Reconstruction of Atrial Signals Derived from the 12-lead ECG using Atrial Signal Extraction Techniques

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Abstract

Several techniques are available for the extraction of the atrial signal from the ECG. Two of these techniques, Independent Component Analysis (ICA) and Principal Component Analysis (PCA), derive global atrial signals which cannot be directly compared with the atrial signals in specific leads. An algorithm for projecting into lead V1 the global atrial signals of these techniques was developed, allowing direct comparisons with the atrial activity in V1 and the atrial signal extracted by Spatiotemporal QRST cancellation (STC) which derives the atrial signal directly from the ECG lead. The reconstructed atrial signals were divided into sections corresponding to ventricular activity and inactivity in lead V1 and compared against atrial activity in lead V1 in terms of amplitude and waveform shape.

1. Introduction

We have reported previously that three techniques for the extraction of the atrial signal from the 12-lead ECG gave close agreement in measured dominant atrial frequencies [1]. To allow a direct comparison of the extracted time domain atrial signals it is necessary to apply a reverse transform to the ICA and PCA techniques. Our aim in this study was to investigate the reconstruction of the atrial signal in a specific lead for the ICA and PCA techniques. Further we compared the atrial signals extracted by each of the techniques.

In atrial fibrillation the amplitude of the atrial signal is variable, however, since the atrial and ventricular activities are decoupled, it can be assumed that the ventricular activations have no effect on the atrial signal amplitude. Therefore, the atrial signal amplitude in times of ventricular inactivity should statistically be the same as the amplitude in times of ventricular activity. This hypothesis allows the quality of the extracted atrial signals to be assessed across the full cardiac cycle.
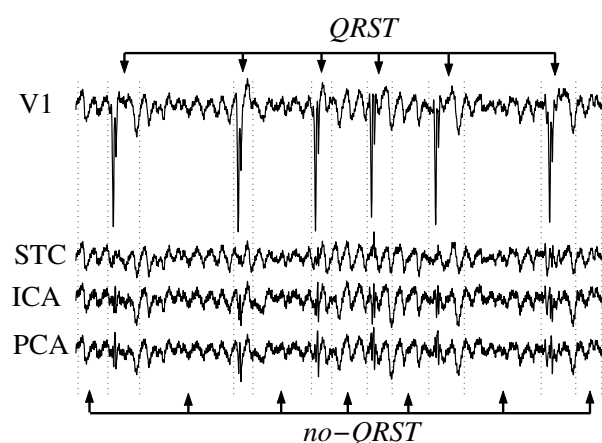

Figure 1. Illustration of *QRST* and *no-QRST* sections.

2. Methods

2.1. Data and preprocessing

12-lead ECGs from 7 patients in atrial fibrillation recorded at the Freeman Hospital were analysed. A 10 s section of the ECG for each patient was analysed. Additionally a 60 s section was used to generate QRST templates for the STC technique. Prior to analysis, the sections of each 10 s recording in lead V1 containing ventricular activities (identified as *QRST* sections) and sections containing no ventricular activities (identified as *no-QRST* sections) were selected manually (figure 1).

2.2. Extraction of the atrial signal

The techniques developed by each of the respective research groups were used. ICA was applied by the Valencia group and PCA by the Newcastle group [2][3]. These techniques separated the atrial and ventricular activities and noise into different signals (transformed signals). The separated atrial signal or signals may have contributions from each lead and represent a global measure

of the atrial activity. Mathematically, these techniques can be described by the linear transformation

$$s_i = \sum_{j=1}^{12} A_{i,j} l(j) \ (i = 1:12)$$

where, A is a matrix of transform coefficients specific to the technique in question, $l(j)$ represents the jth lead from the 12-lead ECG, and s_i are the transformed signals.

STC was applied by the Lund group. This technique derives the atrial signal directly from the ECG leads by subtraction of QRST templates derived from average beat groups from ECGs of duration 60 s [4].

2.3. Derivation of atrial signals in lead V1 for ICA and PCA

To allow direct comparisons between the time domain atrial signals produced by each of the techniques it was necessary to apply a reverse transform to the ICA and PCA atrial signals, effectively projecting the global atrial signals derived by these techniques back into the ECG leads. The reverse transform can be described by

$$\hat{l}(j) = \sum_{i=k_1}^{k_n} A_{i,j}^{-1} s_i \ (k \in 1:12)$$

where, $\hat{l}(j)$ is the reconstructed j^{th} ECG lead. The selection of transformed signals (s_i) to include in the reverse transform is important as this affects the properties of the atrial signal. Logically these would be the ones containing only the atrial activities, but these are often distributed across several transformed signals. In order to automate this selection all possible combinations of transformed signals ($2^{12} - 1$ combinations) were used to reconstruct lead V1 and the set providing the optimum atrial signal was selected. The number of tranformed signals is dependent upon the characteristics of the ECG under analysis, but would typically be less than 6. We restricted our analysis to lead V1 as this is the lead which generally exhibits most clearly the atrial fibrillation waveform, but could be applied to other leads.

Several algorithms for determining the optimal atrial signal were considered. Algorithms which compare atrial signal features in *no-QRST* sections alone fail since, by including all the transformed signals, both ICA and PCA would perfectly reconstruct the original signal in these sections, but at the same time they would perfectly reconstruct the QRS and T waves in the *QRST* sections. An algorithm which minimized the following error function was found to provide the optimum signals in the majority of cases and was used in this study:

$$e = \sqrt{(A_{no-QRST} - \hat{A}_{QRST})^2 + (A_{no-QRST} - \hat{A}_{no-QRST})^2}$$

$A_{no-QRST}$ is the mean peak-to-peak amplitude of V1 in *no-QRST* sections, $\hat{A}_{QRST}$ and $\hat{A}_{no-QRST}$ are the mean peak-to-peak amplitudes of the reconstructed lead V1 in *QRST* and *no-QRST* sections respectively. The algorithm selected the combination of transformed signals which gave the least combined error in atrial signal amplitude in both *QRST* and *no-QRST* sections.

2.4. Comparing the atrial signals

The aim of atrial signal extraction is to remove QRS and T waves without distorting the atrial component of the ECG. Quantifying the quality of the extracted atrial signals is difficult since the true atrial signal on the body surface during the QRS complex and T wave is unknown. It was expected that the atrial activity during ventricular activity would be similar to that during ventricular inactivity, since the ventricular and atrial activities in atrial fibrillation are decoupled. With this assumption it was possible to compare statistically the amplitudes of the atrial signals within and without periods of ventricular activity. This was achieved by measuring the mean and standard deviation of peak-to-peak amplitude across *no-QRST* sections of V1, and similarly, the peak-to-peak amplitude of the reconstructed atrial signals in *QRST* sections. The mean amplitudes were compared using the t-test.

It was also anticipated that the extracted and original atrial signals, measurable during periods of ventricular inactivity, would be morphologically the same, excepting distortions produced by the extraction technique. Therefore, to quantify morphological distortions of the atrial signal due to the extraction (and reconstruction) process, we compared the amplitudes of the extracted atrial signals in *no-QRST* sections with those of V1 in the same sections using the paired t-test. Additionally, the mean square errors (MSE) between original and extracted signals of these sections were calculated.

3. Results

Figure 2 compares the amplitudes of the atrial signal in *no-QRST* sections of V1 to the extracted atrial signals in both *no-QRST* sections and *QRST* sections. Significant differences in amplitude are indicted. Table 1 summarises the results from this figure by quantifying for each technique the number of significant increases or decreases in atrial signal amplitude compared to that of V1.
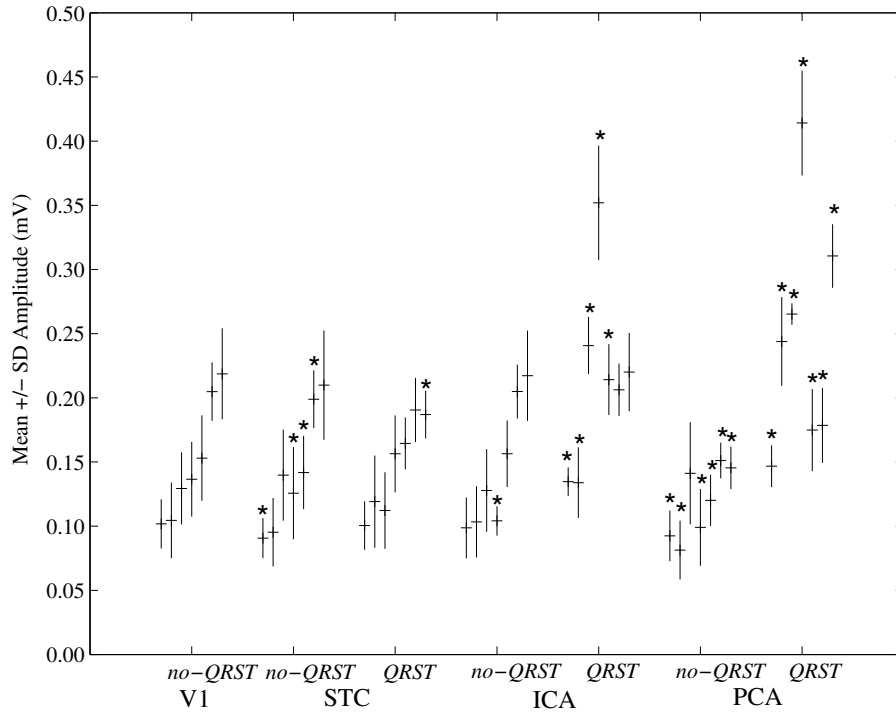
MSE for each of the techniques is shown in figure 3.

Figure 2. Atrial signal amplitudes of *QRST* and *no-QRST* sections for all patients (in order 1 to 7) for STC, ICA and PCA compared with amplitudes in V1. * indicates $p < 0.05$ for amplitudes compared with V1 *no-QRST*.

Table 1. The number of patients for which there were significant increases (↑) or decreases (↓) in extracted atrial signal amplitudes in *no-QRST* and *QRST* sections compared with *no-QRST* sections in V1.

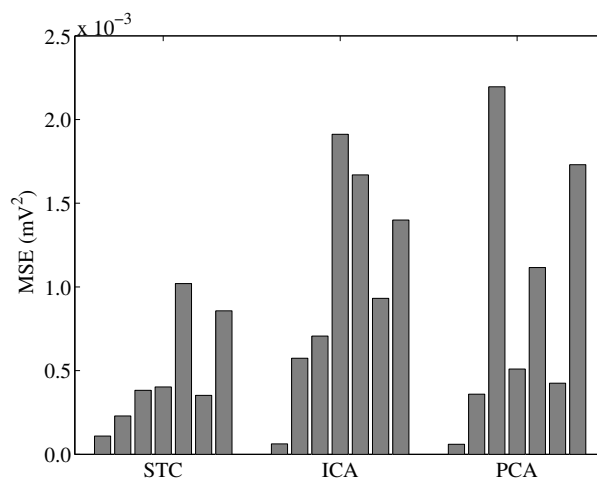|	no-QRST		QRST	
	↑	↓	↑	↓
STC	0	4	0	1
ICA	0	1	5	0
PCA	0	6	7	0

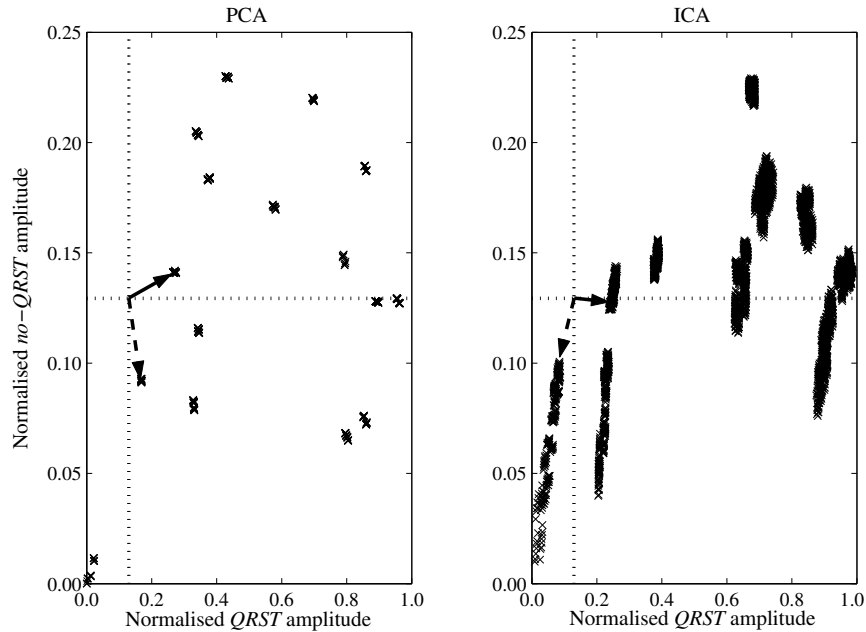Figure 3. MSE for all patients (in order 1 to 7) by each technique.

Figure 4. Normalised *QRST* and *no-QRST* amplitudes for all reconstructed V1 leads for patient 3 for PCA and ICA. Dashed lines indicate target atrial signal amplitude. Solid arrow indicates the reconstruction selected by the algorithm. Dashed arrow indicates possible alternative reconstruction but which results in reduced atrial signal amplitude.

4.   Discussion

This is the first study to reconstruct the atrial activity in V1 from the extracted atrial signals of the ICA and PCA techniques. One of the problems has been determining which set of transformed signals to use in the reconstruction to give the optimal atrial signal. Figure 4 relates the amplitude of the *QRST* and *no-QRST* sections in $2^{12} - 1$ reconstructed V1 leads for ICA and PCA techniques for patient 3. The algorithm used in this study selects the reconstruction which minimises the distance from the origin ($x = y = A_{no-QRST}$), as indicated by the solid arrow in figure 4. In this example, for both ICA and PCA techniques, the selected atrial signals have amplitudes in the *QRST* section that are approximately twice that of the atrial amplitude in V1. Selection of other reconstructions for example, as indicated by the dashed arrow in figure 4, would bring the amplitude of the *QRST* section closer to the target value but at the cost of reduced amplitude in the *no-QRST* section. It is apparent that in this case no reconstruction is possible which would give good agreement in atrial signal amplitude in both *QRST* and *no-QRST* sections. The STC technique has the advantage that it derives the atrial signal directly from the lead in question and this technique may be better for analysis of specific leads of the 12-lead ECG, whereas the other techniques may be better at providing global information relating to atrial activities.

References

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