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Exploiting Intracardiac and Surface Recording Modalities for Atrial Signal Extraction in Atrial Fibrillation

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Abstract— **During atrial fibrillation (AF), atrial activity (AA) on the surface ECG consists of a pattern of quasi-periodic oscillations (f-waves), which are related to the electrical activation of the atrial substrate. However, to date no direct comparison between the extracted f-wave pattern in surface recordings and specific activation sites within the atria has been carried out. In the present study, one reference intracardiac modality consisting of a bipolar electrogram (EGM) recorded from the left atrial appendage (LAA) is exploited for the first time to guide the extraction of LAA electrical activity from standard 12-lead ECG recordings. A periodic component analysis (πCA) technique is employed for this task. The performance of the proposed multimodal extraction technique is compared to that obtained employing a noninvasive, fully blind approach, namely, independent component analysis (ICA). On a database of 31 AF patients, results suggest that the estimation of LAA activity is indeed possible, even though its contribution to the ECG total power is relatively low. Interestingly, ICA seems to provide a slightly better estimation of LAA activation rate, expressed in terms of dominant frequency (DF). On the other hand, the multimodal invasive approach performs better QRST complex suppression and provides AA waveforms with narrower spectra.**

I. INTRODUCTION

Atrial fibrillation (AF) is a form of supraventricular arrhythmia characterized by a broad variety of atrial activity (AA). The depolarization of the atrial substrate is triggered by the presence of ectopic sources of electrical activity and is characterized by the propagation of multiple self-sustaining wavelets [1]. Invasive techniques, consisting of uni- or multi-polar intracardiac mapping catheters placed in both left and right atrium (LA and RA, respectively), have been adopted to explore AA in different sites of the atria. From the measured electrograms (EGM), information can be obtained about the number and location of propagating wavelets, local wave propagation velocity and activation rate, usually expressed as dominant frequency (DF). This latter has received particular attention, as it is thought to correlate to atrial tissue refractoriness and thus to provide understanding of AF electrophysiological properties [2].

As opposed to invasive techniques, the surface electrocardiogram (ECG) provides a noninvasive and inexpensive tool to study AF. AA on ECG recording takes the shape of a fluctuating baseline (f-waves), whose morphological and spectral properties have been correlated with the response to treatment [3], [4]. The ECG gives an insight into the propagation of the electrical fields resulting from heart cells activation. Hence, whereas the EGM provides information about local cellular activation, the ECG represents the electric potential resulting from the sum of the electrical vectors due to several sources, both of atrial and ventricular origin. For these reasons, the EGM and ECG recordings can be considered as two distinct modalities.

Understanding the contributions of the propagating wavelets to the ECG recordings during AF is an important topic, with the potential to make the ECG an even more powerful clinical tool to treat AF. In [4], a comparison carried out in terms of DF between ECG lead V1 and simultaneous EGMs, showed that the considered lead mainly contains RA activity. The only work that considers the contribution of AA to the standard 12 ECG leads is that found in [5], where a study is carried out to elucidate which leads better reflect AA in the LA. Although the above cited works establish a link between EGM and ECG modalities, they only focus on the DF, without quantitatively specifying to which extent one specific AA pattern contributes to the whole ECG.

In the present work, the direct extraction of LA activity from the 12-lead ECG recording is attempted for the first time. To this purpose, one EGM from the left atrial appendage (LAA) is simultaneously recorded with the ECG and is employed to guide the extraction, in a semi-blind approach that exploits the pseudo-periodicity of AA during AF and the synchronicity between the two modalities. Periodic component analysis (πCA), a decomposition technique specifically designed for pseudo-periodic sources, is considered to solve this problem. The method was first employed in [6] for the extraction of fetal activity from abdominal ECG recordings but, to our knowledge, its application to AF signal analysis has never been attempted before. Moreover, a restatement of πCA is proposed in this work, in order to make the algorithm better suited for the problem in hand.

The multimodal approach for AA extraction is compared to a classical fully blind source separation (BSS) method, the independent component analysis (ICA). BSS and ICA have been shown to successfully tackle the extraction of AA in AF ECG recordings exploiting the spatial diversity provided by multiple leads [7], [8], [9]. Interestingly, in all these works the analysis of AA has been limited to that of the most significant AA-related signal: following ICA, the source showing the highest spectral concentration (SC) is retained as the most representative of the global AA derived from all leads. Further information of atrial origin that may be possibly present in the other ICA components is therefore

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neglected. For this reason, in the present work the ICA source showing the strongest agreement in DF with the reference LAA EGM is retained and compared to the ICA source with the highest SC and the multimodally-extracted source. On a database of 31 AF patients, blindly and multimodally extracted AAs were compared in terms of their agreement in DF with the LAA EGM, as well as of two extraction quality assessment parameters, such as a QRST residual index [10] and SC [8]. Finally, a study of the contribution of the atrial sources to the ECG leads in terms of explained power is performed to show the applicability of the method presented.

II. METHODS

A. Database, Signal Acquisition and Preprocessing

Standard 12-lead ECG were recorded on 31 patients affected by long-lasting persistent AF and undergoing stepwise catheter ablation at the Cardiology Department of Princess Grace Hospital, Monaco. One simultaneous invasive recording was also obtained for each patient, by placing a bipolar catheter within the LAA. Recordings were acquired at a sample rate of 977 Hz and lasted about 60 s each.

ECG recordings were filtered by a 4th order zero-phase band-pass Chebyshev filter with a lower cutoff frequency of 3 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 myoelectric interference.

LAA EGM recordings were preprocessed using the method proposed in [11] to overcome the difficulties brought by the sharp biphasic morphology of the atrial depolarization waves in bipolar EGMs, which makes Fourier analysis easily fail in representing the actual depolarization rate of the atrial tissue. The so-preprocessed EGM is transformed in the frequency domain and the LAA DF is determined as the peak frequency of Welch's power spectral density estimate.

B. Blind Atrial Activity Extraction

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. We employed the RobustICA-f algorithm [9], since it has been shown to compare favorably to other AA extraction techniques. ICA-based algorithms, such as RobustICA-f, typically exploit the fact that the AA shows a narrowband frequency spectrum to detect the atrial source among the 12 ICA sources. SC is taken as a measure of spectrum narrowness:

$$\mathrm{SC} = \frac{\sum_{0.82 f_p}^{1.17 f_p} P_{AA}(f)}{\sum_{0}^{f_s/2} P_{AA}(f)} \tag{1}$$

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 source s with peak frequency in the 4-9 Hz range and the highest SC is typically selected as representative of AA, and its $f_p(s)$ is taken as the AA DF. The ICA method based on this source selection criterion will be referred to as ICA_{sc} hereafter.

In this work, we argue that LAA activation information may be present in sources with SC values lower than the maximum. Therefore, we also retain the source s_{laa} satisfying the following condition:

$$s_{laa} = \min_{s} |\mathrm{DF}_{laa} - f_p(s)| \tag{2}$$

where DF_{laa} is the DF of the LAA EGM modality. Hence, the agreement in terms of peak frequency between the sources issued from RobustICA-f and the LAA EGM is also employed as a criterion for source selection; the resulting method is hereafter denoted by ICA_{laa}.

C. Periodic Component Analysis (πCA)

This method represents an algebraic alternative to ICA for the extraction of one or more cyclic sources whose periodic structure is known a priori. The method was extended to periodic sources with time-varying period in [6], where it was also applied to the extraction of the fetal ECG from maternal abdominal leads.

Assume the period τ of a specific source of interest is known. Then source extraction is performed by the weight vector $\hat{\mathbf{w}}$ that maximizes the following measure of τ-periodicity:

$$\psi = \frac{\mathbf{w}^T \mathbf{C}_\tau \mathbf{w}}{\mathbf{w}^T \mathbf{C_0} \mathbf{w}} \tag{3}$$

where $\mathbf{C}_\tau$ and $\mathbf{C_0}$ are the observation covariance matrices at lag τ and 0, respectively. Maximization of (3) is obtained by choosing the highest eigenvector/eigenvalue pair $(\mathbf{v}, \lambda)$ that solves the generalized eigenvalue decomposition problem $\mathbf{C}_\tau \mathbf{v} = \lambda \mathbf{C_0} \mathbf{v}$, and taking $\hat{\mathbf{w}} = \mathbf{v}$. This corresponds to jointly whitening the data and diagonalizing matrix $\mathbf{C}_\tau$, which performs source extraction under the given model assumptions.

When the source of interest presents a time-varying period τ_t, the method proposed in [6] suggests to assign a linear phase function $\phi(t)$ to each sample, in order to phase-wrap the τ_t-periodic cycles onto the $[-\pi, \pi]$ interval, relative to a significant feature of the signal (e.g., an amplitude peak) that repeats in a quasi-periodic manner. The time-varying period τ_t is determined on a sample-to-sample basis, so as to satisfy the following condition:

$$\tau_t = \min\{\tau \mid \phi(t+\tau) = \phi(t), \tau > 0\}. \tag{4}$$

This method is particularly suitable for the problem in hand, as AA is a pseudo-periodic signal, whose prior information about the period can be obtained from the intracardiac modality. Peak detection is performed on the LAA signal and each peak-to-peak interval is employed to define $\phi(t)$ and determine τ_t for recovering the projection of LAA AA on the ECG recording.

D. πCA for AA Extraction with EGM Modality

The phase-wrapping procedure performed by πCA aims at making each sample as phase-aligned as possible to its corresponding sample at the following cycle, as shown in (4). Although this is suitable in an application such as

that presented in [6], where each cycle is characterized by several components (i.e., the P, Q, R, S and T-waves), this condition appears too hard on a signal with a less defined pattern, such as AA on the ECG. Moreover, $\phi(t)$ implicitly deforms the signal waveform before performing the correlation, especially if the period of atrial activations presents a strong variability. For these reasons, in the present study the condition in (4) is relaxed, imposing that only the samples in correspondence with the LAA EGM peaks be perfectly aligned. Matrix $\mathbf{C}_\tau$ at the nominator of (3) is replaced by the following second order statistics:

$$\Gamma_k = \sum_{i=1}^{N-k} \mathbf{x}_i(t)\mathbf{x}_{i+k}^T(t), \qquad k = 1, 2, ..., K \tag{5}$$

where $\mathbf{x}_i(t)$ is the vector containing the 12-lead observation segments centered around the i^{th} LAA depolarization peak, with $i = 1, 2, ..., N$, and K is the maximum period-lag considered. In the following, this modified version of the πCA algorithm will be referred to as πCA_{mod}.

III. RESULTS

A. Dominant Frequency Correlation Analysis

Fig. 1 shows the correlation between the DF of the reference EGM modality and the AA sources extracted from the ECG with the different criteria considered for the 31 patients in our database. Note that, although all criteria produce high correlation coefficients, the ICA_{sc} source shows the poorest agreement with the LAA (Fig. 1(a)).

The πCA method proposed in [6] (Fig. 1(c)) performs slightly worse than the restated version of the algorithm (Fig. 1(d)), thus supporting the relaxation on phase-alignment made in Section II-D.

The comparison between Fig. 1(b), (c) and (d) suggests that the RobustICA-f algorithm based on criterion (2) performs slightly better than the multimodal approach, providing the strongest agreement in DF between ECG-extracted AA activity and the LAA EGM.

B. Extraction Quality Assessment

The quality of the extracted sources is tested in the time domain by comparing the intervals of ventricular activation (QT segments) to the intervals of ventricular latence (TQ segments). To this purpose, a ventricular residual (VR) index is adopted as in [10]. For the sake of completeness, a comparison is also performed in terms of the SC index given in (1), which has previously been employed in the ICA algorithm as a source selection criterion [8].

Results of this analysis are depicted in Fig. 2, where performance differences among the different methods can be appreciated. The ICA_{laa} clearly presents the strongest QRST complex residual, despite the high correlation with the reference AA in terms of DF, as seen in the previous section. On the other hand, ICA_{sc} AA barely contains any ventricular remainder, despite the comparatively low agreement with the LAA EGM. The multimodally-extracted sources perform equally well relative to each other and better than ICA_{laa}.

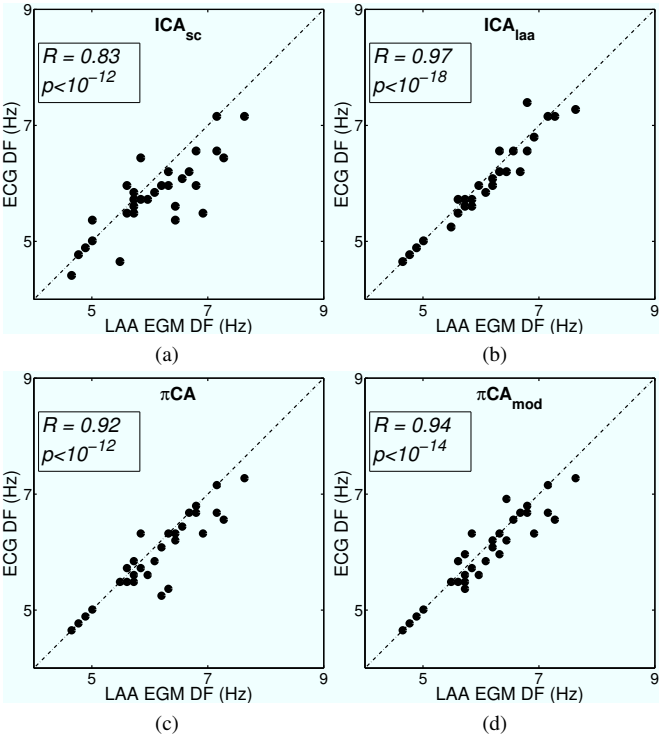

Fig. 1. Correlation between LAA DF and DF of the source obtained by the four methods under comparison. Top panels: ICA with AA selection criterion based on (a) SC value (ICA_{sc}) and (b) on agreement in DF with LAA (ICA_{laa}). Bottom panels: πCA, (c) as proposed in [6] and (d) in its modified version (πCA_{mod}).

The results of the analysis in terms of SC, reported in the box-and-whiskers plot on the right of Fig. 2, are in general agreement with those relative to the VR index, suggesting that the two indices employed are strongly correlated in assessing extraction quality.

C. Contribution of the LAA to the surface ECG recording

The contribution of the estimated source $s(t)$ to the ECG observations $\mathbf{x}(t)$ is found as follows. First, the linear regression problem $\mathbf{x}_{tq}(t) = \hat{\mathbf{h}} s_{tq}(t)$ is solved via the minimum mean square error solution, with $s_{tq}(t)$ normalized to unit power. Subscript tq indicates that only the TQ segments of the signals are considered, in order to avoid that the ventricular residuals in the extracted source affect the estimation of weight vector $\hat{\mathbf{h}}$. Next, the relative power of lead l explained by source $s(t)$ is found as:

$$P_l^s = \frac{\hat{h}_l^2}{r_{ll}}, \qquad l = 1, 2, ..., 12 \tag{6}$$

where r_{ll} is the l^{th} diagonal entry of the observations correlation matrix $\mathbf{R} = E\{\mathbf{x}(t)\mathbf{x}^T(t)\}$. Similarly, the total contribution of source $s(t)$ to the 12 leads is determined as:

$$P_{ECG}^s = \frac{\hat{\mathbf{h}}^T\hat{\mathbf{h}}}{\text{tr}(\mathbf{R})} \tag{7}$$

where function $\text{tr}(\cdot)$ denotes the trace of a matrix.

The box-and-whiskers plot on the left panel of Fig. 3 shows that the πCA_{mod} source contribution to the total ECG power is quite modest with respect to the ICA_{sc} source. The

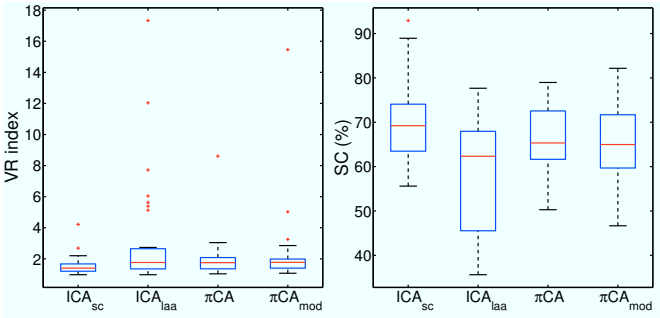

Fig. 2. Extraction performance assessment for the four methods considered, in terms of the VR index (left) and the SC index (right).

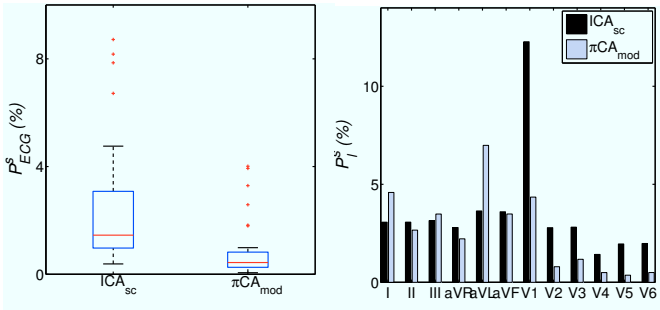

Fig. 3. Contribution of ICA_{sc} and πCA_{mod} sources to the 12-lead ECG in terms of explained power. Contribution to the full ECG (left) and to the ECG leads considered individually (right).

histogram on the right side of the figure shows that the ICA_{sc} source significantly contributes to lead V1, whereas the LAA source does not. Although the comparative contribution of the ICA_{sc} source is higher for almost all leads, the LAA source contributes best on limb lead I and augmented lead aVL. Note that the ICA_{laa} and πCA methods have been discarded from this analysis for the sake of clarity, since they were shown to perform similarly to the πCA_{mod} in terms LAA source extraction quality.

IV. DISCUSSION AND CONCLUSIONS

The present work has attempted for the first time the direct extraction of the LAA activation pattern on the multilead ECG during AF. Previous works [3], [4] aimed at determining how the AA is reflected on the ECG recordings during AF, but their analyses were limited to lead V1. The study in [5] is an exception, in that it considered the 12 standard leads, but only focused on the agreement in DF between EGM and ECG modalities. In the present work, the knowledge about the time instants of LAA depolarization provided by the peaks in the EGM modality has been explicitly exploited to guide the extraction of a local AA. The good results obtained in terms of correlation in DF between the multimodally-extracted source and the LAA EGM recording, as well as of extraction quality both in time and frequency domains, corroborates the suitability of the proposed approach.

Furthermore, we have compared the multimodally-extracted sources with those obtained by means of a fully blind approach (ICA). We have shown that the ICA source typically considered as representative of the global AA generally shows a comparatively low correlation in DF with the LAA EGM. On the other hand, other ICA sources that are neglected by the typical selection criterion seem more representative of LA electrophysiology. In our analysis of the contribution of the extracted sources to the ECG, the strong percentage of power explained by the ICA_{sc} source supports the idea that it is representative of the global AA derived from all leads. The fact that its agreement in DF with the LAA EGM is relatively low and its contribution to lead V1 is significant, may also mean that it better reflects RA electrophysiology, which is considered to be responsible for the major contribution to the f-waves in lead V1 [4]. On the other hand, the multimodally-extracted AA seems to reflect a more localized AF electrophysiology, as its overall contribution to the ECG is low. Its comparatively low contribution to V1 agrees with the fact that the LA is hidden behind the RA from the point of view of this lead.

In conclusion, the direct implications of this work are twofold. First, it opens the way to the explicit analysis of a local AA pattern on the multilead ECG recording during AF. Second, a new approach to source selection for AA extraction using ICA has been put forward, suggesting that atrial electrophysiology may be spread among several independent sources. These results should be corroborated by more extensive intracardiac measurements in future works.

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