Identification and visualisation of domain structure of experimentally induced ventricular fibrillation

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Abstract. The mechanisms generating spatio-temporal irregularity of electrical activity in the fibrillating heart need to be validated by using common methods to visualise experimental and model generated data streams. We identify spatial frequency domains in data from visualisations of surface activity in isolated, perfused ventricular myocardium, partial differential equation models of ventricular tissue, and from surface electrograms from the human heart during induced fibrillation.

1 Introduction

The long term goal of visualising the pattern of propagation within the myocardium during an episode of ventricular fibrillation may be achieved by combining computational simulation of biophysically detailed excitation processes within a histologically (muscle fibre orientation) and morphologically detailed geometry, with data streams from a database of actual cardiac geometry (say reconstructed from MRI) and from multichannel electrophysiological recordings. For such a fusion of simulation and data to serve as a basis for interventions the behaviour of the virtual cardiac tissue needs to be validated. Here we examine surface electrical activity during simulated fibrillation in virtual tissue, experimental fibrillation in myocardial wall and induced clinical fibrillation. The basic idea is that fibrillation is generated by interacting re-entrant waves, and that the complicated surface spatio-temporal activation patterns may be generated by relatively simple three-dimensional re-entrant scroll (the 3-dimensional generalisation of a spiral) waves within the ventricular wall.

Figure 1 illustrates fibrillation as a nonlinear wave process in a three dimensional excitable medium [1], with re-entrant waves propagating around curved intramural filaments (60 x 60 x 20 mm Fenton-Karma model [2] with parameters to reproduce Beeler-Reuter kinetics). The transmural rotational anisotropy has broken down a single scroll wave into multiple re-entrant wavelets. It is natural to assume that the filaments can intersect the surface, where re-entry would be manifest as a spiral wave: in practice because of three dimensional effects, such spirals are rarely seen on the surface.

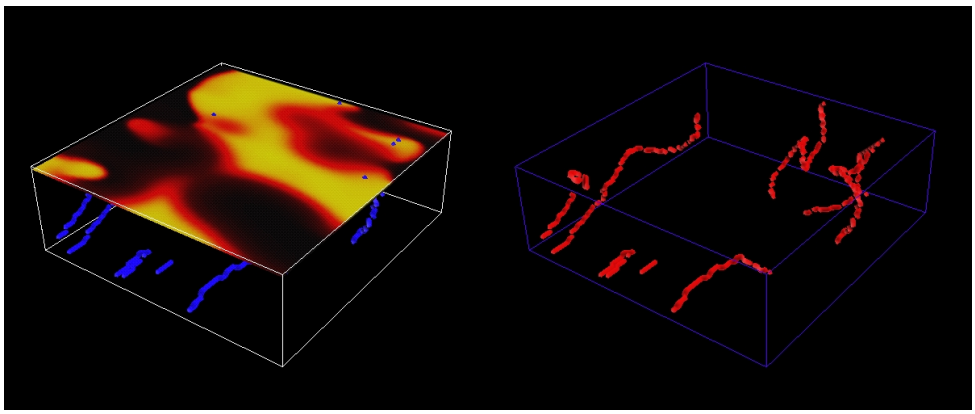

Figure 1. Snapshot from movie of simulated fibrillation in a slab of ventricular tissue, with 120 degrees rotational anisotropy, showing epicardial activation patterns (depolarisation coloured) and intramural filaments.

2 Optical monitoring of propagation

In cardiac preparations perfused with a voltage sensitive dye the surface patterns of electrical activity may be monitored optically [3]. Pertsov et al [4] have developed an isolated, perfused ventricular wall

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preparation where endocardial and epicardial activity can be observed simultaneously during induced fibrillation. In this preparation there is a strong local temporal periodicity during induced fibrillation. The spatial distribution of the dominant temporal frequencies of excitation has a domain organization, the domains persist for minutes and occupy a few square cms.

2.1 Visualisation of surface activity

Optical mapping experiments provide monochrome movies of spatio-temporal activity, at 120 frames/s with a spatial resolution of approximately 0.5mm. The interpretation of these images is facilitated by a time-delay colouring method - see Figure 2 . Each frame shows the instantaneous activation and its pattern of excitation, and re-entrant spirals can be identified as points around which the whole colour loop (the sequence red-yellow-green-cyan-blue-magenta-red) is seen: this is essentially equivalent to the colour-coding of phase [3].

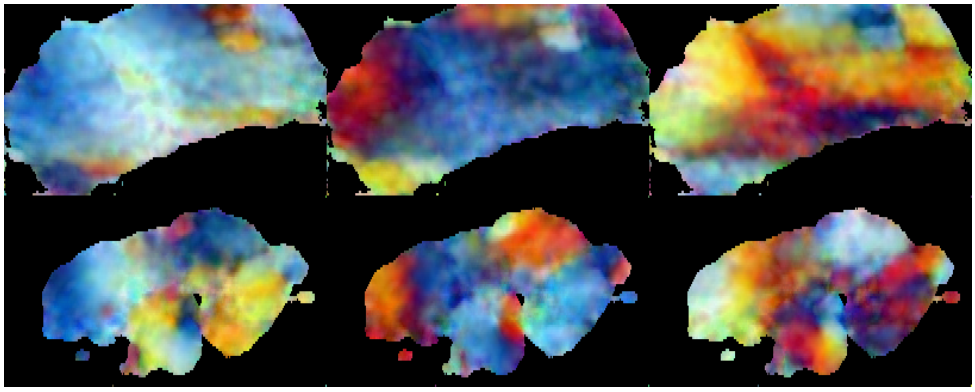

Figure 2. Surface view of induced polymorphic tachycardia, epicardial surface (top) endocardial surface (bottom). Visualisation uses time-delay colouring method: three copies of the same movie are made, at times t, t+25, t+50ms, and coloured red, blue and green, and then superimposed. The frames show the instantaneous activation pattern, with red the front of the activation wave.

Since the patterns on the two surfaces are different the process of fibrillation is essentially three-dimensional - both simple surface patterns ("monomorphic tachycardia") and complicated patterns such as in Figure 2 can be reproduced by a small number of re-entrant waves sources within the ventricular wall, with their filament axes intramural (roughly parallel to the surface) rather than transmural [5].

2.2 Domain structure

The domain structure of experimental or simulated surface activity can be visualised by obtaining the cumulative power spectrum, identifying the frequency peaks, and filtering each local time series by narrow bandpass filters that cover only one peak: these distribution of power can then be colour coded over the surface. An example is shown in Figure 3, where two dominant frequency bands (of 15 and 12.5 Hz., giving a ratio 6:5) are present on both surfaces. In the examples analysed the dominant frequency ratios were always close to a simple integer ratio e.g. 4:3 or 4:3:2. This can be accounted for by a common source and Wenckebach-like frequency division [6] produced by a sharp or smooth change in medium properties.

2.3 Karhunen-Loève Decomposition

The methods illustrated above are qualitative and visual: Karhunen-Loève (KL) decomposition provides a means of quantifying these ideas. The KL spectra for the separate and conjoint endo- and epicardial can be computed and used to evaluate the complexities of the separate and conjoint signals. Tests for the independence or linear dependence between the signals from the two surfaces provide quantitative diagnostics for whether or not the signals are being generated by a common or different re-entrant sources; and these spectra can be quantified as KL entropies. These measures have been applied to the data illustrated in Figures 2 and 3 in [7]. KL decomposition should also expose the spatial structure of the domains: Figure 4 illustrates the visual similarities between the frequency domains and some of the modes.

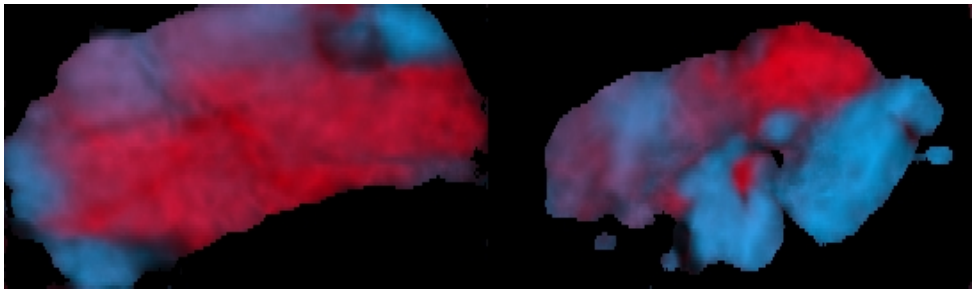

Figure 3. High (blue) and low (red) frequency domains on endo- (left) and epicardial (right) surfaces for data of Figure 2

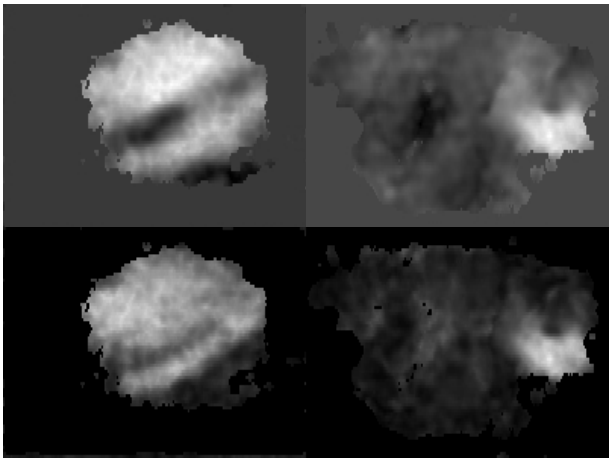

Figure 4. Top: First KL mode for an epicardial sequence and third KL mode for a concurrent endocardial sequence; bottom: the low frequency domains (analogous to the red domains of Figures 3 and 5) for these endo and epicardial surfaces

3 Medium heterogeneity and domain boundaries

Although the domain structure can be reproduced by frequency division at the boundaries between regions of different medium properties, in two dimensional [6] and three-dimensional simulations [8] the domain boundaries do not simply map the boundaries between regions with different medium parameters: they are more irregular and displaced towards the part of medium that has a reduced excitability.

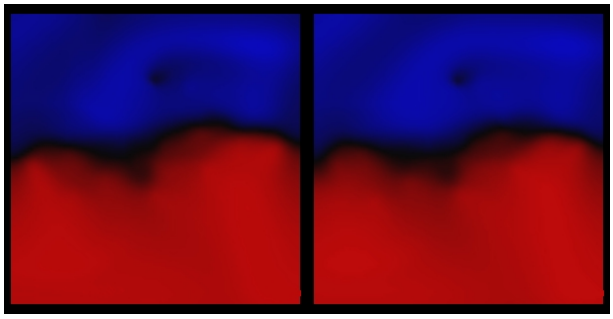

Figure 5. High (blue) and low (red) frequency domains for top (left) and bottom (right) surfaces of cuboid of excitable tissue with half the medium with reduced excitability

4 Clinical fibrillation

We have analysed epicardial electrograms provided by Peter Taggart that were obtained as in [9] from 5 patients, with no history of myocardial infarction, undergoing routine coronary bypass surgery for the relief of angina. The electrograms were recorded by a 2 x 4 grid of electrodes on the anterior wall of the left ventricle, with an interelectrode spacing of 0.5 cm and inter-row spacing of 1 cm. Once on cardiopulmonary bypass the ventricles were electrically fibrillated and recordings made for up to two minutes. Each recording showed a dominant frequency peak: these are plotted for one recording in Figure

6, where there is evidence of domains between 9 and 17 s. However, domains were only identifiable in recordings from 2 of the 5 patients: if the domain size was similar to that seen in the sheep ventricle preparation the electrode grid should have spanned one or more domains. Thus if a domain structure was present it would have been detected. For most of the recordings, and for most of the time, the pattern was analogous to that illustrated for 20-30s: the different electrodes showing changing, different dominant frequencies.

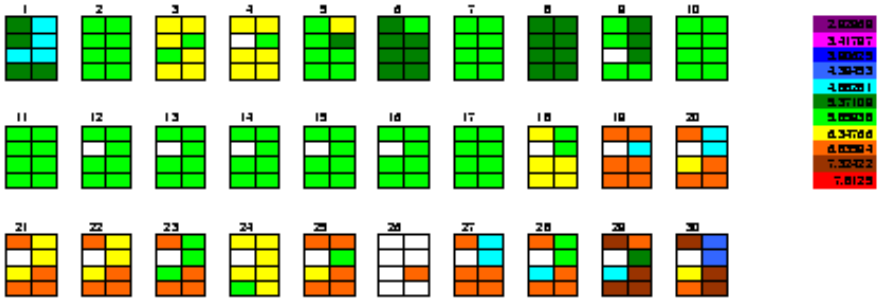

Figure 6. Dominant frequency of fibrillation recorded at each electrode between 1 and 30 s. Each panel codes the dominant frequency obtained over one s interval at the grid of eight electrodes. Data from in vivo perfused human heart

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