level. In our experimental setting, these blueprints are the principal components of the activities stored.

After that we subtract the blueprints in the wavelet domain, for each level, for coefficients that influence the portion of the original signal (coefficients where the wavelet overlap the VFF for more than 50 % duration) where a far-field has been detected. And finally we reconstruct the signal without those blueprints.

Figures 1, 2, 3 illustrate the ventricular far-field removal. Ventricular far-field is significantly reduced in the section of no superposition with the atrial near-field while the atrial near-field is reconstructed in the case of superposition, resulting in the increase of the signal to noise ratio (see section 3.1 for a definition). Hence, the method will allow more accurate visual or automatic analysis.

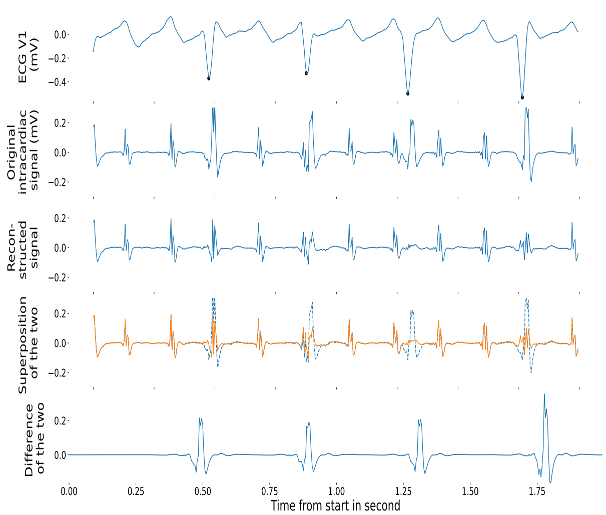

Figure 1. Example of ventricular far-field removal with, from top to bottom, ECG lead V1 with R peaks, original CS dipole signal, reconstructed signal, superposition of the two, difference of the two.

3. Results and discussion

We use cycle length estimation performance to assess the benefit of our method. So far, two methods have been widely used to estimate intracardiac electrograms cycle length [9]: those relying on frequency based approaches as Fast Fourier Transform for dominant frequency estimation or auto-correlation study; or different adaptive thresholding methods based on amplitude-based detection of atrial activations. In this study we improve both meth-

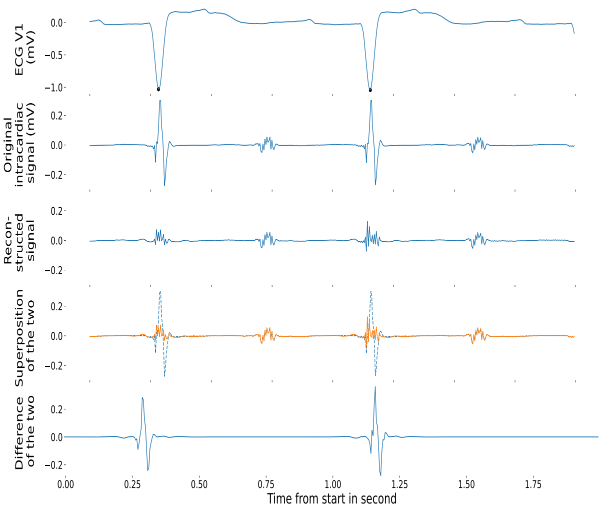

Figure 2. Second example, similar to figure 1 for another batch of another AT segment.

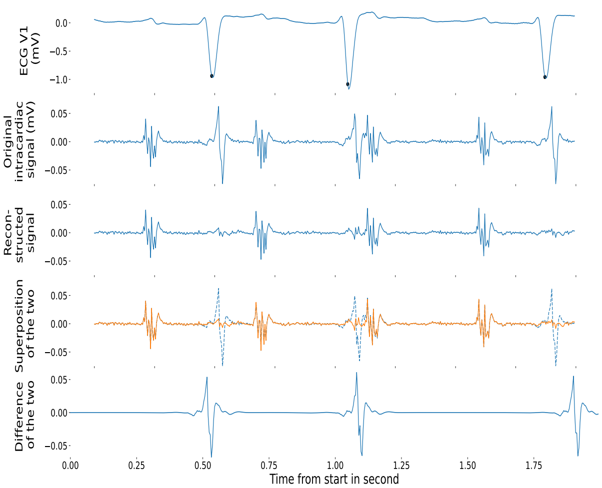

Figure 3. Third example, similar to figure 1 for another batch of another AT segment.

ods enabling a higher cycle length performance. First, we improved the signal to noise ratio by implementing an auto-correlation evaluation method. Then, we utilized Volta Medical proprietary cycle length algorithm based on amplitude-based detection of atrial activations.

3.1. Auto-correlation evaluation method

We use the section 2.1 dataset to assess the improvement of the signal to noise ratio (SNR) after the VFF removal. To compute the SNR, we model EGMs as an isoelectric line with periodic pattern. That is why we consider auto-correlation around the annotated cycle length value to represent the useful atrial activity and every other correlation between multiples of this cycle length as noise.

Hence the proposed SNR for a batch signal s with measured cycle length p and a mean half activity size δ (taken to be 60 ms) can be computed as: $SNR = P_{signal}/P_{noise}$ with:

$$P_{signal} = \max_{[p-\delta, p+\delta]} \text{Auto-correlation}(s)$$

$$P_{noise} = \max_{[\delta, p-\delta] \cup [p+\delta, 2\times p-\delta]} \text{Auto-correlation}(s)$$

$$\text{or } \text{std}_{[\delta, p-\delta] \cup [p+\delta, 2\times p-\delta]} \text{Auto-correlation}(s)$$

Figure 4 illustrates the impact of our VFF removal method on the auto-correlation of the signals shown in figure 3. Table 1 presents quantitative results.

Table 1. Mean SNR score

Score	VFF removal	Original	Blanking
SNR_{max}	10.7	7.1	10.3
$SNR_{max/std}$	44.4	26.9	44.7

3.2. Higher cycle length estimation reliability

We use VFF-free signals to estimate a CL in a streaming real-time manner on the section 2.1 database (2 seconds batch, atrial activity detection with a wavelet domain thresholding method and an adaptive covariance Kalman Filter for cycle length estimation [10]). We test the hypothesis that in comparison with human adjudications, far-field removed electrograms would yield higher algorithmic performance levels than non-far-field removed electrograms, or with VFF region blanked as a baseline method (turning the VFF region to be an isoelectric line, even in superposition).

The score is computed as the average of the per-rhythm mean absolute difference (MAD) between estimated and annotated CL.

The algorithm's performance (see table 2), with far-field removal, achieve the best result. This performance is higher compared to performances of the algorithm without far-field removal or with VFF blanking.

Table 2. Mean CL estimation score

Score	VFF removal	Original	Blanking
MAD	7.4 ± 13.7 ms	18.2 ± 36.9 ms	20.8 ± 47.7 ms

4. Conclusion

The presented method successfully removes ventricular far-field, whether the VFF is isolated or overlapping an

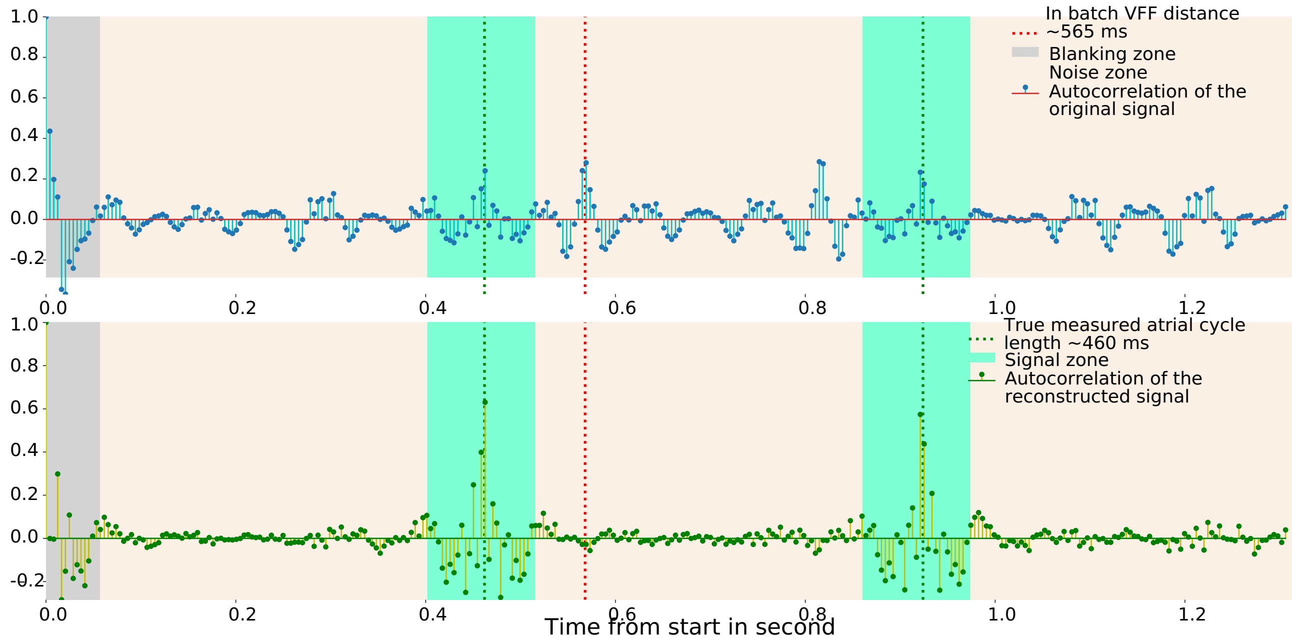

Figure 4. Illustration of the auto-correlation evaluation method on the figure 3 batch signals. SNR of the original signal is 0.8, SNR of the reconstructed signal is 5.4

atrial activity, reconstructing the atrial activity in the case of superposition.

The removal of ventricular far-field potentials from intracardiac electrograms provides signal denoising for a range of cardiac electrophysiology algorithms. It has proved, in particular, its efficiency for the estimation of atrial cycle length. Finally, its implementation in real time allows its use in an operating room environment and could therefore be a useful tool during AF/AT catheter ablation procedures.

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