Fibrillatory Waves Automatic Delineation in Atrial Fibrillation Surface Recordings Based on Mathematical Morphology

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Abstract

The estimation of atrial activation times in atrial fibrillation (AF) has become an established way to evaluate AF through several indices like organization of the arrhythmia, atrial cycle length, etc. Classic fibrillatory (f) waves delineation uses atrial electrograms because larger f waves are present in these recordings. This work introduces a new f waves delineator based on mathematical morphology (MM) able to operate on surface AF recordings. The method used lead V1 from the standard ECG. Next, ventricular activity was cancelled out and the remaining atrial activity (AA) was delineated through MM. To validate results, all the f waves were manually delineated and location error between manual and automatic annotations was computed. The average location error was lower than 7 ms and the average detection accuracy was above 98%. As conclusion, MM-based f-waves automatic delineation is able to provide reliable atrial activation times, thus allowing to quantify in a new way the AA signal pattern from surface AF recordings.

1. Introduction

Atrial fibrillation (AF) is the most common arrhythmia in clinical practice. It accounts for approximately one third of hospitalizations for cardiac rhythm disturbances and is associated with an increased long-term risk of stroke, heart failure, and all-cause mortality [1]. After many years of research, several authors have demonstrated that a strict correlation between AF organization, defined as how repetitive is the AF signal pattern, and the number of wavefronts wandering the atrial tissue exists. Hence, different algorithms have been developed in an attempt to estimate atrial activation timings and quantify AF organization from invasive recordings [2]. To this respect, endocardial activation timing detection has been preferred due to the much higher fibrillatory (f) waves amplitude in these recordings [2].

However, from a clinical point of view, the assessment of atrial activation times from the standard surface ECG would be very interesting, because it could be the previous step to facilitate a precise and short time AF organization estimation. In this respect, only two indirect non-invasive AF organization estimators have been proposed in the literature. On the one hand, the dominant atrial frequency (DAF), which is defined as the highest amplitude frequency within the 3-9 Hz range of the atrial activity (AA) spectral content [3]. On the other hand, sample entropy (SampEn), which has proved its usefulness in a number of applications, such as the predictions of paroxysmal AF termination, the electrical cardioversion outcome of persistent AF, etc. [4].

Obviously, the drawback of the two aforementioned non-invasive organization estimators is the lack of strict accuracy in the process. In this respect, both SampEn and DAF can only yield an average AF organization assessment because both indices estimate f waves regularity as a whole, i.e., without considering explicitly the timing associated to each f wave. Thus, the possible short-time information that the wave-to-wave analysis or each atrial activation may provide is blurred. Overall, this work proposes a new algorithm for automatic and short-time f waves delineation from the surface ECG. The method is able to delineate every single f wave timing, thus serving as the previous step to estimate AF organization in a wave-to-wave fashion by measuring f waves morphology repetitiveness along onward atrial activations.

2. Materials

The database consisted of 30 patients undergoing cardiac surgery who developed postoperative AF. For each patient, standard 12-lead ECG and unipolar epicardial recordings were considered. Signals were digitized at 1 kHz with an amplitude resolution of 0.4 μV. The electrograms were used to yield a manual classification of AF episodes. They were inspected separately by different cardiologists and classified as type I, II, or III AF following Wells' criteria [5]. The final labeled dataset consisted of 30 AF segments of surface ECGs (10 AF-I, 10 AF-II and 10 AF-III) of 15 seconds in length in which f waves timings were manually annotated.

For the analysis lead V1 was chosen because the atrial signal is larger in this lead [6]. Thereafter, this lead was filtered to remove baseline wander, high-frequency noise and powerline interference [3]. Next, the Atrial Activity (AA) was extracted by QRST cancellation [7].

3. Methods

3.1. Delineation of the f waves

The operations comprising the algorithm to delineate the f waves, are based on applying morphological operators to the AA signal. Mathematical morphology (MM), which is based on sets operations [8], provides an approach to the development of non-linear signal processing methods in which the shape information of a signal is incorporated [9]. The use of MM operators has been proposed for ECG signal enhancement [10] and for QRS detection through different approaches [11].

In MM operations the result of a set transformed by another set depends on the shapes of the two sets involved. The shape information of a signal can be extracted by using a structuring element to operate on the signal [8].

Let consider that $x[n]$, $\{n = 0, 1, \cdots, N-1\}$ and $s[m]$, $\{m = 0, 1, \cdots, M-1\}$ denote two discrete sequences of length N and M, respectively. Moreover, we will further assume that $N > M$. The *erosion* of the discrete sequence $x[n]$ by the sequence $s[n]$, which is called the structuring element, is defined as

$$(x \ominus s)[n] = \min_{m=0,\cdots,M-1} x[n+m] - s[m], \quad \text{for} \quad n = 0, \cdots, N-M. \tag{1}$$

On the other hand, the *dilation* of $x[n]$ by the structuring element $s[n]$, is defined as

$$(x \oplus s)[n] = \max_{m=n-M+1,\cdots,n} x[m] + s[n-m], \quad \text{for} \quad n = M-1, M, \cdots, N-1. \tag{2}$$

In order to preserve the resulting waveform of the processed sequence, the two operations, erosion and dilation, are usually applied in tandem. Depending on the order of application, two derived operations can be defined. The *opening* of a discrete sequence x by an structuring element s is defined as an erosion followed by a dilation with the same structuring element, thus

$$(x \circ s)[n] = ((x \ominus s)[n] \oplus s)[n], \tag{3}$$

the opening of a data sequence can be interpreted as sliding the structuirng element along the data sequence from beneath and the result is the highest points reached by any part of the structuring element.

In a similar way, the *closing* of the sequence x by the element s is defined as a dilation followed by an erosion with the same structuring element,

$$(x \bullet s)[n] = ((x \oplus s)[n] \ominus s)[n], \tag{4}$$

thus, the closing of a data sequence can be interpreted as sliding an inverted copy of the structuring element along the data sequence from above and the result is the lowest points reached by any part of the structuring element.

Obviously, the output of either opening or closing operations is directly affected by the shape of the structuring element. As a consequence, a specific structuring element has to be designed depending on the signal pattern of interest. In this work, we opted for designing two structuring elements, s_1 and s_2. The first one was thought to be adapted to the f waves fundamental cycle and extract its peaks and pits, whereas s_2 was designed to extract a stepwise signal able to suppress the typical drift between atrial cycles. In the case of AF, the fundamental pattern of the f waves can be approximated to a sawtooth signal [12] and, hence, the structuring element s_1 to get the f waves peaks and pits has been designed as an even triangular shape of length L_1 with the form,

$$s_1[n] = \begin{cases} \frac{2n}{L_1+1}, & \text{if} \quad 1 \leq n \leq \frac{L_1+1}{2} \\ \frac{2(L_1-n+1)}{L_1+1}, & \text{if} \quad \frac{L_1+1}{2} \leq n \leq L_1 \end{cases} . \tag{5}$$

Moreover, the length L_1 of the structuring element s_1 was adapted to the concrete f waves under processing. Thus, after several tests, the best results were achieved by choosing $L_1 = 1/(3 \cdot \text{DAF})$. Regarding the structuring element for the atrial cycle drift, s_2, we opted for a rectangular shape of length L_2. In this case, the shape had to be wider than the f waves fundamental pattern and, after some tests, the best results were achieved for $L_2 = 3/(2 \cdot \text{DAF})$.

With the structuring elements defined, the combination of operations to enhance the f waves peaks and pits and suppress the atrial cycle drift was defined as

$$\begin{aligned} y[n] = \{(x \bullet s_1[n]) - ((x \bullet s_1[n]) \circ s_2[n]) + \\ +(x \circ s_1[n]) - ((x \circ s_1[n]) \bullet s_2[n])\}. \end{aligned} \tag{6}$$

Finally, a center clipping operation on the resulting signal was performed whith the clipping function

$$z[n] = \begin{cases} y[n] - \alpha, & \text{if} \quad y[n] > \alpha \\ 0, & \text{if} \quad \alpha \leq y[n] \leq -\alpha \\ y[n] + \alpha, & \text{if} \quad y[n] < -\alpha \end{cases} , \tag{7}$$

where the clipping factor α was set to the 20% of the RMS value from the f waves segment under processing. The clipped signal, $z[n]$, will contain positive and negative peaks. These peaks are detected with the second version of the algorithm presented in [13]. This version is able to detect all the peaks in a signal which exceed a given level of significance, h, its advantage being that it does not rely upon filtering, nor on any direct thresholding techniques. The significance of a peak is a scalar value normalized to the range $(0, 1)$ and we selected $h = 0.6$ as level of significance. Finally, the detected peaks will serve to delineate the f waves activation points.

3.2. Performance evaluation

Algorithm's performance was evaluated by comparing manual and automatically detected atrial activations. If the candidate activation fell into a time window of ± 10 ms, with respect to the actual activation, it was scored as a true positive (TP) detection. On the contrary, if the candidate activation occurred outside these boundaries, it was counted as a false positive (FP). In a similar way, a false negative (FN) was defined as a fail in the detection of a true activation. In this way, sensitivity (Se) and positive predictivity (P^+) were defined as

$$\mathrm{Se}(\%) = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}}; \quad \mathrm{P}^+(\%) = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}}, \qquad (8)$$

whereas accuracy (Acc) was given by

$$\mathrm{Acc}(\%) = \frac{1-(\mathrm{FP}+\mathrm{FN})}{\sum \mathrm{AA}}, \qquad (9)$$

where $\sum$AA stands for the total number of type I, II or III AF atrial activations in the database. Performance was evaluated independently for each AF type in order to assess whether AF organization could involve some effect on delineation accuracy.

4. Results

The average location error between manual and automatic f waves delineation was lower than 7 ms for the three AF types. More precisely, it was 3.2 $\pm$ 5.7 ms for type I AF, 4.4 $\pm$ 6.8 ms for type II AF and 6.9 $\pm$ 16.2 ms for type III. Results for sensitivity, positive predictivity and accuracy are shown in Table 1 organized as a function of the AF type. The column with $\sum$AA stands for the total number of atrial activations of the corresponding AF type in the database. Overall, an average accuracy of 98.6% was achieved for the three AF types. Finally, Figure 1 plots a delineation example for the three different types of AF recordings. As can be seen, the delineation algorithm is able to detect accurately the maxima and the minima associated to each f wave regardless of the AF type.

5. Discussion

The present work proposes the first algorithm to automatically delineate f waves timing in AF from surface ECG recordings. A reliable delineation represents a crucial step in AF regularity assessment. To this respect, the use of MM operations has been crucial in determining the f waves shape information, thus, minimizing false fiducial points detection. Furthermore, by comparing f waves MM-based delineation with manual annotations performed by expert cardiologists, it has been demonstrated that the proposed automatic delineator is able to provide reliable f

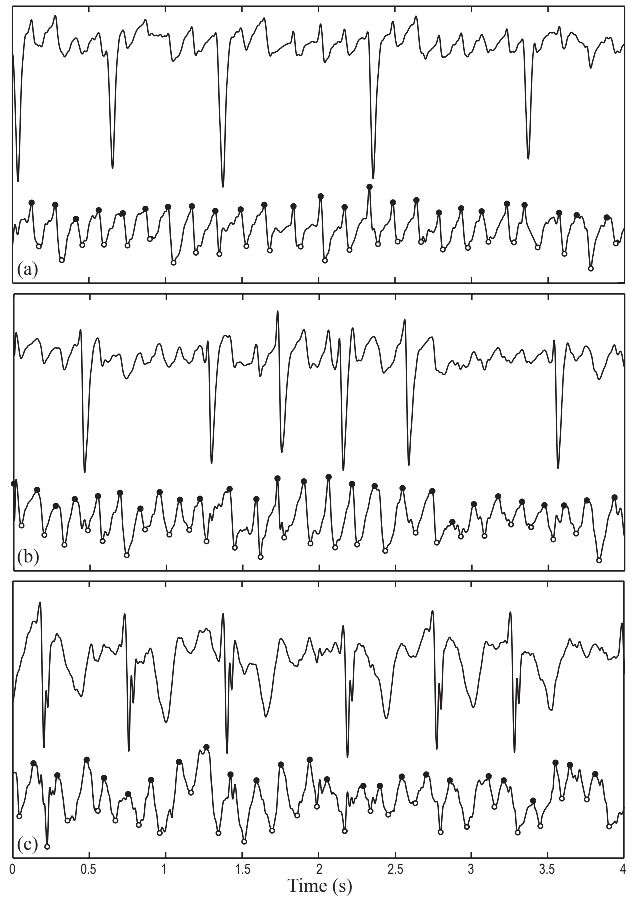

Figure 1. Delineation of the f waves for typical 4 second segments corresponding to (a) type I, (b) type II and (c) type III AF episodes, respectively. For each segment, the surface ECG and the corresponding AA are displayed. The black dots mark the instant of the maximum amplitude of the f waves, whereas the empty circles indicate their boundaries.

Table 1. Performance f waves delineation results computed as a function of the AF type

	$\sum$AA	TP	FP	FN	Se(%)	P^+(%)	Acc(%)
Type I	884	865	12	14	98.4	98.6	99.1
Type II	972	940	21	17	98.1	97.8	98.7
Type III	1091	1045	30	21	98.0	97.2	98.2

waves timing estimation. In view of results, the proposed algorithm performs slightly better in organized AF recordings of type I, thus decreasing accuracy as the f waves become more irregular from type II up to type III AF. This result can be considered as normal given that the f waves morphology variability increases with the AF type, thus hindering accurate delineation.

On the other hand, although DAF computation is needed prior to f waves delineation, this step does not imply any limitation. To this respect, the DAF estimation is used only to get an approximate size of the structuring element. However, due to the chaotic behavior of AF, each f wave will have its own size which will be different from each other. Hence, during the several seconds needed to compute the DAF, there will exist a wide variety of f waves lengths. Consequently, the structuring element will not fit exactly to a large number of waves in each case, but will approximately have a comparable size. Therefore, small deviations in the computation of the DAF would not imply any malfunction of the proposed delineator. In fact, f waves fiducial points are precisely detected in a second step, regardless of the DAF. In case of very large errors in DAF estimation, the method could eventually produce an unsuccessful result. Anyway, largely erroneous DAF values are only present in very noisy recordings which, in fact, will be very difficult to analyze through any other method.

The proposed algorithm could open a new perspective in the analysis of AF organization from the ECG. Thus, an individualized and detailed analysis of each f wave could reveal useful information about electrophysiolgical features of the atria in short-time which, in other cases, is blurred when these waves are averaged or considered in large blocks, like in the computation of DAF or in many other time-frequency studies [3].

6. Conclusions

A new alternative for short-time non-invasive assessment of fibrillatory waves timing has been introduced. Results indicated a high delineation accuracy, thus providing the basis for the development of new AF organization estimators able to operate in short time. These potentialities may provide new insights in the non-invasive study of AF physiological mechanisms and may open new perspectives in the improvement of its treatment.

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