Epicardial Mapping of Ventricular Fibrillation in the Human Heart during Ischaemia and Reperfusion

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Abstract

The aim of this study was to map electrical activity over the ventricular epicardial surface during ventricular fibrillation (VF) in the human heart, and to document changes associated with ischaemia and reperfusion. In 5 patients undergoing cardiopulmonary bypass VF was induced by burst pacing, and three 30 s episodes of epicardial activity were recorded at 1 kHz using an epicardial sock with 256 unipolar contact electrodes. The first episode of activity was recorded at the start of VF, the second after 2 minutes of ischaemia, and the third during coronary reperfusion. Following 2 minutes of ischaemia the mean dominant frequency (DF) of the epicardial signals fell from 5.6 Hz to 4.5 Hz, and the mean number of epicardial phase singularities increased from 7.8 to 10.5. Following coronary reperfusion the mean DF increased to 6.5 Hz, but there was no significant change in the mean number of epicardial phase singularities.

1. Introduction

Human ventricular fibrillation (VF) is generally accompanied by ischaemia. Although some studies indicate that cardiopulmonary resuscitation may improve the efficacy of defibrillation [1], others are more equivocal [2] indicating that VF in the ischaemic and reperfused human heart is not well understood.

Experimental studies in animal hearts have indicated that VF can be sustained by different mechanisms [3], and our recent studies of VF in the human heart have shown evidence that multiple wavelets and dominant rotors may be important at different times during the same episode of VF [4]. Other experimental studies have highlighted the role of experimental conditions in determining VF mechanism [5]. Ischaemia has shown to play an important role in rabbit hearts, determining whether VF is sustained by a large number of transient wavelets or a small number of persistent rotors [6].

The aim of this study was therefore to map patterns of epicardial activation during VF in the human heart, following initiation, a period of ischaemia and then reperfusion. In this paper we present preliminary results from 5 patients.

2. Methods

In 5 patients undergoing cardiopulmonary bypass for routine cardiac surgery (3 for coronary artery bypass graft, and 2 for aortic valve replacement), an epicardial sock with 256 unipolar contact electrodes was placed over the heart as described previously [4], and illustrated in Figure 1. VF was induced by burst pacing, and a 30 s episode of epicardial activity was sampled at 1 kHz. The aorta was then cross-clamped and after two minutes of ischaemia a further 30 s episode of activity was recorded. The cross clamp was then released, and a final 30 s episode of activity was recorded during coronary reperfusion.

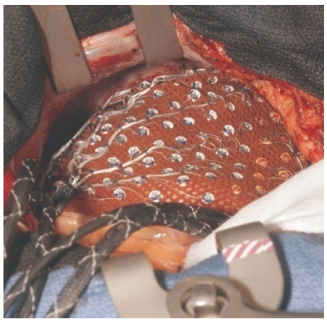

Figure 1. Epicardial sock used to record VF

Noisy signals were rejected, and the signals were detrended as described previously [4]. For the 5 patients included in this study, signals from between 213 and 252 electrodes were available for analysis.

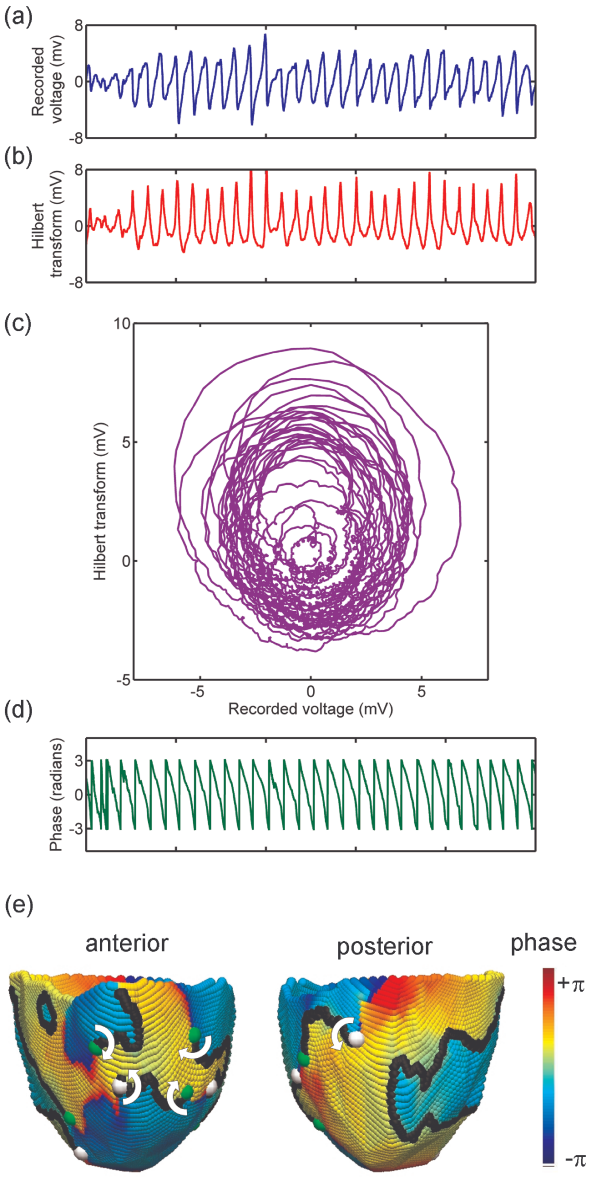

Figure 2. (a) 5 s extract of example voltage data. (b) Hilbert transform of data in (a). (c) Phase plane plot of data in (a) and (b). (d) Phase data. (e) Phase, PS, and wavefronts mapped onto epicardial surface.

Throughout each recording we estimated the spectrum at each electrode using a fast Fourier transform on a 4.096 ms moving window. The dominant frequency (DF) was the frequency of the dominant spectral peak.

We also estimated the number of phase singularities (PS) by first interpolating the electrode data onto a regular grid, and then transforming the interpolated voltage data into phase using a Hilbert transform [4]. Figure 2 illustrates how a voltage signal is transformed into phase.

Figure 2(a) shows electrode voltage and Figure 2(b) shows the Hilbert transform of the data in Figure 2(a). Figure 2(c) shows a phase plane plot, where the data shown in Figure 2(b) is plotted agains those shown in Figure 2(a). Figure 2(d) shows phase, which is the angle subtended by a line linking the origin of Figure 2(c) with each point on the line shown in Figure 2(c). Figure 2(e) shows phase mapped onto the epicardial surface. PS were identified using a convolution based method [7]. In Figure 2(e) PS are shown at the end of wavefronts, which are indicated by solid black lines. The colour (or shading) of the PS indicates its chirality, with arrows indicating the direction of rotation.

3. Results

Figure 3 shows an example of how the electrograms, DF and the number of PS changed during a single recording of VF. The top panels show 5 s extracts from the signal recorded at a single electrode. The extracts are centred on (a) 15 s after initiation of VF, (b) 15 s before the end of 2.5 minutes of ischaemia, and (c) 15 s after the start of coronary reperfusion. Slower activity can be seen following ischaemia and faster activity during reperfusion. Figure 3(d) shows the mean (solid line) and standard deviations (dotted lines) of DF averaged over all of the electrodes. Figure 3(e) shows the; the shaded lines indicate the wide variability in the number of PS, each point is the average number of PS over a 1 s window, and these indicate the overall trend in the number of PS.

Figure 4(a) shows that in all except one of the recordings there was an increase in mean DF during the initial period of VF. All of the recordings showed a lower DF following ischaemia, and all of the recordings showed a dramatic increase of DF during reperfusion. Figure 4(b) shows the corresponding PS data, where the points plotted are the mean number of PS calculated over 1 s, as shown in Figure 3(e). The overall trend is less clear, with a slight increase in the number of PS during the initial period of VF, but little change thereafter.

Figure 5(a) aims to summarise these trends by showing boxplots for DF. In these plots the mean DF values for all 5 recordings have been pooled for the first and last 5 s of the initial period of VF, for the last 5 s of ischaemia, and for the last 5 s of coronary reperfusion. In these plots, the top and bottom of each box indicate the 25th and 75th percentiles, the line in the middle of each box indicates the median, the whiskers indicate points that are within 1.5 of the interquartile range above or

below the edges of the box, and any data lying outside the whiskers are plotted separately as outliers.

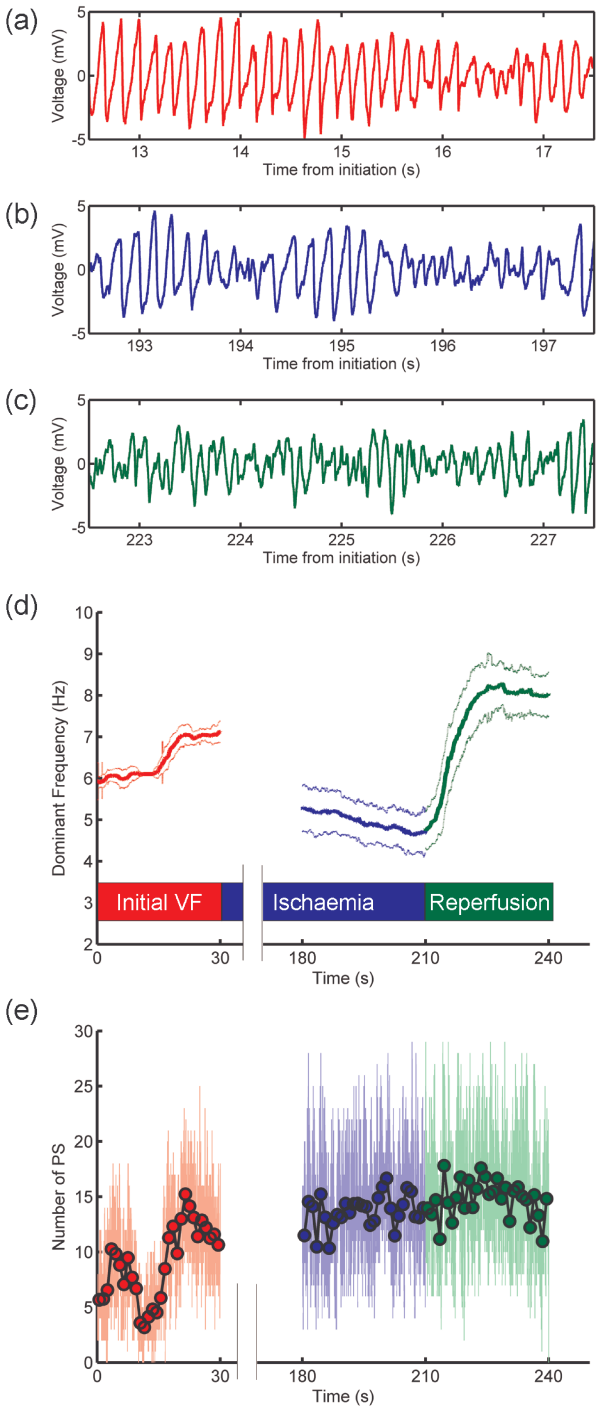

Figure 3. Example of electrograms recorded during initial VF (a), ischaemia (b), and coronary reperfusion (c). (d) Change in mean DF, and (e) change in number of PS.

These data represent means of means, and so any statistical analysis should be interpreted very cautiously. Nevertheless a one way analysis of variance shows significant ($p<0.05$) differences between each of these samples, indicating significant changes in DF during the first 30 s of VF, following 2.5 minutes of ischaemia, and following 30 s of coronary reperfusion. This observation is consistent with the overall trends shown in Figures 3 and 4.

Figure 5(b) shows a similar plot for the number of phase singularities averaged over 1 s windows. Again, these data represent means of means, and so should be interpreted cautiously. One way analysis of variance showed a significant ($p<0.05$) increase during the first 30 s of VF, and following 2.5 minutes of ischaemia, but no significant change during coronary reperfusion. As with the DF data, these observations are consistent with the trends in Figures 3 and 4.

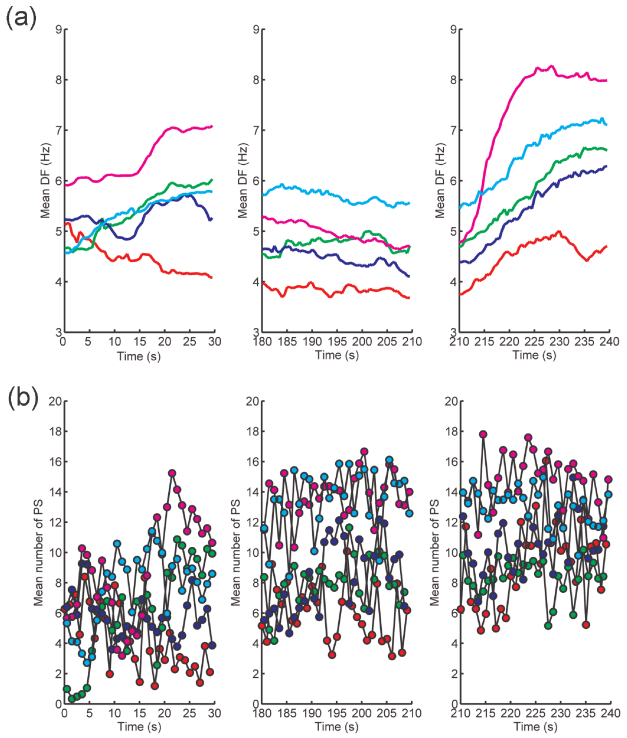

Figure 4. Trends in mean DF (a) and number of PS (b) for each of the five patients.

4. Discussion and conclusions

This preliminary study in 5 patients indicates that a short period of ischaemia followed by coronary reperfusion alters the dynamics of VF in the human heart. The activation rate of VF estimated from mean DF tended to increase during an initial period of perfused VF, but fell during ischaemia. Following reperfusion the activation rate increased dramatically. The number of PS provides an index of spatiotemporal complexity, and we

found in this study that the number of PS tended to increase during the initial period of VF, with little change during coronary reperfusion.

There are some important limitations to this study that should be noted. We have only examined recordings from 5 patients, and our recordings are restricted to specific locations on the epicardial surface. Although our DF measurements are obtained from the individual electrodes, the PS data are obtained by interpolation between electrodes, and the number and locations of PS obtained by this technique may be affected by the interpolation process. Further work is underway to investigate other methods of quantifying spatiotemporal complexity that do not depend on interpolation.

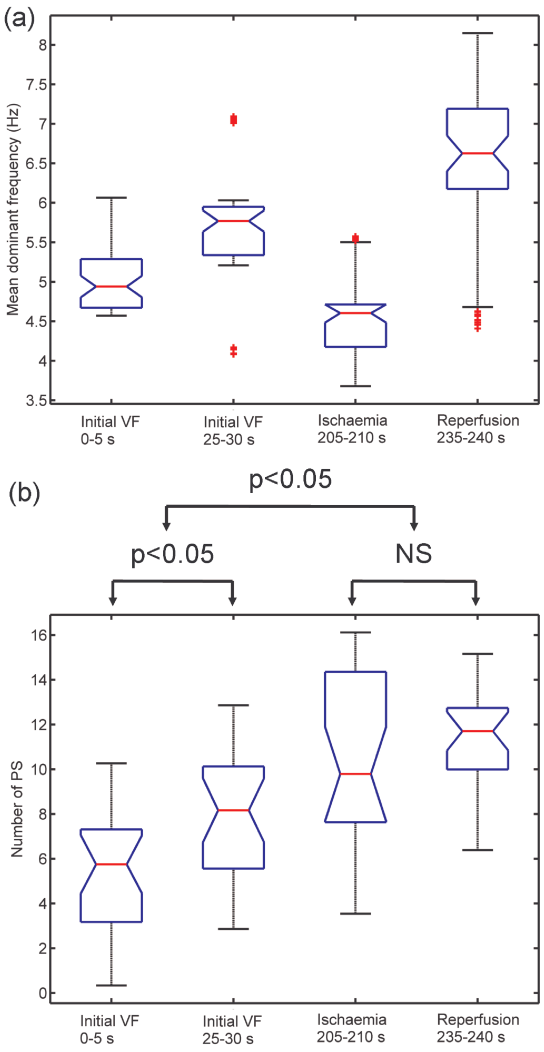

Figure 5. Boxplots showing DF (a) and number of PS (b), obtained from pooling data during 5 s periods at the beginning and end of the initial period of VF, at the end of 2.5 minutes of ischaemia, and after 25 s of reperfusion.

Despite these limitations, these findings are consistent with the idea that mechanisms sustaining VF in the human heart are modulated by both ischaemia and reperfusion. Further work is needed to establish the implications of these ideas for our understanding of the mechanisms that sustain VF in the human heart, and for clinical practice.

Acknowledgements

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