Preservation of Spatial Transfer Coefficients in Surface ECG Atrial Fibrillation Analysis

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Abstract

This study demonstrates empirically that the transfer coefficients, relating epicardial potentials and ECG potentials, are preserved approximately throughout several seconds of real atrial fibrillation (AF) recordings. The methodology has consisted of applying independent component analysis over an AF segment to obtain both atrial and ventricular activities along with the mixing matrix of the process, whose entries can be associated to the spatial filter coefficients that relate cardiac activities with ECG potentials. Next, it is demonstrated that the coefficients from one AF segment can be used to extract the atrial activity (AA) present in different segments of the same recording, thus proving the preservation of the spatial filters. Results over 32 AF segments show a mean cross-correlation of $\overline{R}_{dp} = 81.5\%$ between the directly estimated AA and the estimated using the preservation property. Changes in spectral concentration from one case to the other ($\overline{\Delta SC}_{dp} = 1.4\%$) are negligible.

1. Introduction

Atrial Fibrillation (AF) has been the subject of intense investigation in recent years but, at the moment, there is still incomplete knowledge about the mechanisms of this arrhythmia [1]. AF is the most common sustained arrhythmia and occurs in 0.4% to 1.0% of the general population. Besides, up to 10% of the population older than 80 years has been diagnosed with AF [2]. Through invasive electrophysiological studies it has been possible to assess that atrial and ventricular activities can be regarded as uncoupled, thus, making it possible to consider them as statistically independent [3]. This fact allows to apply successfully independent component analysis (ICA) techniques, to separate uncoupled cardioelectric activities [4]. Moreover, ICA has been used successfully in applications related to AF like the suppression of artifacts from internal epicardial recordings [5] and the discrimination among supraventricular arrhythmias [6].

With the aid of the forward electrocardiography [7] it is well known that movements of the heart, such as chaotic contraction of the atria during fibrillation, contraction of the ventricles in the cardiac cycle and other relative movements, causes changes in the spatial transfer coefficients that relate the epicardial potentials and the body surface ECG potentials that may affect the recorded signal [8]. In this work we present a study to demonstrate empirically that these transfer coefficients (or spatial filters) are preserved approximately throughout several seconds of real AF recordings, thus clarifying that there is no significant variation in these spatial filters and, hence, its influence over the resulting ECG signal in AF recordings is negligible. In addition this observation proves that the physical sources of the heart can be considered as spatially stationary in AF studies.

2. Spatial transfer coefficients study

Having a column vector of observed signals, $\mathbf{x}$, obtained by linearly mixing a column vector of sources, $\mathbf{s}$, with a mixing matrix $\mathbf{A}$, the matrix form ICA model can be defined as $\mathbf{x} = \mathbf{A}\mathbf{s}$ [9]. Therefore, the skin-electrode signal vector arising from the 12–lead ECG in AF can be identified with the set of observations, the set of sources being composed of the independent atrial and ventricular cardiac activities and other nuisance signals. Finally the mixing matrix entries will depend on body geometry, tissue conductivity, electrode position, etc., and can be associated with the transfer coefficients relating the potentials from the heart towards the body surface [3, 4].

To corroborate the spatial filters preservation we propose to analyze each AF recording divided into two non-overlapped segments (see Fig. 1). In the first segment we can define the directly estimated atrial activity, $\widehat{\mathrm{AA}}_{d1}$, as the activity obtained after performing ICA over it. This will also give us the mixing and separation matrices for the first segment, $\mathbf{A_1}$ and $\mathbf{W_1}$, respectively, where $\mathbf{W_1} = \mathbf{A_1^{-1}}$. Following the same procedure, it is possible to obtain $\widehat{\mathrm{AA}}_{d2}$ and matrices $\mathbf{A_2}$ and $\mathbf{W_2}$ for

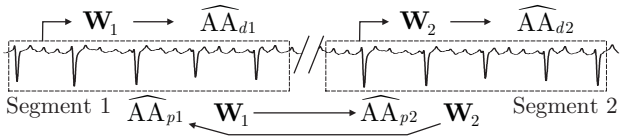

Figure 1. Proposed methodology for the spatial filters preservation analysis. In each AF segment the AA can be directly estimated ($\widehat{\mathrm{AA}}_{d1}$ and $\widehat{\mathrm{AA}}_{d2}$) or indirectly via the preservation property ($\widehat{\mathrm{AA}}_{p1}$ and $\widehat{\mathrm{AA}}_{p2}$).

the second segment. Hence, the verification of the spatial transfer coefficients preservation will consist of applying the separation matrices $\mathbf{W_1}$ and $\mathbf{W_2}$ over the second and first ECG segments, respectively, with the aim of obtaining the activities $\widehat{\mathrm{AA}}_{p2}$ and $\widehat{\mathrm{AA}}_{p1}$ (see Fig. 1). Evaluating the similarity degree between $\widehat{\mathrm{AA}}_{d1}$ and $\widehat{\mathrm{AA}}_{p1}$, for the first segment, and $\widehat{\mathrm{AA}}_{d2}$ and $\widehat{\mathrm{AA}}_{p2}$ for the second one, it will be possible to assess the preservation of the mixing matrix between segments and, hence, of the spatial filters.

3. Measurement of estimation quality

Considering that the typical spectral morphology for AA is characterized by a very pronounced peak in frequencies from 5 to 8Hz, with no harmonics and insignificant amplitudes above 15Hz [10], it is possible to define a performance extraction index capable of evaluating AA extraction quality based on the spectral concentration [11]. The spectral concentration (SC) can be defined as

$$SC = \left(\int_{0.82 f_p}^{1.17 f_p} P_{AA}(f) df \right) \Big/ \left(\int_{0}^{\frac{f_s}{2}} P_{AA}(f) df \right) \quad (1)$$

where f_p is the frequency of the AF main peak, P_{AA} is the power spectral density (PSD) of the AA signal and f_s is the sampling frequency. Note that SC is able to evaluate the decrease in spectral concentration around the main atrial peak due to the presence of other nuisance signals (mainly ventricular activity, ECG artifacts and noise). Considering that one AA signal has a concrete PSD, a high SC will indicate an efficient elimination of non-AA components and, therefore, SC can be used as an extraction quality index. Note that the problem here is the a priori unavailability of the AA signal that has to be estimated when dealing with real AF recordings.

4. Methods

To evaluate the spatial transfer coefficients preservation AF recordings were analyzed from the authors' own signal database. The database comprised 12-lead ECG recordings from 16 patients in persistent AF sampled at 1kHz. To corroborate the preservation property over each AF patient the procedure consisted of selecting a 20 second recording; then, FastICA was applied over the first 8 seconds, thus comprising the first segment, and giving us $\widehat{\mathrm{AA}}_{d1}$, $\mathbf{A_1}$ and $\mathbf{W_1}$ for that patient. Next, the second segment comprised the last 8 seconds in the recording (from 12 to 20s.), obtaining $\widehat{\mathrm{AA}}_{d2}$, $\mathbf{A_2}$ and $\mathbf{W_2}$, thus the segment distance for each AF recording was 4 seconds in length. Next, by using the separation matrices, the AA estimation from each segment was obtained indirectly to verify the coefficients preservation property. Therefore $\widehat{\mathrm{AA}}_{p1}$ was extracted using $\mathbf{W_2}$ and $\widehat{\mathrm{AA}}_{p2}$ using $\mathbf{W_1}$, respectively. The FastICA algorithm was used to perform the ICA separation due to its availability, fast convergence and robust performance [9].

In order to analyze the AA derived from ICA and compute the spectral concentration, the PSD was calculated for the separated source associated with AA. The procedure consisted of obtaining the modified periodogram using the Welch–WOSA method [12] with a Hamming 4096 point window, a 50% overlapping between adjacent windowed sections and an 8192-point FFT. The spectral content above 20Hz was discarded due to its low contribution.

5. Results and discussion

Fig. 2 shows the AA waveforms obtained after applying ICA over the first segment of patient #10 and the same activity obtained via $\mathbf{W_2}$, i.e., making use of the preservation property. As can be seen, a significant similarity exists between both waveforms, thus corroborating the pseudostationarity of the mixing matrix and, hence, the preservation of the spatial transfer coefficients. Below the waveforms are the PSD representations of both activities. As can be seen, the spectral morphology and main peak frequency are extremely similar, being very difficult to distinguish between them by visual inspection. There is a slight variation in the main peak amplitude and in the spectral concentration (SC_{d1} vs SC_{p1}), quite acceptable when dealing with real AF recordings. Therefore, the only way of establishing differences between both activities is using the spectral concentration. This parameter let us know that the direct method is able to give better results than the indirect one, but, on the other hand, the latter demonstrates the preservation property. Also for this AA estimation pair, the cross-correlation percentage between both waveforms is 81.7%.

The aforementioned high-similarity results in time and frequency domain for the directly and indirectly estimated AA, proving the preservation of the spatial filters, can also be reinforced via the analysis, for each segment, of the ICA mixing matrix column associated with AA. In this

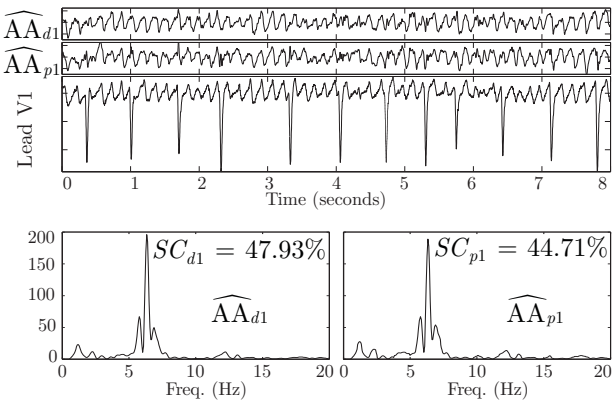

Figure 2. Waveform of the directly estimated atrial activity $\widehat{\mathrm{AA}}_{d1}$ from the first segment of patient #10, and the same activity obtained by means of the preservation property $\widehat{\mathrm{AA}}_{p1}$. Lead V1 is included for comparison. Below it is shown the PSD of both activities together with the spectral concentration values.

sense, Fig. 3 plots the absolute value of the columns for the mixing matrices $\mathbf{A_1}$ and $\mathbf{A_2}$ associated with the AA source from the ECG recording of Fig. 2. As can be seen, AA spreads across all the ECG leads, but showing a clearly larger contribution in leads II, III, aVF and V1. It is accepted by electrophysiological studies that these leads present the larger amount of AA in the surface ECG [2], hence, the result of the ICA mixing matrices verifies this observation.

With the comparison, from the first to the second segment, between the column entries across these most relevant AA leads, it is possible to obtain an additional reinforcement of the spatial filters preservation. On the other hand, it can also be seen that the variability of the column entries for the rest of the leads seems to be larger from one segment to the other. Anyway it should be remarked that Fig. 3 only plots the columns associated with the AA source, which is the main objective of this study and, hence, the presence or absence of other extracted ICA sources may be very variable. Looking at the evolution of other mixing matrices columns, associated with sources like ventricular activity, the pseudostationarity holds in the same way as in AA and, in this case, the large variability of the entries is associated with sources other than ventricular activity.

Finally Fig. 4 illustrates the result of the spatial filters preservation analysis for the 16 patients in the database. Above each patient number there are six bars, the first three ones for the first AF segment and the others for the second segment. Within each bar group, the first bar indicates SC_{d1} in percentage, i.e., the spectral concentration of $\widehat{\mathrm{AA}}_{d1}$. The second bar is SC_{p1} associated with $\widehat{\mathrm{AA}}_{p1}$ and

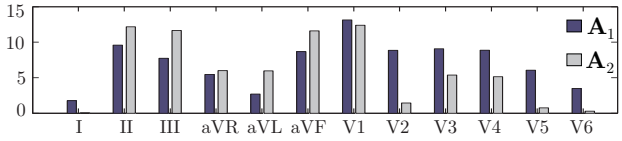

Figure 3. Column chart comparison for the entries, in absolute value, of the mixing matrices $\mathbf{A_1}$ and $\mathbf{A_2}$ related to the AA source from the ECG recording of Fig. 2.

the third bar indicates the percentage of cross-correlation between both activities within the first segment, R_{dp1}. Exactly the same is applicable to the bar group on the right above each patient. As can be seen, the differences between the SC_d and SC_p pairs for each segment and patient are generally small, the cross-correlation being lower than 75% in only 6 of the 32 cases analyzed. More concretely, the mean difference considering both segments, between SC_d and SC_p is $\overline{\Delta SC}_{dp} = 1.47\%$ in spectral concentration for all the patients, meaning that there is a very low variation in SC. Regarding correlation, its mean value for the same 32 situations is $\overline{R}_{dp} = 81.56 \pm 10.74\%$, thus reinforcing the large similarity between $\widehat{\mathrm{AA}}_d$ and $\widehat{\mathrm{AA}}_p$ for all cases.

Nevertheless, note that the application of ICA techniques for AA estimation in AF recordings assumes the fulfillment of the ICA model for this biomedical problem. Therefore, results are based on the statistical analysis of the data and may not be completely correct if the ICA model does not exactly hold. More specifically, it will only be possible to derive the spatial filters associated with the mixing matrix entries and the sources from the ECG, when the physical sources associated with heart's activity are spatially stationary in time and the total number of these sources is lower than the observations (ECG leads), as indicated in [13]. Strictly speaking, movements of the heart, such as contraction of the atria during fibrillation, contraction of the ventricles in the cardiac cycle, and other relative movements from sources to observations, like patient's own breathing, could violate the ICA assumption of spatial stationarity of the physical sources. In general, the authors consider that these possible variations do not affect significantly the ICA model for AF episodes. This consideration is sustained by means of several observations. Firstly, results providing the estimation of the AA waveform have demonstrated its validity in previous works [4]. Secondly, the comparison of the main atrial frequency of AA using this ICA-based BSS technique gives similar results to those obtained through the application of other accepted AA extraction techniques, as proved in [10]. Finally, the mixing matrix pseudostationarity corroboration gives the final support to say that the 12-lead ECG of an AF recording fulfills the instantaneous linear mixing ICA model.

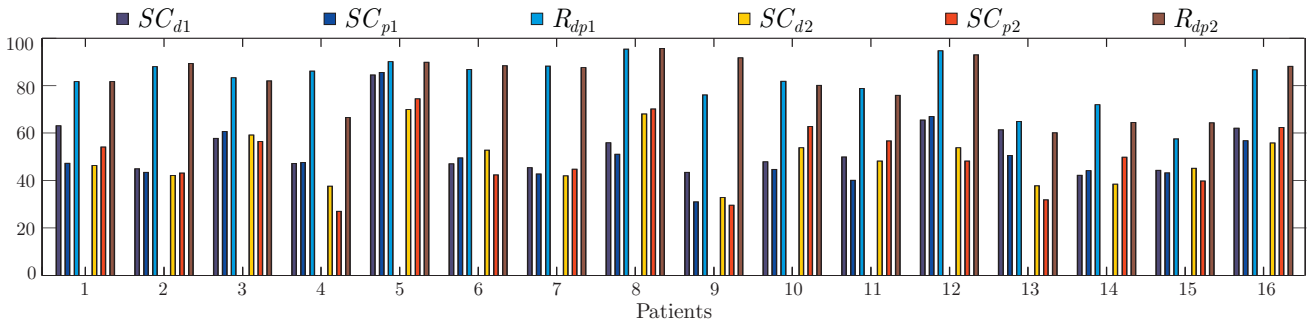

Figure 4. $SC(\%)$ for each segment and cross-correlation between activities for the direct and the indirect methodology.

6. Conclusions

The present contribution has demonstrated that the AA from one AF segment can be recovered applying the separation matrix from a different segment of the same recording. This observation gives the definitive support to the fulfillment of the instantaneous linear mixing ICA model for the ECG in AF. Besides, there is no significant variation in the spatial filters being negligible its influence over the resulting ECG signal in AF recordings. This proves that the physical cardiac sources can be considered as spatially stationary. This fact may imply the birth of other ICA-based studies on the evolution and periodicity of the spatial filters across the cardiac cycle or the patient's own breathing, not only in atrial fibrillation, but in other supraventricular arrhythmias and cardiac pathologies where atrial and ventricular activities can be regarded as decoupled or independent.

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References

[1] Waldo AL. Mechanisms of atrial fibrillation. J of Cardiovascular Electrophysiology 2003;14(s12):S267–S274.

[2] Fuster V, Ryden LE, Asinger RW, Cannom DS, Crijns HJ, Frye RL, Halperin JL, Kay GN, et al. ACC/AHA/ESC guidelines for the management of patients with atrial fibrillation. Circulation 2001;104(17):2118–2150.

[3] Rieta JJ, Castells F, Sanchez C, Moratal D, Millet J. Bioelectric model of atrial fibrillation: Applicability of blind source separation techniques for atrial activity estimation in atrial fibrillation episodes. IEEE Computers in Cardiology 2003;30:525–528, Thessaloniki, Greece.

[4] Rieta JJ, Castells F, Sanchez C, Zarzoso V, Millet J. Atrial activity extraction for atrial fibrillation analysis using blind source separation. IEEE Transactions on Biomedical Engineering 2004;51(7):1176–1186.

[5] Liu JH, Kao T. Removing artifacts from atrial epicardial signals during atrial fibrillation. International Conference on Independent Component Analysis and Blind Signal Separation ICA 2003;4:179–183, Nara, Japan.

[6] Rieta JJ, Millet J, Zarzoso V, Castells F, Sanchez C, Garcia R, Morell S. Atrial fibrillation, atrial flutter and normal sinus rhythm discrimination by means of blind source separation and spectral parameters extraction. IEEE Computers in Cardiology 2002;29:25–28, Memphis, TN.

[7] Gulrajani RM. The forward and inverse problems of electrocardiography. IEEE Engineering in Medicine and Biology Magazine 1998;17(5):84–101.

[8] Klepfer RN, Johnson CR, MacLeod RS. The effects of inhomogeneities and anisotropies on electrocardiographic fields: A 3-d finite-element study. IEEE Trans Biomed Eng 1997;44(8):706–719.

[9] Hyvarinen A, Karhunen J, Oja E. Independent Component Analysis. John Wiley & Sons, Inc., 2001.

[10] Langley P, Stridh M, Rieta JJ, Sörnmo L, Millet J, Murray A. Comparison of atrial rhythm extraction techniques for the detection of the main atrial frequency from the 12-lead ECG in atrial fibrillation. IEEE Computers in Cardiology 2002;29:29–32, Memphis, (TN).

[11] Castells F, Ruiz R, Rieta JJ, Millet J. An integral atrial wave identification approach based on spatiotemporal source separation: Clinical validation. IEEE Computers in Cardiology 2003;30:717–720, Thessaloniki, Greece.

[12] Welch PD. Use of fast fourier transform for estimation of power spectra: A method based on time averaging over short modified periodograms. IEEE Transactions on Audio and Electroacoustics 1967;15(2):70–73.

[13] Jung TP, Makeig S, Lee TW, McKeown MJ, Brown G, Bell AJ, Sejnowski TJ. Independent component analysis of biomedical signals. International Conference on Independent Component Analysis and Blind Signal Separation ICA 2000;2:633–644.

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