Linear and Nonlinear Characteristics of ECG Signals Produced by Simulations of Ventricular Tachyarrhythmias


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Abstract

The aim of this study was to compare pseudo-ECGs produced by different configurations of re-entry in a computational model. We initiated single, double and multiple re-entrant waves in a cuboid with Fitz-Hugh Nagumo excitability. We estimated one component of the pseudo-ECG, and applied linear time-frequency and nonlinear dimensional analysis. The pseudo-ECG produced by a single re-entrant wave was periodic, whereas that produced by a double re-entrant wave was quasiperiodic with slow changes in both frequency content and amplitude. The dimension of these time series was around 1 and 3 respectively. The time-frequency distribution of the pseudo-ECG produced by multiple re-entrant waves was more complex with rapid changes in frequency and amplitude, and the dimension of the pseudo-ECG time series was around 4. Thus different configurations of re-entrant wave are associated with qualitatively and quantitatively different pseudo-ECG time series.

1. Introduction

Despite considerable progress in recent years, the mechanisms of ventricular fibrillation and polymorphic ventricular tachycardia in the human heart remain poorly understood. One of the reasons for this is that detailed information about action potential propagation in the in situ human heart is difficult to obtain, even when the heart is in sinus rhythm. The body surface ECG is the most widely used clinical tool for assessing arrhythmias, sometimes in conjunction with endocardial electrograms. During VF and PVT the ECG resembles an irregular and disordered time series, yet analysis of VF time series has revealed evidence of unexpected order and structure [1-3].

Experimental and computational studies have shown that re-entry is a candidate mechanism for many ventricular tachyarrhythmias [4], and some recent work has shown that the pseudo-ECG produced by a re-entrant wave in a computational model has striking similarities to the ECG of VF [5]. In this preliminary study we sought to quantitatively compare the pseudo-ECGs produced by different configurations of simulated re-entrant wave.

2. Methods

We simulated re-entrant waves in a numerical caricature of myocardium. All simulations were computed in a cuboid 100 x 100 x 50 elements in size and with excitability described by Fitz-Hugh Nagumo equations with a diffusion coefficient of 1, β=0.75 γ=0.50 and ε=0.30 [6]. The three dimensional cable equations were solved for the excitation variable u and the recovery variable v with a time step of 0.03 time units and a space step of 0.50 space units. We simulated three configurations of re-entrant wave. A single re-entrant wave was initiated by partial block of a propagating plane wave. A double re-entrant wave was also initiated by partial block of a plane wave. Multiple re-entrant waves were initiated from a single twisted re-entrant wave which was allowed to fragment. Isosurfaces of the u (excitation) variable for each of the three simulations are shown in Figures 1-3.

![Figure 1. Snapshot of the u (excitation variable) isosurface for the single re-entrant wave simulation.](image-url)
the correlation integral and estimated the dimension of both pseudo-ECG and surrogate time series using the Gaussian kernel algorithm [10,11], which assumes that the time series has both high dimensional and stochastic components.

3. Results

The pseudo-ECG time series from each simulation are shown in Figure 4. The time series from a single rotating re-entrant wave is periodic and stationary, reflecting the ordered rotation in this simulation. During the simulation with two re-entrant waves, the cores slowly orbited around a central point, and this is reflected in slow changes in the amplitude of the pseudo-ECG time series. The time series from multiple re-entrant waves is much more complex, and qualitatively resembles the ECG of VF.

Figure 4: Pseudo-ECG time series from a single re-entrant wave (top), two re-entrant waves (middle) and multiple re-entrant waves (bottom).

The TFDs of the time series shown in Figure 4 are depicted in Figure 5. These plots emphasise the graduation from periodic characteristics with one re-entrant wave, through quasiperiodicity with two re-entrant waves, and rapid changes in the amplitude and frequency of the pseudo-ECG components with multiple re-entrant waves.

Figure 6 shows correlation integral plots for each simulation at an embedding dimension of 8. In each case the difference between the surrogate and pseudo-ECG time series increased with increasing embedding dimension up to a maximum value. The difference between the real and surrogate time series was significant,
indicating that none of the pseudo-ECG time series could be described as linearly filtered random noise.

Figure 5: Time frequency distribution for pseudo-ECG signals from one (top), two (middle), and multiple (bottom) re-entrant waves.

Plots of dimension as a function of embedding dimension are shown in Figure 7. The dimension converged to around 1 for a single re-entrant wave, around 3 for two re-entrant waves, and around 4 for multiple re-entrant waves. The high dimensional component was around 10% for multiple re-entrant waves, and close to zero for the other two simulations.

4. Discussion

This study has shown that different configurations of re-entrant wave produce pseudo-ECG time series that are qualitatively and quantitatively different.

Figure 6: Plots of correlation integral against correlation length for one (top), two (middle) and multiple (bottom) re-entrant waves. The bunched lines are correlation integral of the 20 surrogate time series, and the single line is the correlation integral of the pseudo-ECG time series.
Non-linear analysis is a promising technique for the analysis of time series. The estimates of dimension in this study reflected the increasing number of active degrees of freedom in the simulations, although the estimate of dimension obtained for multiple re-entrant waves was less than the value of 5-6 obtained from recordings of VF in pigs (5-6) [12]. The most likely explanation for this difference is another level of complexity imposed by more complex geometry, excitability, and action potential propagation than the simple caricature presented here.

Nevertheless, this study has indicated the potential offered by the combination of non-linear analysis, computational models of re-entry, and real ECG data to expand our understanding of re-entry in real hearts. This study complements a recent report that shows how re-entrant and focal arrhythmias could be distinguished from their electrograms [10]. Further work will use more biophysically accurate computations using more realistic ventricular geometry for propagation and a simulated torso for ECG computations.

5. Conclusions

In this study we have shown that the pseudo-ECG produced by single, double, and multiple re-entrant waves in a numerical caricature of myocardium have different linear and nonlinear properties.

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References


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