Separation of Atrial and Ventricular Components of Body Surface Potentials in Atrial Fibrillation Using Principal Component Analysis: A Computer Modelling Study

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Abstract

We present a computer model which is used to assess Principal Component Analysis (PCA) as an algorithm for separating atrial and ventricular activity from body surface potentials (BSP). The model is based on separate dipoles for atrial and ventricular activity, where the amplitude and orientation of the dipoles has been extracted from real data taken from 12-lead ECGs. The model simulates BSPs at over 300 sites on a cylindrical torso. Principal components (PC) of the BSPs were calculated for models with i) atrial dipole only, ii) ventricular dipole only and iii) simultaneous atrial and ventricular dipoles. Maps of the individual contributions to the PCs from the BSPs were produced. The atrial and ventricular activities produced distinct maps for the individual dipoles. There were distinct regions on the torso corresponding to atrial and ventricular activities for simultaneous atrial and ventricular dipoles.

1. Introduction

PCA has been used to isolate the atrial activity from the ventricular activity to allow the atrial signal to be analysed unimpeded by the large ventricular signal in patients with atrial fibrillation (AF).[1] One method of validation has been to compare the extracted atrial signals with those of other algorithms.[2] However, it is difficult to validate these algorithms because the true body surface atrial signal is unknown. Therefore our aim was to produce a computer model consisting of separate atrial and ventricular sources in which the atrial and ventricular sources could be controlled independently and would be useful for validating these algorithms.

2. Methods

2.1. Assumptions of the computer model

The model consisted of separate dipoles, representing the atrial and ventricular sources placed in a cylindrical torso model. The assumptions of our model were that the atrial and ventricular activities could be represented by individual dipole sources, and that these could be placed in an infinite, homogenous space. Within that space the elliptical cylindrical mesh forming the torso surface defined the points on which the potentials were calculated. The bases of the dipoles remained fixed, at locations corresponding to approximate atrial and ventricular anatomical sites within the cylindrical torso.

2.2. Deriving atrial and ventricular dipoles from the ECG

The tips of the dipoles, and hence the dipole momentum, were extracted from 12-lead ECG data collected from a patient in AF and a patient in sinus rhythm. The atrial dipole was derived from a segment of ECG containing the fibrillatory waveform and no ventricular activity. The ventricular dipole was derived from the average QRST segment calculated from many ventricular beats. The dipole vectors were extracted from the ECG, using the assumption that the X, Y and Z components of the dipoles corresponded to leads V_2, V_5, -aVF respectively.[3] The X, Y and Z components of the dipole vectors are shown in figure 1.

2.3. Torso model and potential calculations

The torso was represented by a mesh of 17 squares high (height 50 cm) and 18 around the circumference (circumference 47.5 cm) giving 306 points on the surface. The conducting medium was homogeneous, with a conductivity, $\sigma = 0.2\ \mathrm{Sm}^{-1}$.

The potential on the surface was calculated using the current dipole equation,

$$\Phi(\vec{r}) = \frac{\vec{p}}{4\pi\sigma} \cdot \frac{\vec{r} - \vec{r}\,'}{|\vec{r} - \vec{r}\,'|^3}$$

where $\vec{p}$ is the dipole momentum, $\vec{r}\,'$ is the base of the dipole and $\vec{r}$ is the point at which the potential is calculated. $\vec{p}$ was derived at each time instant from the

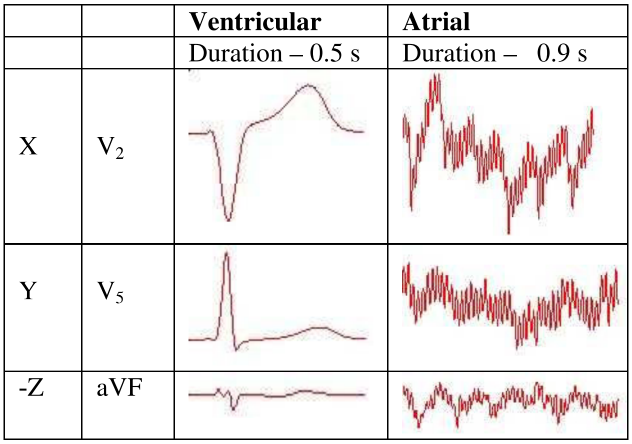

Figure 1. X, Y and -Z components of the atrial and ventricular dipoles which are equal to leads V_2, V_5, and aVF. The atrial activity has been amplified with respect to the ventricular activity to help visual inspection and the recording contains electrical mains interference.

vectors of the atrial and ventricular dipoles. The time varying BSPs were calculated for three scenarios: i) atrial dipole only; ii) ventricular dipole only; iii) simultaneous atrial and ventricular dipoles. Figure 2 illustrates the model.

An indication of model accuracy was made by visually comparing the simulated ECG derived from the simulated BSPs with the real ECG. Scenarios i) and ii) served to define the body surface activities arising from the singular dipoles which were compared to the separated atrial and ventricular activities using PCA from scenario iii).

2.4. PCA for separating the ventricular and atrial activities

PCs were calculated from the simulated BSPs using all sites across the torso. These were calculated using the linear transformation

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

where, A is a matrix of transformation coefficients derived from the eigenvalues of the covariance matrix of the simulated BSPs, $l(j)$ represents the j^{th} BSP signal, s_i are the PCs and n is the total number of BSP signals (306). Maps of the transformation coefficients (loads) which describe the contribution of each BSP signal to the PCs were plotted for the PCs containing the cardiac activities.

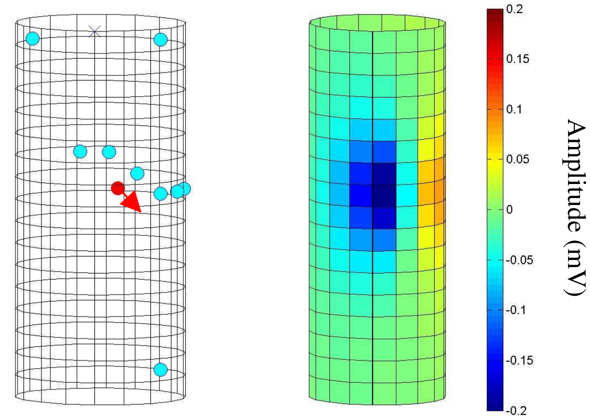

Figure 2. Left: cylindrical torso model showing the standard 12-lead ECG positions (circles) and a single dipole representing the ventricular activity. A reference head marker (cross) centrally placed at the top defines the front of the model. Right: the corresponding potentials on the torso.

3. Results

3.1. Model accuracy

For the case of a lone ventricular dipole, the simulated ventricular depolarization showed good agreement with the real ECG. Although the polarity of the simulated T waves was correct, the simulated T waves were much lower in amplitude than the real ones, as illustrated in figure 3. There was good agreement between real and simulated ECGs for the case of a lone atrial dipole as illustrated in figure 4.

3.2. PCA analysis

Only the first three PCs contained the cardiac activity for the case of a single atrial or ventricular dipole. Figures 5 and 6 show these and corresponding maps of the loads for the individual ventricular and atrial activities respectively. It is clear that the maps for the atrial and ventricular loadings show very distinct patterns, indicating that the atrial and ventricular sources give rise to different spatial features of BSP.

For the case of the simultaneous atrial and ventricular dipoles six PCs contained the cardiac activities. These are illustrated in figure 7 along with the PC load maps. Comparing the PCs from the simultaneous ventricular and atrial dipole simulation (figure 7) with those of the simulations with the individual dipoles (figures 5 & 6) it appears that the main features of the atrial and ventricular

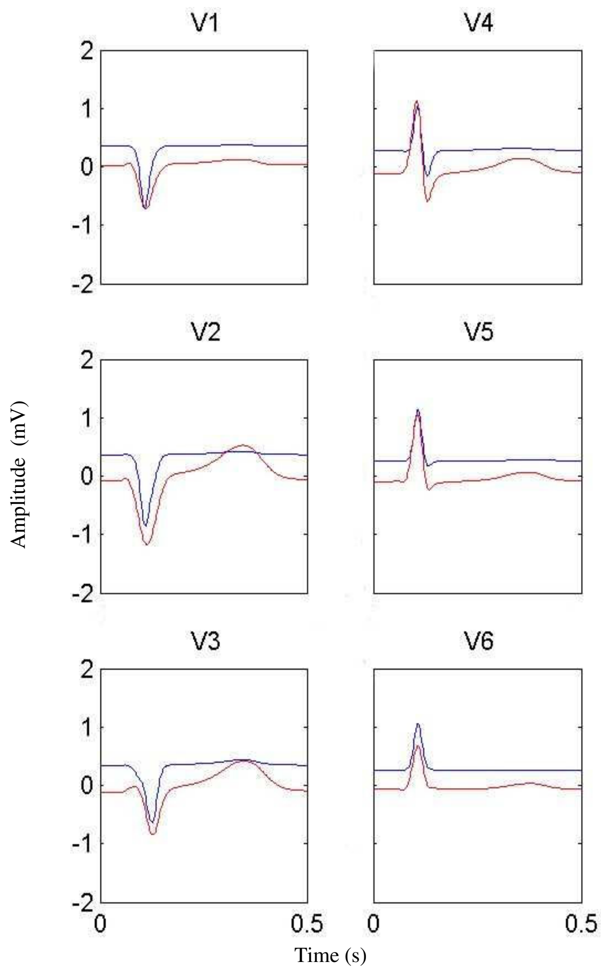

Figure 3. Real (bottom trace in each plot) and simulated ECG for ventricular dipole only. The signals have been offset to allow visual comparison.

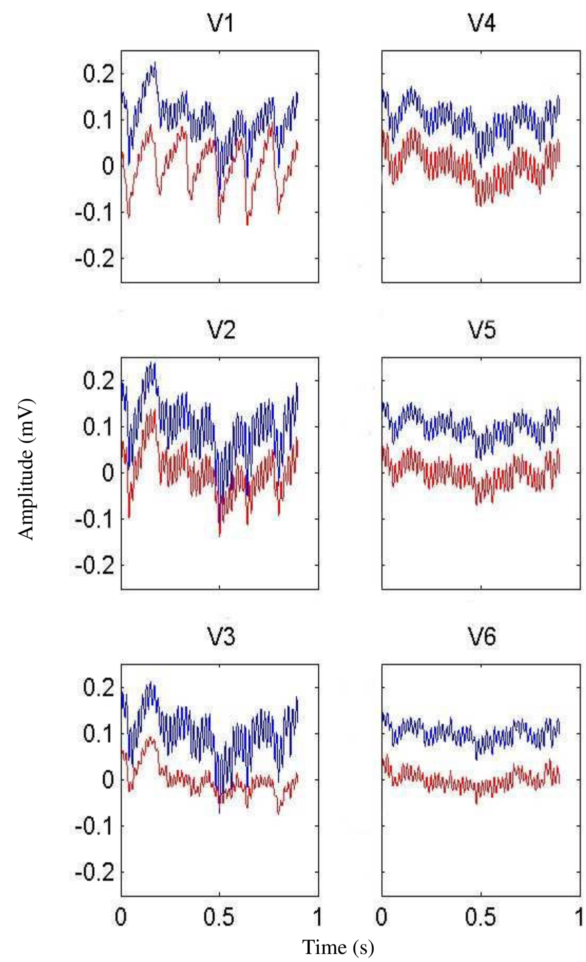

Figure 4. Real (bottom trace in each plot) and simulated ECG for atrial dipole only. The signals have been offset to allow visual comparison.

activities have been separated. For example, Signal $PC1_{av}$ is equivalent to $PC1_{v}$, $PC3_{av}$ is largely equivalent to $PC1_{a}$. It is only $PC4_{av}$ which exhibits mixed atrial and ventricular activities. When comparing the load maps for these different scenarios it is more obvious that there are mixed atrial and ventricular activities in 4 of the 6 PCs. Moreover, the body surface sites contributing to the mixed activities are apparent.

4. Discussion and conclusions

A number of interesting observations have arisen from this study. Firstly, a very simple model, consisting of only a single dipole, accurately simulated the atrial component of the ECG in atrial fibrillation.

Secondly, this model accurately simulated ventricular depolarisation, but not repolarisation. This may indicate that ventricular repolarisation is more dispersed than depolarisation, requiring a multi-dipole model. Thirdly, maps of the PC loads provide a visual indication of the relative contributions of the atrial and ventricular activities and their spatial distribution. In conclusion, the simple dipole model provides a useful tool for the evaluation of algorithms for separating the atrial and ventricular components of the BSPs.

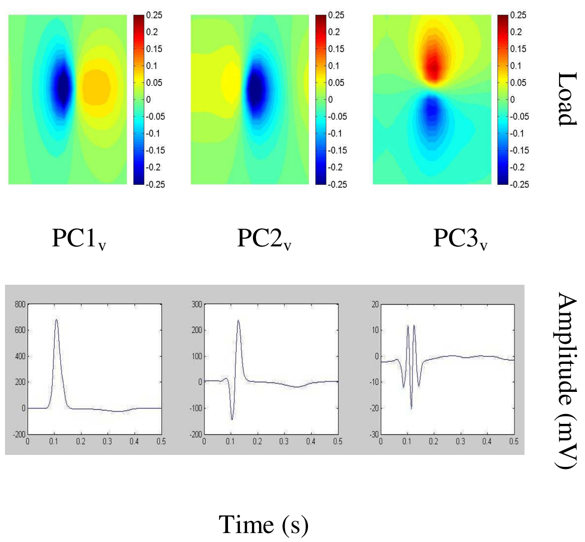

Figure 5. The first three PCs and corresponding load maps produced by the ventricular dipole. The maps are presented with the cylindrical torso 'opened out' with the head in the centre, top position.

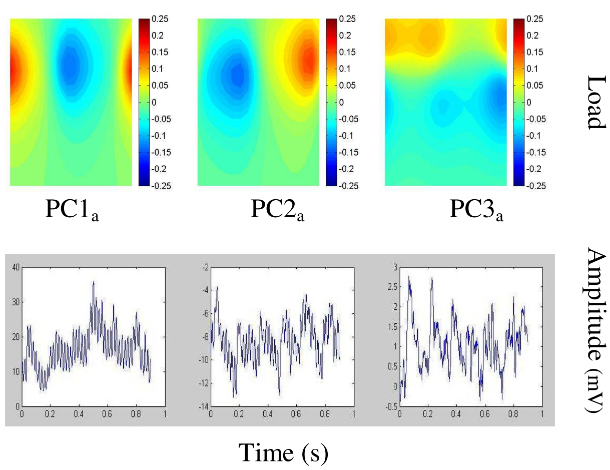

Figure 6. The first three PCs and corresponding load maps produced by the atrial dipole.

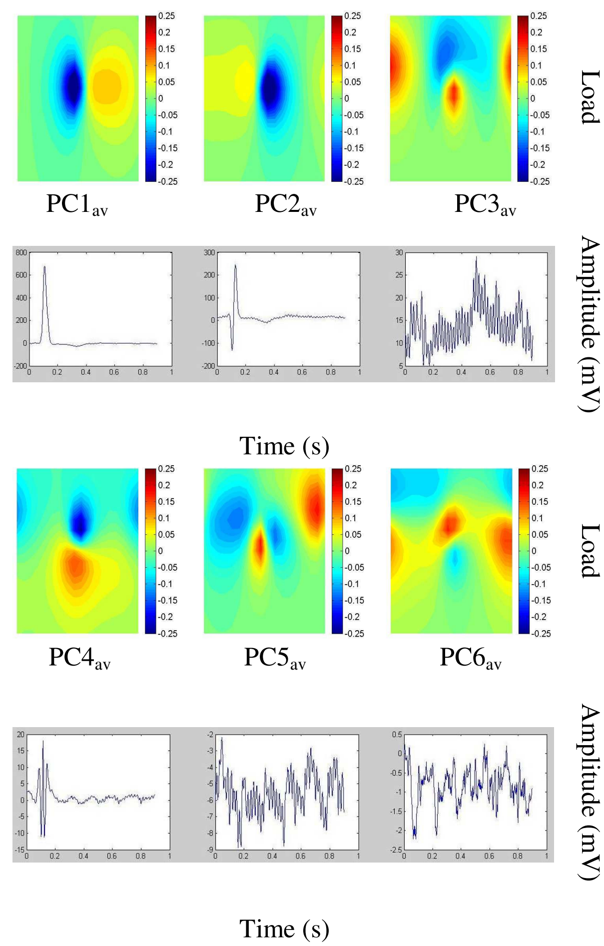

Figure 7. The first six PCs and corresponding load maps produced by the simultaneous atrial and ventricular dipoles.

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