A Model for Multi-site Pacing of Fibrillation Using Nonlinear Dynamics Feedback

Victor D. Hosfeld · Steffan Puwal · Keith Jankowski · Bradley J. Roth

Abstract Traditionally, cardiac defibrillation requires a strong electric shock. Many unwanted side effects of this shock could be eliminated if defibrillation were performed using weak stimuli applied to several locations throughout the heart. Such multi-site pacing algorithms have been shown to defibrillate both experimentally (Pak et al., Am J Physiol 285: H2704–H2711, 2003) and theoretically (Puwal and Roth, J Biol Systems 14:101–112, 2006). Gauthier et al. (Chaos, 12:952–961, 2002) proposed a method to pace the heart using an algorithm based on nonlinear dynamics feedback applied through a single electrode. Our study applies a related but simpler algorithm, which essentially configures each electrode as a demand pacemaker, to simulate the multi-site pacing of fibrillating cardiac tissue. We use the numerical model developed by Fenton et al. (Chaos, 12:852–892, 2002) as the reaction term in a reaction–diffusion equation that we solve over a two-dimensional sheet of tissue. The defibrillation rate after pacing for 3 s is about 30%, which is significantly higher than the spontaneous defibrillation rate and is higher than observed in previous experimental and theoretical studies. Tuning the algorithm period can increase this rate to 45%.

Keywords Defibrillation · Pacing · Feedback · Nonlinear dynamics · Numerical simulation · Heart

1 Introduction

Ventricular fibrillation (VF) renders the heart ineffective at pumping blood. If not corrected within minutes, the condition is fatal. Currently, the most effective treatment is defibrillation: the delivery of a high-energy shock to the heart. The large energy used to defibrillate is painful to the patient and possibly damaging to cardiac tissue. Our goal is to develop algorithms to control the nonlinear chaotic behavior of VF using weak enough
stimuli to eliminate pain and other side effects, thereby reducing the problem of defibrillation to one of pacing [1].

Many researchers have studied electrical control techniques to suppress cardiac arrhythmias [1–7], particularly to control alternans (an alternating response to a periodic stimulus) [8–12]. Often, control can be maintained over a limited region surrounding the stimulating electrode (regional capture). In our study, we consider a multi-site electrode geometry, similar to that used by Pak et al. [6] in their attempt to stop VF in rabbit hearts by feedback pacing, and implement a nonlinear feedback algorithm motivated by the work of Gauthier et al. [7]. The Fenton-Karma model [13, 14], which characterizes the cardiac tissue, accounts for spiral wave breakup and the development of fibrillation. Our specific aim is to determine whether our algorithm – using low energy stimuli with a magnitude only modestly larger than the diastolic threshold – will increase the success rate of defibrillation compared to previous studies involving the multi-site application of low energy stimuli to terminate VF.

2 Methods

Except when stated otherwise, the mathematical model is the same as that used by Puwal and Roth [15]: an isotropic two dimensional tissue sheet, 5.25×5.25 cm, is discretized with a 350×350 array of nodes, implying a space step of 0.015 cm. Four stimulus electrodes form a square, 1.32 cm on each side, centered in the tissue sheet (Fig. 1). The electrodes themselves are 0.075×0.075 cm. Periodic boundary conditions determine the behavior of the tissue at the edge of the sheet and give the tissue a toroidal shape.

The transmembrane potential, $V$, obeys a reaction–diffusion equation

$$\frac{\partial V}{\partial t} = D \nabla^2 V - \frac{I_{\text{stim}} + I_{\text{fi}} + I_{\text{si}} + I_{\text{so}}}{C_m},$$  \hfill (1)

where $D$ is the diffusion constant (1 cm$^2$/s) and $C_m$ is the membrane capacitance (1 $\mu$F/cm$^2$). The three ionic currents – $I_{\text{fi}}$, $I_{\text{si}}$, and $I_{\text{so}}$ – are described by the Fenton et al. [14] and

Fig. 1 The geometry of the tissue sheet and four pacing electrodes

1  2  3  4

1 cm