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Algorithms for Atrial Signal Extraction in Atrial Fibrillation ECGs: A Comparison Based on the Correlation Between Endocardial and Surface Dominant Frequency

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Abstract

The non-invasive analysis of atrial fibrillation (AF) relies on the extraction of atrial activity from surface ECG recordings. The present study compares three different methods for AA extraction from multi-lead ECG recordings: The adaptive singular value QRST cancellation, the spatio-temporal QRST cancellation and Independent Component Analysis (ICA). A criterion for assessing the performance of the extracting techniques on real data is proposed, based on the correlation r between surface and endocardial atrial fibrillation dominant frequency. Performance results obtained with the proposed criterion are compared with those obtained considering the spectral concentration index (SC) of the estimated atrial signal as an estimator of extraction quality. On a database of 20 surface 12-lead ECG and endocardial recordings of persistent AF, results show that higher SC corresponds to better dominant frequency correlation. In addition, the ICA-based method was found to perform better in terms of this two criteria (SC= $68.2\% \pm 10.4\%$ *and* $r = 0.57$ *,* $p < 0.01$*).*

Keywords *Atrial Activity Extraction, Atrial Fibrillation, Dominant Frequency, Multi-lead ECG*

1 Introduction

Atrial fibrillation (AF) is a supraventricular arrhythmia in which the electrical activation shows an uncoordinated pattern. AF is the most common arrhythmia in elderly people and a potential risk factor for stroke. Hemodynamic impairment and thromboembolic events result in significant morbidity, mortality, and cost. Atrial fibrillation dominant frequency (AFDF) is the frequency at which the peak of the power spectrum of the atrial activity (AA) is found and represents the rate of depolarization of the atrial substrate. It constitutes an important parameter for assessing the progress of AF, as it was found to provide information about the effects of drug administration [1], [2] and to play a role as a predictor of spontaneous termination of paroxysmal AF [3], [4], as well as of termination of persistent AF by catheter ablation [5]. More importantly, AFDF can be estimated non-invasively from surface ECG recordings.

Nonetheless, the extraction of information from surface recordings requires to cancel out the electrical activity not associated with the atrial sources. Ventricular activity (VA) represents the main artifact in terms of amplitude and its spectral distribution partially overlaps that of AA, thus making linear filtering unsuccessful. Several methods for QRST complex subtraction have been proposed in the literature and all of them are based on the common assumption about a certain degree of decorrelation between AA and VA, which is plausible in AF. Average beat subtraction (ABS) constitutes the most widely used technique for VA cancellation and relies on the assumption that the average beat to be subtracted is a good approximation for the entire set of beats. Hence, the performance of this methodology is strongly influenced by the beat-to-beat QRST morphology variations that can occur primarily due to respiration and patient movements. More sophisticated techniques have been proposed, for adaptive QRST cancelation from single- [6] and multi-lead recordings [1], [7]. As opposed to VA cancellation techniques, the blind source separation (BSS) approach does not assume specific morphology or repetitive structure for VA and it mainly relies on the statistical independence of VA and AA to successfully tackle the extraction of AA [8], [9], [10]. The estimation of the atrial signal is performed by means of spatial filtering suitably combining the different leads according to the independent component analysis (ICA) of the AF ECG.

In the present study, three specific examples of algorithms for AA extraction are compared, the adaptive singular value cancellation (ASVC) method proposed in [6], the spatiotemporal cancellation (STC) proposed in [7] and the BSS-based RobustICA-f method proposed in [10]. Given the importance of AFDF for the characterization of AF, this parameter is exploited for assessing the quality of AA extraction for the three methods under study. The AFDF is estimated from the extracted atrial signals and from the corresponding simultaneous endocardial electrogram (EGM) recordings taken from patients undergoing catheter ablation therapy for the treatment of persistent AF. The correlation between EGM and ECG AFDF is taken as an indicator of AA extraction quality. Performance results obtained using the proposed criterion are compared with those offered by the spectral concentration index(SC) of the estimated atrial signal, which has already been proposed as a parameter for assessing the quality of AA extraction [9].

A comparison of different methods for atrial signal extraction has been made in [11], including spatio-temporal cancellation of [1], principal component analysis (PCA) and ICA. However, the study considered performance criteria based on parameters estimated from the surface recordings only. By contrast, the criterion proposed herein for extraction quality assessment also takes into account the "ground truth" provided by the EGM reference, thus constituting a more objective validation of other ECG-based criteria.

2 Methods

2.1 Database and Signal Preprocessing

Standard 12-lead ECG as well as EGM left atrial appendage recordings were performed on 20 patients affected by long-lasting persistent AF and undergoing catheter ablation at the Cardiology Department of Princess Grace Hospital, Monaco. Recordings were acquired before the beginning of ablation procedure. All signals were digitally recorded at a sample rate of 977 Hz and lasted about 60 s each. They were filtered by applying a third-order zero-phase band-pass Chebyshev filter with a lower cutoff frequency of 0.5 Hz and an upper cutoff frequency of 30 Hz, in order to remove low-frequency baseline wandering due to physiological interference (e.g., breathing) and high frequency artifacts, such as power-line and myocardial interference.

2.2 Atrial activity extraction in surface recordings

The three AA extraction methods compared in this study are briefly summarized below:

1) ASVC [6]: A matrix is built with the N QT segments that correlate best with the current beat. An optimal value of $N = 24$ beats was found to provide the best trade-off between ventricular cancellation in QT segments and atrial wave preservation in the TQ intervals [6]. The ventricular beats are synchronized on the most energetic wave (i.e., the R wave). The principal component is taken as the optimal estimation of the average QRST template representing the ventricular activity in the current QT segment. The offsets defining the QRST start and end points were determined as proposed in [6]. Two steps are adopted in order to avoid sudden transitions at the beginning and at the end of the QRST segments. The first consists in the truncation of the QRST template in correspondence of the minimum distance between the template and the original signal within an interval of P samples after the starting point and before the end point of each QRST complex. The second step consists in applying a Gaussian window of length $2M$ samples over each transition. Both parameters were assigned the values suggested in [6]. The method is implemented on lead V1, as it is widely considered the lead with largest atrial-to-ventricular amplitude ratio.

2) STC [7], [12]: Similarly as for ASVC, the method exploits the repetitiveness of VA to compute an average beat matrix, containing the average beat for each of the 12 ECG leads. Each QRST complex in the 12-lead recording is then modeled as a linear combination of a reduced set of basis vectors obtained performing PCA of the average beat matrix and retaining the resulting components that explain over 99% of the observed variance. The linear combination providing the best AA estimate is found maximizing the likelihood of the observed ECG, under the assumption that AA distribution is Gaussian in AF with known covariance matrix. This covariance matrix is estimated from residual ECG obtained by the least square estimate of linear combination parameters. The offsets defining the beginning and the end of each beat with respect to the R peak are set as for the ASVC method.

3) RobustICA-f [10]: Independent Component Analysis (ICA) is a statistical tool belonging to the family of BSS techniques that aims to separate the statistically independent sources contributing to an observed linear mixture. ICA does not require sources to be spatially orthogonal nor Gaussian, thus resulting more suitable for atrial source extraction compared to other BSS techniques such as PCA [8]. In the present setting, ECG signals are first divided into 8 s long segments with 7 s overlap, and source separation is performed on each segment, in order to take into account the temporal evolution of the atrial signal. Data are prewhitened in the time domain and then transformed into the frequency domain using an T_f-point FFT, with T_f chosen as:

$$T_f = 2^{\lceil log_2 T \rceil} \quad (1)$$

where T is the length of the recording in the time domain, expressed in number of samples, and function $\lceil \cdot \rceil$ denotes the closest integer equal or larger than its argument. The search for directions of maximum independence is performed in the frequency domain and relies on higher order statistics (kurtosis contrast). The extracted sources are then transformed back to the time domain. To identify the AA among the 12 independent sources, we exploit the fact that the AA typically shows a narrowband frequency spectrum, whereas VA is a wideband signal. Hence, SC is employed as an indicator of AA quality [9]. This index is defined as:

$$SC = \frac{\sum_{0.82 f_p}^{1.17 f_p} P_{AA}(f)}{\sum_{0}^{f_s/2} P_{AA}(f)} \quad (2)$$

where P_{AA} is the Power spectrum of the estimated AA, f_p is the peak frequency and f_s is the sampling frequency. The atrial source is detected among the 12 independent components by selecting the one with highest SC and dominant peak in the 3-9 Hz range, which is considered the typical AF frequency band. To account for the quasi-periodic character of AA in AF, fundamental frequency and the second harmonic (f_p and $2f_p$) are considered for the computation of SC in the present study.

2.3 Measurement of the AFDF

From the atrial signal provided by each of the three methods under investigation the AFDF was computed as follows. To assess the temporal evolution of AFDF,

	AFDF (Hz) (mean ± std)	SC (mean ± std)	r (p-value)
EGM Ref.	6.14 ± 0.72	81.9 ± 5.37	-
R.ICA-f	5.77 ± 0.68	68.2 ± 10.4	$0.57\ (< 0.01)$
ASVC	5.69 ± 0.95	45.6 ± 8.71	0.21 (NS)
STC	5.69 ± 0.93	41.0 ± 9.05	0.26 (NS)

Table 1: AFDF, SC and r over the 20 ECG recordings; std stands for standard deviation; SC is expressed in %.

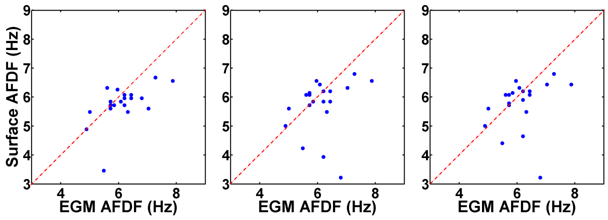
the obtained atrial signal was windowed as for the RobustICA-f described above (8 s segments, 7 s overlap). The power spectrum density (PSD) of each segment was computed using Welch's averaged modified periodogram as in [8], [9] (4096-point Hamming window, 2048-point overlap and 8192-point Fourier transform). AFDF was then calculated as the peak frequency of the PSD in the 3-9 Hz range. The median of the AFDF among the different segments was finally taken as the best estimation of the AFDF for a given patient, because of the robustness of this measure to outliers compared to the sample mean. EGM recordings were analyzed as aforementioned for ECG recordings, but were first preprocessed using the method proposed in [13] to overcome the difficulties brought by the sharp biphasic morphology of the atrial depolarization waves in bipolar EGMs.

2.4 ECG/EGM correlation analysis

Linear regression analysis and Pearson's correlation coefficient r were used to assess the correlation between ECG and EGM AFDF. Statistical significance was tested using Student's t-test. The correlation was considered significant for values of $p < 0.05$. NS stands for non-significant. The values of AFDF and SC provided by the three methods under investigation were compared using one-way ANOVA and a multiple comparison test to determine which pairs of SC distribution means were significantly different. Gaussianity of the distributions was verified using Lilliefors test.

3 Results

Results of the comparison between the three extraction methods are summarized in Table 1, where the performance of each method is expressed in terms of SC and r values, as well as statistical significance of correlation (p-value). The results of EGM/ECG AFDF correlation are presented in Fig. 1, where the scatter plots for each of the method under comparison are shown, as well as the $x = y$ reference line. Correlation between EGM and ECG AFDF was found to be significant only for RobustICA-f, whereas the mean surface ECG AFDF values computed with the different methods are not statistically different ($p = 0.26$). ANOVA and multiple comparison tests also showed that the SC value obtained employing RobustICA-f is significantly higher than for the two other methods under investigation ($p < 10^{-8}$). The box-and-whiskers plot in Fig. 2 visually confirms this result.



(a) (b) (c)

Figure 1: ECG/EGM AFDF correlation after AA extraction using (a) RobustICA-f, (b) ASVC and (c) STC.

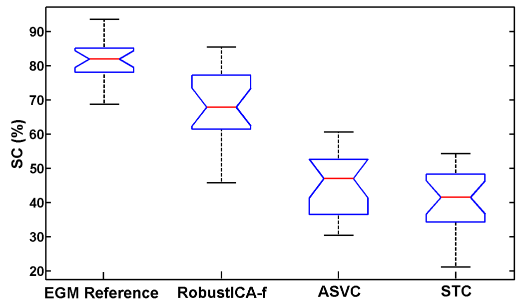


Figure 2: Box-and-whiskers plot of the SC for the EGM reference and the methods under comparison.

4 Discussion

This study compared three different methods for AA extraction from ECG recordings in AF by means of EGM/ECG correlation and SC of the estimated AA signal. The correspondence between EGM/ECG AFDF correlation and mean SC values provides additional support for the validity of SC as an atrial extraction quality index, and points to the possibility of using EGM/ECG correlation for validating other ECG-based criteria

Results from 20 persistent AF recordings showed that the BSS-based technique provides the best results in terms of SC and r. The manual selection of parameters required by the ASVC and the STC methods appeared to play an important role in determining their final comparative performance. In particular, the identification of QT segments for QRST synchronization prior to averaging is manually defined, as in [6], thus making the algorithm less robust to QRST length changes and strong heart rate variability. In order to show the importance of this point, the computation of performance parameters was repeated discarding two patients showing a strong heart rate variability. For these two patients the estimated AA after QRST suppression by ASVC and STC resulted strongly affected by T-wave residuals, due to poor QRST interval segmentation. If the remaining 18 patients are considered, EGM/ECG correlation becomes significant for these two methods (ASVC: $r = 0.60$, $p < 0.01$, SC$= 40.8 \pm 15.9$, STC: $r = 0.53$, $p < 0.05$, SC$= 30.64 \pm 19.9$), whereas the performance of RobustICA-f does not improve so significantly($r = 0.70$, $p < 0.01$, SC$= 64.2 \pm 23.30$). Moreover, STC could probably obtain better performance with the adaptive beat selection strategy proposed for ASVC, but testing this was out of our scope.

The study of the correlation between EGM and ECG AFDF for the validation of surface-based parameters has already been proposed in [14], where the AFDF estimated from precordial lead V1 appeared to be strongly correlated with the AFDF estimated from EGM signals recorded by means of unipolar electrodes placed on the epicardium of the right atrium. The mismatch between the correlation results in [14] and the present work should be attributed to the different placement of electrodes, the epicardium in the former, the endocardium in the latter. The endocardium is the inner layer of the heart and the surface where the atrial depolarization wave starts propagating towards the epicardium. Hence, endocardial EGM are expected to provide a more localized information about atrial depolarization compared to epicardial ones. Especially for those patients whose fibrillatory activity is highly disorganized, endocardially recorded propagation should not necessarily be totally reflected on surface ECG recordings, where rather global information about fibrillatory activation is captured. Moreover, in the present work the endocardial electrodes were placed within the left atrium, which is further away from lead V1 than the right atrium. This may explain the result that the lowest r value was obtained when ASVC is employed, as it only considers lead V1 for AFDF estimation.

In [5] it is shown that the atrial cycle length computed within the LAA highly correlates with the atrial cycle length manually measured on lead V1 for 90 patients in persistent AF. Nevertheless, the spatial variability of AFDF should be explored for the patients in our database to make sure that LAA can be used as a reference.

Another limitation of this study was the use of a spectral parameter, SC, as an ECG-based indicator of AA extraction quality. Other indicators exist [1], [6], [11] but they have not been considered, due to space constraints. Further extensions of this study should include the evaluation of different ECG-based extraction quality assessment criteria by means of the proposed comparison with the values of ECG/EGM AFDF correlation.

5 Conclusions

The present study compared three methods for non-invasive AA extraction. A new criterion for the assessment of the comparative performance of these methods was proposed, based on the correlation r between EGM and ECG AFDF. This choice relies on the importance of AFDF in the study of AF and on the possibility of using its endocardially recorded value as a reference for the one recorded on the body surface. Performance results obtained through the proposed criterion were compared with those offered by SC. It was shown that the two criteria provide similar information in terms of comparative performance assessment. Hence, the correlation-based criterion appears to validate ECG-only based criteria. Moreover, the BSS-based RobustICA-f method was shown to outperform the ABS-based ASVC and STC methods both in terms of r and SC index. However, we argued that the comparative performance of ASVC and STC could probably be improved by defining their QT-interval segmentation parameters in a more adaptive fashion.

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