

# Dependence of Cardiac Spectrum on the Spatial Resolution of the Electrode Systems in a Realistic Model of the Canine Ventricles

Ferney A. Beltrán-Molina<sup>1</sup>, Emeterio Cruz-Salazar<sup>2</sup> and Jesús Requena-Carrión<sup>3</sup>

**Abstract**—Body-surface dominant frequency (DF) mapping has been proposed as a technique for non-invasively identifying high-frequency cardiac sources during fibrillation. However, previous studies indicate that volume conduction could distort the spectrum of body-surface cardiac signals and hence, affect body-surface DF maps. In this study, we analyze the effects of volume conduction on the spectrum of cardiac signals in a realistic computer model of the canine ventricles. We simulate complex cardiac dynamics on the ventricular model and analyze the dependence of the bandwidth (BW) of simulated unipolar cardiac signals on the spatial resolution of the corresponding unipolar electrode, which we quantify with the lead equivalent volume (LEV). Our analysis shows that the BW decreases for increasing LEV values and saturates for high LEV values. Our results also indicate that the LEV saturation value is low for low degrees of spatiotemporal correlation. We conclude that the spectral effects of volume conduction might limit our ability to accurately identify high-frequency sources in body-surface DF maps during cardiac fibrillation.

## I. INTRODUCTION

It has been hypothesized that cardiac fibrillation may be driven by spatially localized, high-frequency cardiac sources. These high-frequency cardiac sources have been related to reentrant-type dynamics, during which cardiac electrical activity rotates around anatomical or functional obstacles. Hence, according to this hypothesis, the analysis of the local activation rate of cardiac tissue during fibrillation could reveal its potential drivers and contribute to a more accurate diagnosis and a more effective treatment.

Dominant frequency (DF) mapping has been used for identifying potential drivers of cardiac fibrillation. In patient studies, DF maps have allowed to localize high-frequency cardiac sources during atrial fibrillation (AF), by providing an estimation of the local activation rate of the myocardium [1], [2], [3]. Most of the studies that use DF maps to analyze the local activation rate of cardiac tissue rely on invasive procedures. For instance, contact mapping approaches measure intracardiac signals by sequentially placing a single bipolar electrode against multiple locations of the endocardium. Another example is non-contact mapping, which reconstruct the local activity of the endocardium by using intracardiac signals simultaneously measured by multiple

electrodes. In either case, the invasive nature of contact and non-contact mapping approaches require hospitalization and their applicability is limited to a restricted set of fibrillation arrhythmias.

The correlation between intracardiac and ECG derived DF values [4], [5], [6] has led to the development of non-invasive approaches for DF mapping. In [7], body surface DF maps were compared to intracardiac DF maps during atrial fibrillation (AF) and the high-frequency sites identified by each method were in good agreement. However, the exact correspondence between intracardiac and body-surface DF maps remains to date unclear. Theoretical and simulation studies indicate that volume conduction can affect the spectrum of body surface signals [8], [9], [10]. Specifically, it has been shown that the spectral bandwidth of signals measured during highly correlated cardiac dynamics is related to the spatial resolution of the electrode system. Hence, the ability of body-surface DF mapping to characterize fibrillation arrhythmias still needs to be assessed.

In this study, the effects of volume conduction on the spectrum cardiac signals are investigated. Following previous theoretical results [10], we hypothesize that the spectral bandwidth is related to the degree of spatiotemporal correlation of cardiac dynamics and the spatial resolution of the electrode system. By simulating complex cardiac dynamics in a realistic model of the canine ventricles, we synthesize cardiac signals measured by electrode systems with different spatial resolutions and analyze their spectra. Our results are compared to previous theoretical results and simulation results on simple 2D systems.

## II. METHODS

### A. Simulation environment

We used the 3D realistic model of the canine ventricles presented in [11] as the anatomical substrate for our cardiac dynamics model. This anatomical model of the canine ventricles is defined by a tetrahedral mesh consisting of 46677 nodes and is shown in Fig. 1 from three different views, namely from the apex, the right ventricle (RV) and the left ventricle (LV).

A probabilistic cellular automata model previously described in [12] was implemented on the 3D model of the canine ventricles. This model captures the macroscopic properties of electrical restitution of both the action potential duration and the conduction velocity and is capable of reproducing complex spatiotemporal dynamics. By simulating a S1-S2 cross stimulation protocol, we were able to generate spiral wave dynamics in our ventricular model.

\*This work was partially supported by grant IPT-2011-0916-900000 from the Spanish Ministry of Science and Innovation.

<sup>1</sup>Ferney A. Beltrán-Molina is with TEIN group of the ECCI University, Bogotá, Colombia fbeltranm@ecci.edu.co

<sup>2</sup>Emeterio Cruz-Salazar is with GINICHUS group of the ECCI University, Bogotá, Colombia ecruzs@ecci.edu.co

<sup>3</sup>Jesús Requena-Carrión is with the School of Electronic Engineering and Computer Science of Queen Mary University of London, London E1 4NS, UK. j.requena@qmul.ac.uk

### B. Spatiotemporal Analysis

We selected three nodes from the canine ventricular model to analyze the spatiotemporal characteristics of the simulated cardiac dynamics. These nodes were located at the apex, the RV and the LV, respectively, and were chosen based on the observation that the dynamics in the regions where they belong presented different spatiotemporal characteristics. We obtained the maximum correlation between the voltage of the selected nodes and the voltage of the rest of the nodes. Then, we calculated the average maximum-correlation as a function of the distance for each selected node. This allowed us to assess the local degree of spatiotemporal correlation.

### C. Electrode System and Cardiac Signals Analysis

Following a lead-field approach [13], we modelled a cardiac signal  $x(t)$  as a linear combination of the distribution of cardiac dipoles:

$$x(t) = \int_V \mathbf{L}(v) \cdot \mathbf{J}(v, t) dv \quad (1)$$

In (1),  $t$  denotes time,  $v$  is a point of the myocardium  $V$ ,  $\mathbf{J}(v, t)$  is the time-varying distribution of cardiac dipoles and  $\mathbf{L}(v)$  denotes the measurement sensitivity distribution (MSD) of the electrode system. The MSD is a vector field that describes the ability of the electrode system to measure dipole sources in  $V$ .

We synthesized the cardiac signals corresponding to unipolar electrodes situated at increasing distances over the locations of the three selected nodes at the apex, the RV and the LV. The MSD of unipolar electrodes was defined as [14]

$$\mathbf{L}(v) = \frac{1}{D(v, v_0)^2} \hat{r} \quad (2)$$

where  $v_0$  is the location of the electrode,  $D(v, v_0)$  denotes the distance between  $v$  and  $v_0$ , and  $\hat{r}$  is a unit vector directed along the line connecting  $v$  and  $v_0$ .

The spatial resolution of each unipolar electrode was quantified by using the notion of lead equivalent volume (LEV) [15]. The LEV of an electrode system characterized by a MSD  $\mathbf{L}(v)$  is defined as

$$LEV = \frac{\int_V L_n(v) dv}{\int_V dv} \quad (3)$$

where  $L_n(v) = \|\mathbf{L}(v)\| / \max \|\mathbf{L}(v)\|$ . By definition,  $0 \leq LEV \leq 1$ . When the MSD is uniformly distributed,  $LEV \approx 1$ , whereas when it is highly localized,  $LEV \approx 0$ .

We estimated the power spectrum of synthesized cardiac signals by using Welch's method. Then, we obtained their 90% power bandwidth (BW). We used the BW of cardiac signals to analyze the low-pass filtering effects of volume conduction. Since, according to [10], a relationship exists between the filtering effects of volume conduction and the spatial resolution of the electrode systems, we analyzed the relationship between the BW of cardiac signals and the LEV of the corresponding electrode system.

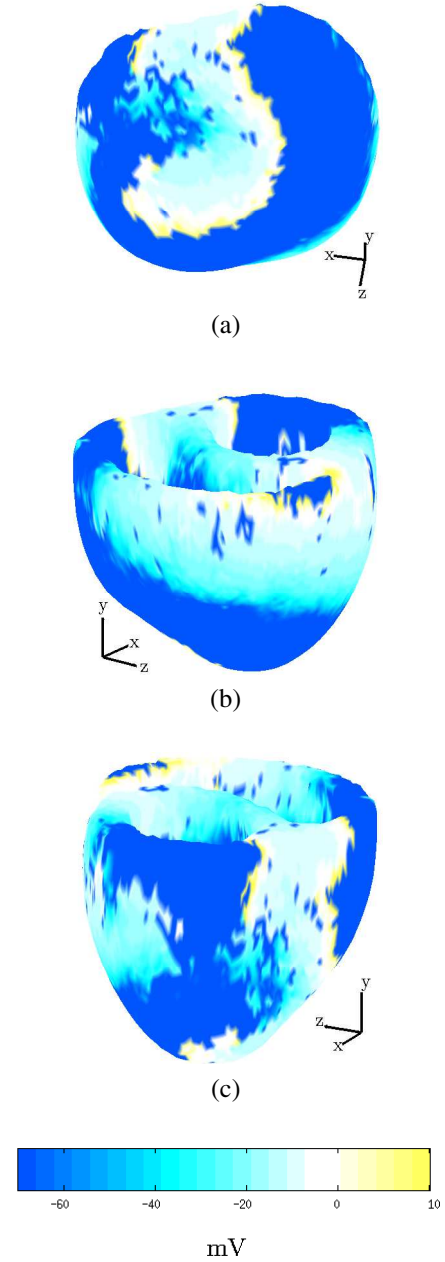


Fig. 1. Simulated spatiotemporal dynamics on the realistic 3D model of the canine ventricles. Panel (a) corresponds to the apex, (b) to the RV and (c) to the LV.

### III. RESULTS

The simulated spatiotemporal dynamics is shown from the apex, the RV and the LV in Fig. 1. Panel (a) in Fig. 1 shows a spiral wave that is anchored around the apex. In Panel (b) we can see that the spiral wave induced plane wavefronts that travelled regularly across the RV. By contrast, as shown in Panel (c), cardiac dynamics were more disorganized across the LV, with fragmented wavefronts that randomly changed their direction. Hence, based on this description, we expect a higher degree of spatiotemporal correlation at the apex and the RV than at the LV, since cardiac activity was more regular at the former two than at the latter.

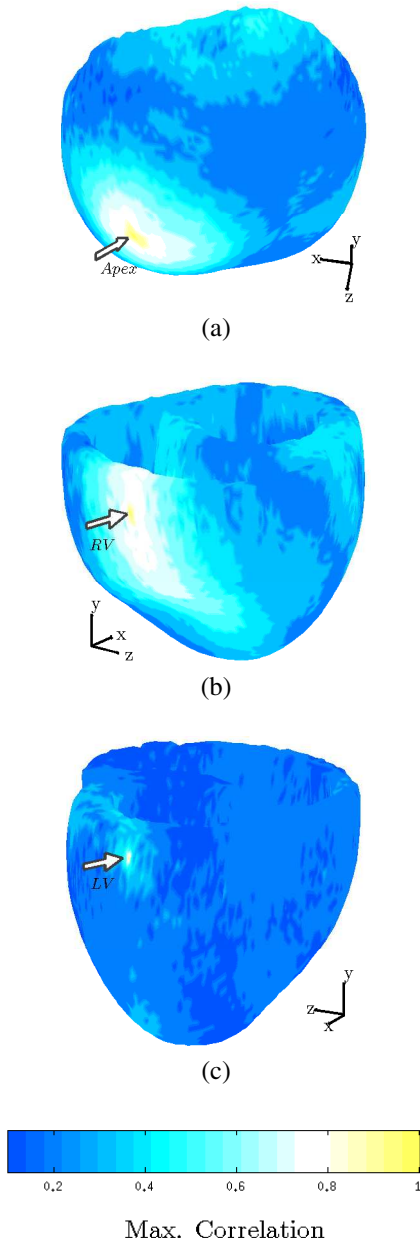


Fig. 2. Correlation maps corresponding to three nodes located at the apex (a), the RV (b) and the LV (c), respectively. Node locations are identified by an arrow. The correlation volume is larger for the nodes located at the apex and the RV than for the node located at the LV.

Figure 2 shows the correlation maps for the three selected nodes. We found that the correlation volume corresponding to the nodes situated at the apex and the RV was larger than the correlation volume corresponding to the node located at the LV. This finding is in agreement with our visual observation that the activity at the apex and the RV was regular, whereas the activity at the LV was more irregular. Hence, the simulated spiral induced different degrees of spatiotemporal correlation in different anatomical regions.

For the sake of clarity, in Figure 3 we show the results for the node at the RV and at the LV, since the results corresponding to the node at the apex were very similar to

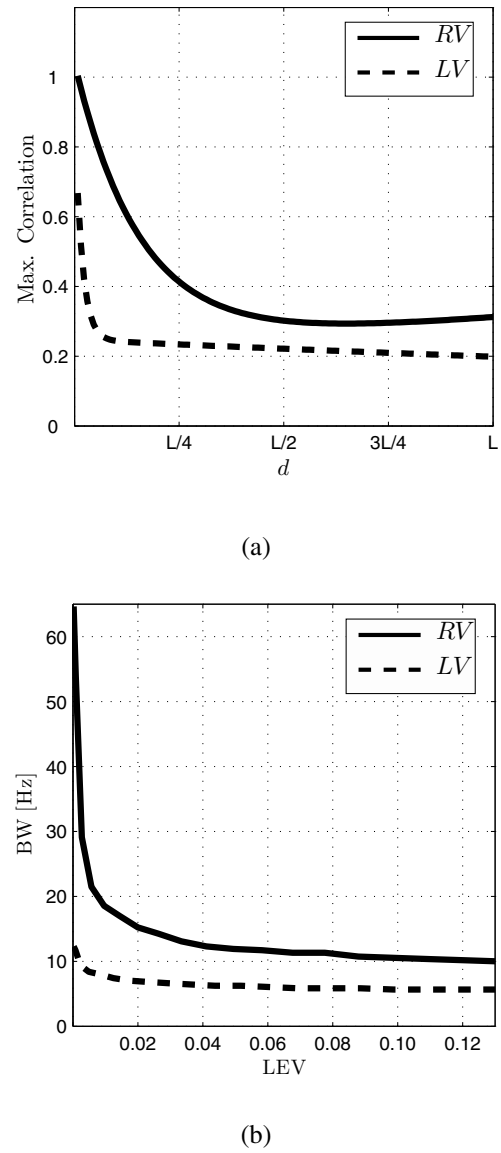


Fig. 3. (a) The maximum correlation between the selected nodes and the rest of the nodes decreased with the distance (results for the apex node not shown). As expected, the correlation length was longer for the node at the RV than for the node at the LV, for which the simulated activity was more irregular. (b) The relationship between BW and LEV shows an inverse relationship for low LEV values and saturation for high LEV values. The saturation point occurred for a higher LEV value in the RV, which showed a larger correlation volume.

the results corresponding to the RV. Figure 3 (a) shows the maximum correlation between the selected nodes and the rest of the nodes as a function of the distance to the selected nodes. As expected, the maximum correlation decreased with the distance and the observed correlation volume was larger for the RV node than for the LV node. As shown in Fig. 3 (b), the BW of synthesized cardiac signals was related inversely to the LEV for low LEV values and saturated for higher values. However, the LEV saturation value was higher at the RV than at the apex and the LV.

#### IV. CONCLUSIONS

Body-surface DF mapping has been proposed as a non-invasive surrogate of intracardiac DF mapping. However, it is still not clear how body-surface DF values relate to the intracardiac ones. The spatial resolution of body-surface electrodes systems was numerically investigated in [15] and it was concluded that because of the inability of body-surface electrode systems to measure local potentials, a one-to-one correspondence between intracardiac and body-surface DF values might not be possible. In addition to this, spectral distortions produced by volume conduction could affect body-surface DF values. Theoretically, it is known that electrode systems characterized by large LEV produce spectra with low pass characteristics when the underlying spatiotemporal dynamics are correlated [10]. This effect has also been observed in simple 2D simulation environments [8], [9]. Finally, the DF is a parameter defined by a non-linear technique which was designed for signals measured in the proximity of the endocardium and hence, morphologically consisting of trains of spikes. It can be argued whether the same signal processing technique makes sense in the case of signals that are measured by electrodes that are far from the myocardium, such as is the case of most body-surface electrodes.

In this study, we have analyzed the effects of volume conduction on the spectrum of cardiac signals in a realistic model of the ventricles. Our results agree with previous simulated and theoretical results according to which, the BW is inversely related to the LEV for correlated spatiotemporal dynamics. We have also observed that the BW saturates for high LEV values. Interestingly, the saturation point is lower when the degree of spatiotemporal correlation of the underlying dynamics is low. This result suggests that low-pass filtering is observed as long as the LEV is within the volume of correlation of the spatiotemporal dynamics.

Our main conclusion is that further signal processing stages might be needed of fully explore the information measured by body-surface electrode systems during fibrillation arrhythmias. Since volume-conduction induced low-pass filtering can be related to the LEV of the recording electrode system, a suitable high-pass filter could be designed to compensate the effects of volume conduction on the spectrum of individual body-surface signals. However, if the signal to noise ratio at high frequencies is low, this high-pass filter would essentially amplify high-frequency noise and thus, it would not be able to recover the original signal properly. In addition to this, it would be necessary to know beforehand the degree of spatiotemporal correlation of cardiac tissue in order to estimate the BW to LEV relationship, and for this, multiple simultaneous recordings would need to be analyzed. In summary, by separately analysing body-surface signals it might be difficult to obtain meaningful spectral descriptions of the underlying dynamics. By contrast, by jointly analyzing multiple body-surface signals, the effects of noise could be reduced and an indirect estimation of the degree of spatiotemporal correlation of cardiac tissue

could be obtained. These observations lead in a natural way to inverse-problem approaches for analyzing body-surface signals. Inverse-problem approaches have already been applied for analyzing cardiac dynamics based on body-surface signals. Based on our observations, they might provide the necessary signal pre-processing framework for analyzing body surface signals and cancel the spectral effects of volume conduction.

#### REFERENCES

- [1] P. Sanders, O. Berenfeld, M. Hocini, P. Jais, R. Vaidyanathan, L. F. Hsu, S. Garrigue, Y. Takahashi, M. Rotter, F. Sacher, C. Scavee, R. Ploutz-Snyder, J. Jalife, M. Haissaguerre, Spectral analysis identifies sites of high-frequency activity maintaining atrial fibrillation in humans, *Circulation* 112 (6) (2005) 789–797.
- [2] F. Atienza, J. Almendral, J. Jalife, S. Zlochiver, R. Ploutz-Snyder, E. G. Torrecilla, A. Arenal, J. Kalifa, F. Fernández-Avilés, O. Berenfeld, Real-time dominant frequency mapping and ablation of dominant frequency sites in atrial fibrillation with left-to-right frequency gradients predicts long-term maintenance of sinus rhythm, *Heart Rhythm* 6 (1) (2009) 33 – 40.
- [3] K. Kumagai, T. Sakamoto, K. Nakamura, S. Nishiuchi, M. Hayano, T. Hayashi, T. Sasaki, K. Aonuma, S. Oshima, Combined dominant frequency and complex fractionated atrial electrogram ablation after circumferential pulmonary vein isolation of atrial fibrillation, *Journal of Cardiovascular Electrophysiology* 24 (9) (2013) 975–983.
- [4] U. Richter, M. Stridh, A. Bollmann, D. Huser, L. Sörnmo. Spatial characteristics of atrial fibrillation electrocardiograms. *Journal of Electrocardiology* 41(2) (2008) 165 –172.
- [5] N. W. Hsu, Y. J. Lin, C. T. Tai, T. Kao, S. L. Chang, W. Wongcharoen, L. W. Lo, A. R. Udyavar, Y. F. Hu, H. W. Tso, Y. J. Chen, S. Higa, S. A. Chen. Frequency analysis of the fibrillatory activity from surface ECG lead V1 and intracardiac recordings: Implications for mapping of AF. *Europace* 10(4) (2008) 438 – 443.
- [6] S. R. Dibs, J. Ng, R. Arora, R. S. Passman, A. H. Kadish, J. J. Goldberger. Spatiotemporal characterization of atrial activation in persistent human atrial fibrillation: Multisite electrogram analysis and surface electrocardiographic correlations - a pilot study. *Heart Rhythm* 5(5) (2008) 68 – 693.
- [7] M. S. Guillem, A. M. Climent, J. Millet, A. Arenal, F. Fernández-Avilés, J. Jalife, F. Atienza, O. Berenfeld, Noninvasive localization of maximal frequency sites of atrial fibrillation by body surface potential mapping, *Circulation: Arrhythmia and Electrophysiology* 6 (2) (2013) 294–301.
- [8] F. A. Beltrán-Molina, A. Muñoz-Gómez, A. Rodríguez, J. J. Vinagre, J. Requena-Carrión. Effects of lead spatial resolution on the spectrum of cardiac signals: A simulation study. In *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE* 30(3) (2011) 3800–3803.
- [9] F. A. Beltrán-Molina, J. Requena-Carrión, J. Väisänen, Analysis of the Effects of Lead Configuration on Cardiac Spectrum, in: *Computing in Cardiology (CinC), IEEE, 2012*, pp. 833–836.
- [10] J. Requena-Carrión, F. A. Beltrán-Molina, A. G. Marques, Relating the spectrum of cardiac signals to the spatiotemporal dynamics of cardiac sources, *Biomedical Signal Processing and Control* 8 (6) (2013) 935–944.
- [11] J. Peyrat, M. Sermesant, X. Pennec, H. Delingette, C. Xu, E. R. McVeigh, N. Ayache, A computational framework for the statistical analysis of cardiac diffusion tensors: Application to a small database of canine hearts, *IEEE Transactions on Medical Imaging* 26 (11) (2007) 1500–1514.
- [12] F. Alonso-Atienza, J. Requena-Carrin, A. Garca-Alberola, J. L. Rojo-Ivarez, J. J. Sanchez-Muoz, J. Martinez-Sanchez, M. Valds-Chvarri, A probabilistic model of cardiac electrical activity based on a cellular automata system, *Revista Española de Cardiología* 58 (1) (2005) 41–47.
- [13] J. Malmivuo, R. Plonsey, *Bioelectromagnetism: principles and applications of bioelectric and biomagnetic fields*, Oxford University Press, New York, 1995.
- [14] J. M. Jenkins, Impact of electrode placement and configuration on performance of morphological measures of intraventricular electrograms. In *IEEE Computers in Cardiology* (1992) 367?370.
- [15] J. Requena-Carrión, J. Väisänen, F. A. Beltrán-Molina, Analysis of the spatial resolution of body-surface dominant-frequency mapping systems, in: *Computing in Cardiology (CinC), IEEE* (2012) 345–348.