Analysis of the Spectrum of Cardiac Signals during Partially Correlated Spatiotemporal Dynamics: A Simulation Approach

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Abstract

The relationship between the spectrum of cardiac signals and the spatial resolution of electrode systems has been previously investigated for highly correlated cardiac dynamics. This relationship is however less understood for partially correlated cardiac dynamics, which can be suitable to model complex arrhythmias such as fibrillation. In this study, we analyze in a 2D simulation environment the spectrum of cardiac signals induced by partially correlated dynamics. We generate cardiac dynamics of different degrees of spatiotemporal correlation and synthesize cardiac signals measured by unipolar electrodes of different spatial resolutions. We quantify the spatial resolution by the lead equivalent volume (LEV) and show that for low LEV values, the bandwidth (BW) is inversely related to the LEV whereas for higher LEV values, the BW saturates. Moreover, the LEV saturation point is lower for lower degrees of spatiotemporal correlation. Our observations could help in devising new techniques for analyzing the spectrum of cardiac signals during complex cardiac arrhythmias.

1. Introduction

Understanding the detailed spatiotemporal characteristics of complex cardiac arrhythmias can be of great importance both during diagnosis and treatment. A widely used technique for determining the spatiotemporal characteristics of regular arrhythmias is activation sequence (AS) mapping. During AS mapping, the timings of activation at multiple myocardial sites are extracted from cardiac signals. This allows to identify the progression of cardiac activation in time and in space. However, when the underlying arrhythmia is highly irregular, it might be difficult to accurately extract local activation times and hence to build AS maps. Dominant frequency (DF) mapping is a spectral technique that overcomes the need for estimating local activation times by providing instead an estimation of the local activation rate at multiple sites of the myocardium [1–3]. This allows to identify the fastest myocardial regions which, according to the mother rotor hypothesis, could potentially act as localized drivers of the arrhythmia. In addition to DF mapping, other spectral approaches have been proposed to analyze the spatiotemporal characteristics of complex arrhythmias, for instance the organization index [4] and the multivariate organization index [5].

The nature of cardiac spectrum is nevertheless still not well established. In order to extract physiologically meaningful information from the spectrum of cardiac signals, it is necessary to improve our understanding of how electrode systems map the spatiotemporal characteristics of cardiac dynamics onto the spectrum of cardiac signals. Theoretical and simulation studies have shown that when cardiac activity is highly correlated, the bandwidth (BW) of cardiac signals is inversely related to the lead equivalent volume (LEV) of the electrode system [6–8]. However, some complex cardiac arrhythmias, such as fibrillation, might be more appropriately modelled as partially correlated processes and the spectrum of cardiac signals induced by such spatiotemporal dynamics is still poorly understood. Previous simulation studies indicate that during partially correlated dynamics the BW of cardiac signals saturate as the LEV of the electrode system increases [9], but no systematic analysis has been carried out to date.

In this study, we develop a simulation environment to explore the spectrum of cardiac signals generated during partially correlated spatiotemporal dynamics. Our simulation environment allows us to quantitatively analyze the relationship between the degree of spatiotemporal correlation of the cardiac source, the spatial resolution of the electrode system and the spectrum of cardiac signals.

2. Simulation environment

In this section we describe the bioelectric model that we used in our simulation environment and the strategies that we implemented to simulate cardiac dynamics of different degrees of spatiotemporal correlation and electrode systems of different spatial resolutions.

2.1. Bioelectric model

Our bioelectric model, which consists of a model of cardiac source and a model of cardiac signal, follows a lead field approach [10]. We modelled cardiac sources as a time-varying dipole distribution $\mathbf{J}(s,t) = [J_x(s,t), J_y(s,t), J_z(s,t)]^T$ within a cardiac tissue sample S, where s denotes a location in S and t denotes time. The dipole distribution $\mathbf{J}(s,t)$ can in turn be obtained by calculating the gradient of the distribution of transmembrane voltage, $V(s,t)$.

Given the dipole distribution $\mathbf{J}(s,t)$, a cardiac signal $c(t)$ measured by an electrode system can be expressed as the integral

$$c(t) = \int_S \mathbf{L^T}(\mathbf{s})\mathbf{J}(\mathbf{s},\mathbf{t})ds, \tag{1}$$

where $\mathbf{L}(s) = [L_x(s), L_y(s), L_z(s)]^T$ is the sensitivity distribution of the electrode system.

In this study, unipolar electrodes placed over the cardiac tissue sample at increasing distances were implemented. We used the following expression for their sensitivity distribution [11]:

$$\mathbf{L}(s) = \frac{1}{[D(s,p)]^2}\hat{r} \tag{2}$$

where $D(s,p)$ is the distance between the location of the electrode p and a location s of the cardiac tissue sample, and $\hat{r}$ is a unit vector in the direction of the the line that connects p and s. By increasing the distance of the unipolar electrode from the cardiac tissue sample, we achieved a more uniform sensitivity distribution over the tissue sample and consequently decreased its spatial resolution.

2.2. Simulated dynamics

Two models of cardiac sources were implemented. The first model consisted of a 2D partially-correlated random field generated by filtering both in time and in space a white, gaussian random field. The second model corresponded to a 2D sheet of cardiac tissue based on a reaction-diffusion cellular automata system previously proposed to simulate cardiac dynamics [12]. Both 2D models allowed us to generate partially-correlated dynamics and parametrically control their degree of spatiotemporal correlation.

The 2D random source model is defined as follows. Firstly, a gaussian, spatially uncorrelated, white noise field is generated on a square 2D substrate. This field is subsequently low-pass filtered in the time domain. Finally, the resulting field is linearly delayed along one of the axis and spatially filtered by a gaussian function of variable width, D_C. Although the applicability of this model to reproduce physiological cardiac dynamics is limited, it offers two advantages. Firstly, its spatiotemporal dynamics can be analytically characterized. Specifically, cardiac dipoles present a partially-correlated cross-spectrum with a gaussian decay. And secondly, by controlling the spatial width D_C, partially-correlated dynamics of different degrees of spatiotemporal correlation can be generated.

Our reaction-diffusion cellular automata model was implemented on a square 2D substrate. We simulated different spatiotemporal dynamics by stimulating the substrate with a uniform array of $N \times N$ electrodes. At each stimulation time, only one randomly chosen electrode of the array was activated. By setting N to increasing values, we were able to decrease the degree of spatiotemporal correlation.

3. Analysis

We subsequently describe how we analyzed the degree of spatiotemporal correlation of the simulated cardiac dynamics, the spatial resolution of the electrode systems and the spectrum of synthesized cardiac signals.

3.1. Spatiotemporal correlation

The degree of spatiotemporal correlation of the simulated cardiac dynamics was analyzed as follows. Firstly, we obtained the correlation between the time-varying transmembrane voltage at the centre of the cardiac sample and at the rest of the locations of the cardiac sample. Then, the value of the maximum correlation was extracted and finally, for every distance d from the center, we calculated the average maximum correlation. This allowed us to analyze how the correlation decayed with the distance.

3.2. Spatial resolution

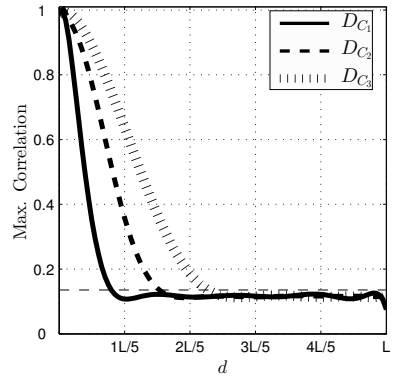
We used the lead equivalent volume (LEV) to quantify the spatial resolution of the unipolar electrodes [13]. The LEV of an electrode system is defined as

$$\text{LEV} = \frac{\int_V L(v)dv}{\int_V L_{max}dv}, \tag{3}$$

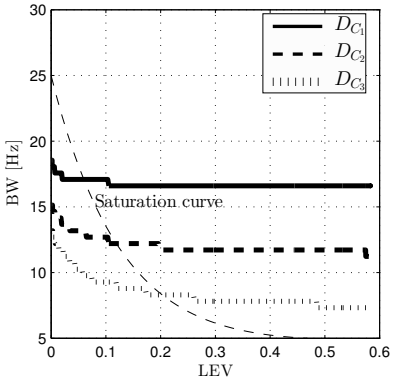
where $L(v)$ is the magnitude of the sensitivity distribution and $L_{max} = \max\{L(v)\}$. For high spatial resolutions, LEV$\ll 1$, whereas for low spatial resolutions LEV$\simeq 1$.

3.3. Cardiac spectrum

We synthesized the cardiac signals induced by each simulated dynamics at each unipolar electrode, estimated their power spectrum by using Welch's method and obtained their 90% power bandwidth (BW). We analyzed the dependence of the BW on the LEV for different degrees of spatiotemporal correlation to investigate the spectral manifestation of partially-correlated dynamics.

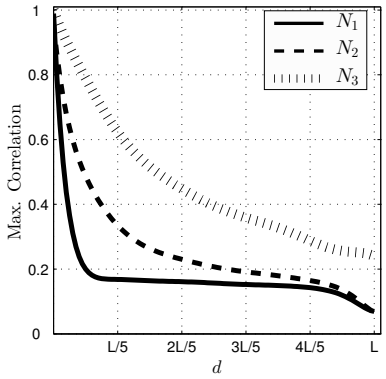


(a)

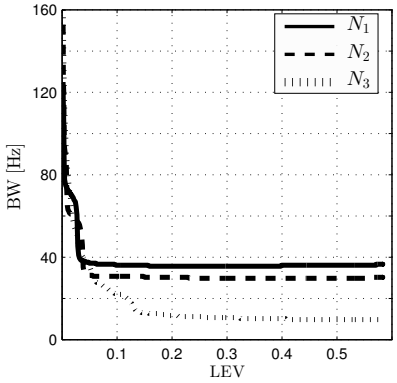


(b)

Figure 1. (a) Maximum correlation dependence with the distance d and (b) BW dependence with the LEV for three dynamics generated by the random model. The gaussian filter width D_C was set for each simulated dynamics to $D_{C_1} = 4\%$, $D_{C_2} = 8\%$ and $D_{C_3} = 12\%$, relative to the width of the tissue sample.



(a)



(b)

Figure 2. (a) Maximum correlation dependence with the distance d and (b) BW dependence with the LEV for three dynamics generated by the cellular automata model. The size of the stimulating array for each simulated dynamics was set to $N_1 \times N_1 = 9 \times 9$, $N_2 \times N_2 = 7 \times 7$ and $N_3 \times N_3 = 3 \times 3$.

4. Results

We simulated three partially correlated spatiotemporal dynamics based on the random model of cardiac source. By setting the width of the gaussian spatial filter to three increasing values, namely $D_{C_1} = 4\%$, $D_{C_2} = 8\%$ and $D_{C_3} = 12\%$ relative to the substrate width, we were able to obtain increasing degrees of spatiotemporal correlation. The maximum correlation between the dipole at the center of the sample and the rest of the dipoles as a function of the distance is shown for each D_C value in Fig. 1 (a). As expected, the maximum correlation curve exhibited a gaussian profile whose width increased with the width of the gaussian filter. The dependence of the BW of the cardiac signals with the LEV of the electrode system is shown for each D_C value in Fig. 1 (b). For small LEV, an inverse relationship between BW and LEV was observed. By contrast, for large LEV, the BW remained approximately constant. This observation is consistent with previous analytical results according to which the BW is inversely related to the LEV during highly correlated dynamics whereas it remains constant during highly uncorrelated ones [8]. The curve separating the region where BW and LEV are related inversely from the region where it remains constant, also shown in Fig. 1 (b), indicates that the BW saturation point is proportional to the underlying correlation length.

By increasing the number of elements of the $N \times N$ stimulating array we were able to simulate partially correlated dynamics with lower degrees of spatiotemporal correlation. We generated three partially correlated spatiotemporal dynamics by setting the size of the stimulating array to $N_1 \times N_1 = 9 \times 9$, $N_2 \times N_2 = 7 \times 7$ and $N_3 \times N_3 = 3 \times 3$. Fig. 2 (a) shows that the simulated correlation decay could be approximated by a laplacian function whose width de-

creased for larger N values. The relationship between the BW of simulated cardiac signals and the LEV of the electrode system agrees with the behaviour observed for the random model, namely, for small LEV values there is an inverse relationship between BW and LEV, whereas for large values the BW saturates (Fig. 2 (b)). This saturation occurred at larger values for dynamics with longer correlation lengths, as was the case with the partially correlated dynamics generated based on the random model.

5. Conclusions

Theoretical and simulation results indicate that during highly correlated cardiac dynamics, the spatial resolution of electrodes systems affect the spectrum of cardiac signals, so that the larger the LEV of the electrode system, the narrower the BW [6–8]. A practical consequence of this is that non-invasive body-surface FD maps might not be commensurable with invasive intracardiac FD maps during highly correlated arrhythmias, since the electrodes of the former are expected to be characterized by a larger LEV than the electrodes of the latter. The low pass characteristics of body surface spectra might be equalized by using a suitable high pass filter as long as high frequency noise is not amplified to unacceptable levels. However, during partially correlated cardiac dynamics we have observed that the BW depends on both the LEV of the electrode system and the degree of spatiotemporal correlation. Hence, finding a suitable equalizing filter for body surface spectra would require an estimation of both the LEV of the recording electrode system and the degree of spatiotemporal correlation of the underlying arrhythmia.

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