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# Effects of Lead Spatial Resolution on the Spectrum of Cardiac Signals: A Simulation Study

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*Abstract*— **Spectral analysis is widely applied to bioelectric cardiac signals for quantifying the spatiotemporal organization of cardiac tissue. Nevertheless, to date it is not well understood how lead characteristics affect the spectrum of recorded cardiac signals and, as a consequence, the interpretation of cardiac spectrum is still controversial. In this paper we use simulation methods to investigate the effects of lead spatial resolution on the spectrum of cardiac signals. We simulate three cardiac rhythms of different degrees of spatiotemporal organization in a square sample of cardiac tissue. Then, by using a lead field approach, we synthesize the signals recorded by four idealized leads of different spatial resolution. Finally, we estimate the spectrum of simulated cardiac signals. Our simulations indicate that lead spatial resolution affects cardiac spectrum, although the effects depend on the organization of the underlying rhythm. Specifically, our simulations show that for highly organized rhythms, the smaller the lead resolution region, the broader the distribution of power in frequency. Since lead resolution can affect significantly cardiac spectrum, we conclude that caution should be used when quantifying cardiac spatiotemporal organization based on the spectrum of cardiac signals.**

## I. Introduction

Spectral theory constitutes a classical signal-processing framework for analyzing and extracting subtle periodicities in quasi-stationary signals. In cardiac electrophysiology, spectral methods have been widely applied to bioelectric signals for describing and quantifying the spatiotemporal organization of cardiac rhythms. Specifically, spectral methods have been applied during arrhythmias traditionally considered to be highly chaotic and disorganized, such as atrial fibrillation (AF) and ventricular fibrillation (VF).

Based on the assumption that the spectrum of cardiac signals convey useful information about tissue spatiotemporal organization, several spectral indices have been used to describe cardiac arrhythmias. In electrocardiographic (ECG) signals recorded during VF, a clear peak frequency (PF) between 3 and 7 Hz has been consistently observed [1]–[3]. Based on this observation, some authors have considered the possibility that VF is not completely chaotic and posses some degree of organization. Also in the ECG, the median frequency (MF), defined as the gravity center of the power spectrum, has been shown to reflect the evolution in time of VF episodes [4]. The dominant frequency (DF) is another spectral index that has been extracted from optical and local electrical recordings for estimating the local activation rate of cardiac tissue during AF [5]–[7] and VF [8], [9]. By analyzing DF maps throughout the myocardium, regional differences have been observed during fibrillation dynamics, suggesting that they have some degree of spatiotemporal organization. Finally, an organization index (OI) has been proposed for quantifying AF organization based on intracardiac recordings [10], [11].

Despite the widespread use of spectral analysis, a rigorous explanation of cardiac spectrum in terms of the spatiotemporal organization of cardiac tissue is still lacking and therefore, the interpretation of cardiac spectrum remains to date controversial. One important issue that to the best of our knowledge has not been fully addressed, is how lead characteristics affect the spectral features of cardiac signals. The lead spatial resolution is one of such characteristic describing the ability of leads to record bioelectric phenomena locally. In electrophysiological studies that investigate the spectrum of cardiac signals, recording leads are commonly chosen based on their spatial resolution; yet, it is not well understood how spectral features are related to both the underlying cardiac rhythm and lead spatial resolution.

In this paper we explore the relationship between cardiac dynamics, lead spatial resolution and cardiac spectrum. We base our approach on numerical simulations of cardiac dynamics and on lead field theory. Firstly, we simulate three cardiac rhythms of different degrees of organization. Then, we synthesize cardiac signals recorded by four idealized leads characterized by different spatial resolution. Finally, we estimate the power spectrum of each simulated signal and analyze how lead resolution affects recorded spectra.

## II. Methods

### A. Model of Cardiac Dynamics

Cardiac dynamics were simulated by using a probabilistic cellular automata (P-CA) approach previously developed in [12]. This P-CA model presents a low computational burden and is able of reproducing complex macroscopic cardiac dynamics, including curvature effects, fibrillatory conduction and rotors.

In our implementation of the P-CA, cardiac tissue is modeled as a rectangular grid $G$ consisting of $100 \times 100$ discrete elements. At every time instant $t$, each element $g \in G$ can adopt one out of three discrete states of physiological significance, namely $REST$, $REFRACTORY_1$ and $REFRACTORY_2$. The depolarization of an element corresponds to the transition from the $REST$ state to the

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(a) (b) (c)

Fig. 1. Simulated cardiac dynamics: (a) plane wave dynamics, (b) double-arm spiral dynamics and (c) chaotic dynamics. Panel (a) also shows the resolution region of leads $W_1$, $W_2$, $W_3$ and $W_4$, which is defined similarly for the three simulated dynamics.

$REFRACTORY_1$ state. This transition obeys a probabilistic rule according to which, the larger the amount of excitation in the immediate neighborhood of the element, and the higher the intrinsic excitability of the element, the higher the probability of depolarization. The excitability of an element was in turn quantified based on the restitution curve of the conduction velocity, which is a function of the duration of the previous diastolic interval (DI). The transitions from $REFRACTORY_1$ to $REFRACTORY_2$ and from $REFRACTORY_2$ to $REST$, corresponding to cardiac repolarization, are such that the total dwelling time in the states $REFRACTORY_1$ and $REFRACTORY_2$ equals the action potential duration (APD). This value was quantified based on the APD restitution curve, which also depends on the duration of the previous DI.

By using this model of cardiac activity, three different types of excitation dynamics were simulated, as shown in Figure 1. The first type corresponded to plane wave excitation dynamics and it was generated at a rate of one beat per second. The second type of dynamics was a double-arm stable spiral, and it was generated by using a two pulse (S1-S2) stimulation protocol. Finally, the third type of dynamics was a chaotic one, and it was also generated by a two pulse (S1-S2) stimulation protocol.

The three cardiac dynamics that were simulated showed different degrees of spatiotemporal organization. At one end, plane wave excitation provided us with a highly regular and organized rhythm. At the other end, chaotic dynamics could be described as a highly disorganized and irregular rhythm. Double-arm spiral dynamics could be considered a partially organized and irregular rhythm.

### *B. Model of Bioelectric Signal*

We described bioelectric signals by following a lead field approach. According to lead field theory, the signal $z(t)$ recorded by a lead system characterized by a sensitivity distribution $\mathbf{L}(g)$ over a bioelectric discretized source $G$ can be expressed mathematically as:

$$z(t) = \sum_{g \in G} \mathbf{L}(g) \cdot \mathbf{J}(t, g) \tag{1}$$

where $\mathbf{J}(t, v)$ is the time-varying bioelectric current distribution that is generated at every source element $g \in G$.

For every cardiac dynamics that were simulated, we obtained the current distribution $\mathbf{J}(t, v)$ by firstly assigning to every element a transmembrane voltage. This transmembrane voltage was obtained by using an action potential template based on the element's state at time instant $t$. After that, each element's current was calculated by using the voltage differences and the conductivity between neighboring elements.

In order to investigate the effects of lead spatial resolution on cardiac spectrum, we used an ideal lead sensitivity distribution model. In this model, the magnitude of the sensitivity distribution is equal to one within a region of interest $W$ and zero outside it. Mathematically, such sensitivity distribution can be formulated as:

$$|\mathbf{L}(v)| = \begin{cases} 1 & \text{if } g \in W \\ 0 & \text{if } g \notin W \end{cases} \tag{2}$$

Consequently, for this idealized sensitivity distribution model, it can be said the size of the region of interest equals the lead resolution region that defines the spatial resolution.

We defined four ideal lead sensitivity distributions of different spatial resolutions and denoted them by $W_1$, $W_2$, $W_3$ and $W_4$. Figure 1 (a) shows how the region of interest of each of the proposed leads was defined within the sample of cardiac tissue that was simulated. The smallest region of interest, corresponding to $W_1$, was located close to the center of the sample of cardiac tissue and covered a square area of $20 \times 20$ elements. The second lead defined by $W_2$ covered a square region four times larger than $W_1$, covering $40 \times 40$ elements. The third region, $W_3$ covered a square region of $60 \times 60$ elements and, finally, $W_4$ covered a square area of $80 \times 80$ elements. By combining each lead sensitivity distribution defined by $W_1$, $W_2$, $W_3$ and $W_4$, with the distribution of bioelectric currents generated by each of the three simulated dynamics, we were able to obtain

four simultaneous bioelectric signals recorded by leads of increasing spatial resolution during the three rhythms of different degrees of spatiotemporal organization.

### C. Power Spectrum Estimation

We estimated the power spectrum of every simulated signal by using Welch's method, which constitutes a modification of the periodogram. Bioelectric signals were synthesized for each one of the four lead sensitivity distributions defined by $W_1$, $W_2$, $W_3$ and $W_4$, during each of the cardiac dynamics that was simulated (plane wave, double-arm spiral, chaotic). The simulation time was 20 s and signals were sampled at a rate of 200 Hz.

A Hamming window of 64 samples was selected for power spectrum estimation and the overlapping among consecutive signal segments was set to 75%. By choosing a small smoothing window and a large amount of segments, we sacrificed spectral resolution for greater spectral stability. In other words, our implementation of the Welch's method provided us mainly with an estimation of the spectral envelope and did not have enough spectral resolution to distinguish harmonic frequencies.

In order to investigate the underlying harmonic structure, we estimated the fundamental frequency as follows. Firstly, we calculated for each tissue element the average time $T_0$ between consecutive activations. The inverse of $T_0$ is by definition the activation rate of each element. Secondly, we averaged the activation rate for all tissue elements, which we took as the the fundamental frequency for the whole tissue sample.

## III. Results

Figure 2 shows the power spectrum of the signals recorded by leads $W_1$, $W_2$, $W_3$ and $W_4$ for the three simulated rhythms. Panel (a) corresponds to the spectra induced by the highly organized rhythm. Panel (b) corresponds to the spectra induced by the partially organized rhythm. Finally, Panel (c) corresponds to the spectra induced by the highly disorganized rhythm.

Figure 2 (a) shows that the power spectral envelope is different for each of the proposed leads. Specifically, we see that by decreasing the size of the resolution region covered by the lead, the contribution of high frequencies to the spectrum increases. As for the harmonic structure, the fundamental frequency was found to be 1 Hz as expected.

Figure 2 (b) shows that during the simulated double-arm spiral dynamics, leads $W_4$, $W_3$ and $W_2$ presented a similar power spectrum. However, the spectrum of the lead characterized by the smallest resolution area, $W_1$, deviated from this general pattern and concentrated a greater proportion of its power at higher frequencies. The spectral harmonic structure was characterized by a fundamental frequency of approximately 6 Hz.

Finally, in the simulation of the chaotic dynamics, the power spectra corresponding to each lead $W_1$, $W_2$, $W_3$ and $W_4$ did not show significant discrepancies, as seen in Figure 2 (c), and the fundamental frequency was found to be approximately 11 Hz. In other words, the power spectrum was the same irrespective of the lead spatial resolution.

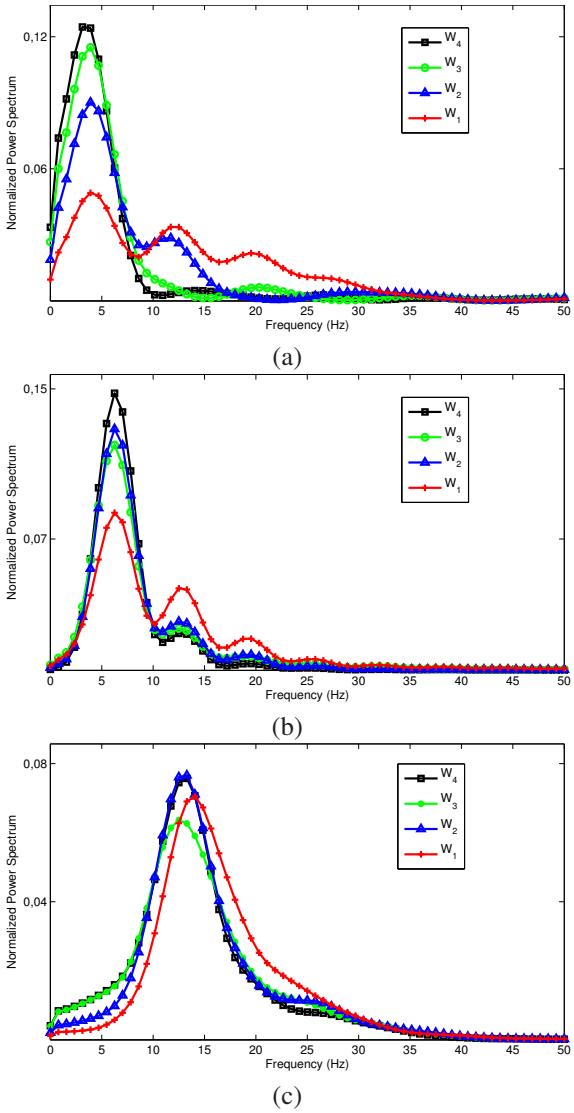


Fig. 2. Normalized power spectrum of the signals recorded by leads $W_1$, $W_2$, $W_3$ and $W_4$ for (a) plane wave excitation dynamics, (b) double-arm spiral dynamics and (c) chaotic dynamics. Note that as a consequence of smoothing, estimated spectra correspond to the spectral envelope and do not show harmonic frequencies.

In summary, we observed for highly organized rhythms and partially organized rhythms differences in cardiac spectra that could be ascribed to differences in lead spatial resolution, while the spectrum of cardiac signals during highly disorganized rhythms did not seem to depend on the spatial resolution of recording leads.

## IV. Conclusions

Spectral methods have been previously used for quantifying the spatiotemporal organization of cardiac tissue. For example, the analysis of DF maps throughout the myocardium during AF [5]–[7] and VF [8], [9] has suggested that fibrillation dynamics have some degree of spatiotemporal organization. Also, the analysis of the OI in intracardiac

signals has been used for investigating the spatiotemporal organization during AF. Nevertheless, the spectrum of cardiac signals is usually interpreted solely in terms of cardiac dynamics and little attention is paid to possible effects of lead characteristics on the spectrum of cardiac signals. As a consequence, the interpretation of cardiac spectrum is still controversial.

In this study, by using a lead field approach we have explored the relationship between cardiac dynamics, the lead sensitivity distribution and the spectrum of cardiac signals. We hypothesized that the lead spatial resolution could affect the spectrum of cardiac signals. In order to test our hypothesis, we investigated the effects of lead spatial resolution on the cardiac spectrum from simulated signals recorded during three rhythms of different spatiotemporal organization, namely plane wave dynamics, double-arm spirals and chaotic dynamics. By using a P-CA model of cardiac dynamics, we simulated the three dynamics in a square sample of cardiac tissue and synthesized the signals recorded by four idealized lead sensitivity distributions of different spatial resolution.

Simulations show that cardiac spectrum is affected by lead spatial resolution. The effect of lead spatial resolution on cardiac spectrum was found to depend on the underlying rhythm. At one end, during highly organized rhythms such as plane wave stable trains, the spectral envelope of cardiac signals concentrated power at lower frequencies for global resolution leads, whereas for local resolution leads power was spread across broader frequency ranges. At the other end, during highly disorganized rhythms lead spatial resolution did not affect spectral envelope. In the case of rhythms of intermediate degree of organization, spectral envelope was affected by lead spatial resolution only for small resolution areas. This observation could be interpreted based on the notion of coherence area. When observing a rhythm of intermediate degree of organization on a region larger than the coherence area, this rhythm can be coarsely described as disorganized. On the other hand, when it is observed on a region smaller than the coherence area, this rhythm can be described as a highly organized. Therefore, depending on the lead spatial resolution, a rhythm of intermediate degree of organization will resemble more an organized rhythm or a disorganized one.

We conclude that caution should be used when applying spectral methods to quantify the spatiotemporal organization of cardiac dynamics, since cardiac spectrum could be significantly affected by lead measurement characteristics. In order to investigate cardiac spatiotemporal organization, a rigorous mathematical framework for explaining cardiac spectrum should be further developed.

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