Feedback Control of Resonant Drift as a Tool for Low Voltage Defibrillation

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1 Motivation

There is a phenomenon of resonant drift of a spiral wave which occurs when applying a periodic stimulus with period equal to that of the spiral wave. It appears that this phenomenon can be used for moving the spiral wave to an area where is would terminate (e.g. an inexcitable piece of cardiac tissue).

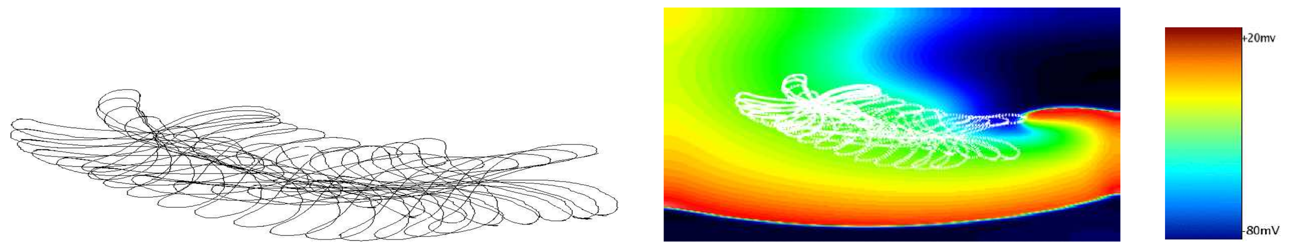

Fig1: Trajectory of resonantly drifting spiral wave

Problems include the choice of frequency of the stimulations and resonant repulsion from boundaries. Biktashev and Holden [2] described a way of overcoming both of these problems by applying feedback controlled stimulations.

The aim of this project is to explore the feasibility of using this phenomenon as a tool for low voltage defibrillation. We conduct numerical experiments using a purely bidomain formulation.

2 Bidomain nature of cardiac tissue

The bidomain representation of cardiac tissue is currently the most complete description of cardiac electrical activity. We use a purely bidomain formulation with a finite element mesh (tetrahedral elements) to discretize a slab of cardiac tissue. Using the fact that the transmembrane potential is $V_m = \phi_i - \phi_e$, the bidomain equations can be written as;

$$\nabla \cdot (\sigma_i + \sigma_e) \nabla \phi_e = -\nabla \cdot \sigma_i \nabla V_m \quad (1)$$

$$\nabla \cdot \sigma_i \nabla V_m = -\nabla \cdot \sigma_i \nabla \phi_e + \beta I_m \quad (2)$$

$$I_m = C_m \frac{\partial V_m}{\partial t} + I_{ion} \quad (3)$$

For (3) we use two modifications of the Courtemanche human atrial model [4] to describe the ionic current kinetics.

(i) As in [7], we incorporated electroporation into the model (see [3]). A formulation for an acetylcholine (ACh) dependent potassium current, $I_{K(ACh)}$ was also added (see [6]). A single rotor spiral (MS) was generated using these modifications which meanders and self terminates after $16000msec$.

(ii) In addition to EP and $I_{K(ACh)}$, we consider the modifications suggested by Xie [5] where $I_{Ca,L}$ is blocked by 65% coupled with a ninefold increase in I_{Ks} and I_{Kr}. Another single rotor spiral was generated (RR), this time it rigidly rotates and never self-terminates.

3 Numerical Methods

A 3D slab of cardiac tissue ($4 \times 2 \times 0.02cm^3$) with $\beta = 1400cm^{-1}$ was discretized with $dx = dy = dz = 100\mu m$ to form a finite-element mesh with tetrahedral elements. All numerical calculations were preformed by CARP [1] which solves the elliptic equations using the conjugate gradient method with an incomplete LU preconditioner, the parabolic equations and ODE's are solved using the forward Euler method.Defibrillating shocks were applied by injecting current into the extracellular space in the volume $1 \times 1 \times 0.1mm^3$ via electrodes which were centered along the left and right edges of the tissue.

Using four different locations for the registration electrode ($2 \times 2 \times 0.1mm^3$), the top left (TL), top right (TR), bottom left (BL) and bottom right (BR) corners of the mesh, feedback controlled shocks were applied as extracellular current of $5msec$ duration and varying strength ($1 \times 10^6 \mu A/cm^3 \leq I_e \leq 1 \times 10^7 \mu A/cm^3$). Here we used a time step, dt, of $10\mu s$ throughout. All shocks were applied at time $t = 0$.

4 RESULTS: Meandering spiral (MS)

Depending on the shock strength different scenarios were observed. The first case is where the original spiral drifted to a boundary where it was annihilated without the formation of new wavefronts.

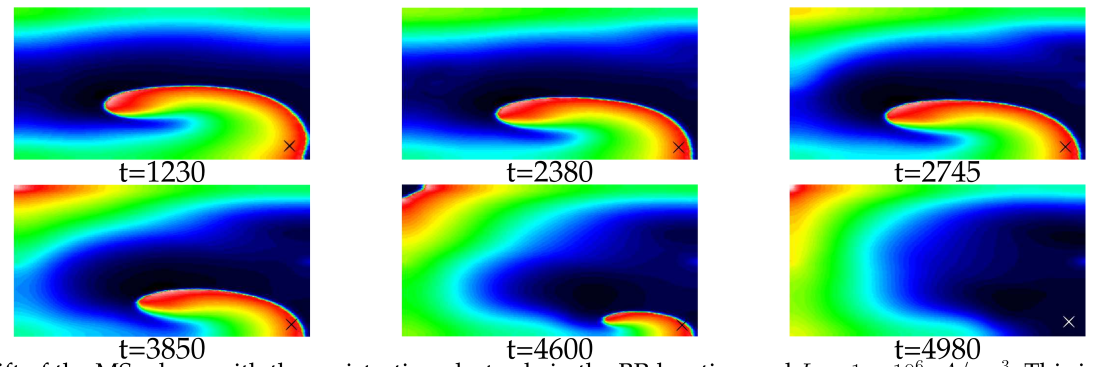

Fig2: Resonant drift of the MS where with the registration electrode in the BR location and $I_e = 1 \times 10^6 \mu A/cm^3$. This is an example of the case where no additional rotors are generated

The second case is where new wavefronts are initiated. In this instance the algorithm first concentrates on eliminating the original spiral before focusing on eliminating new ones

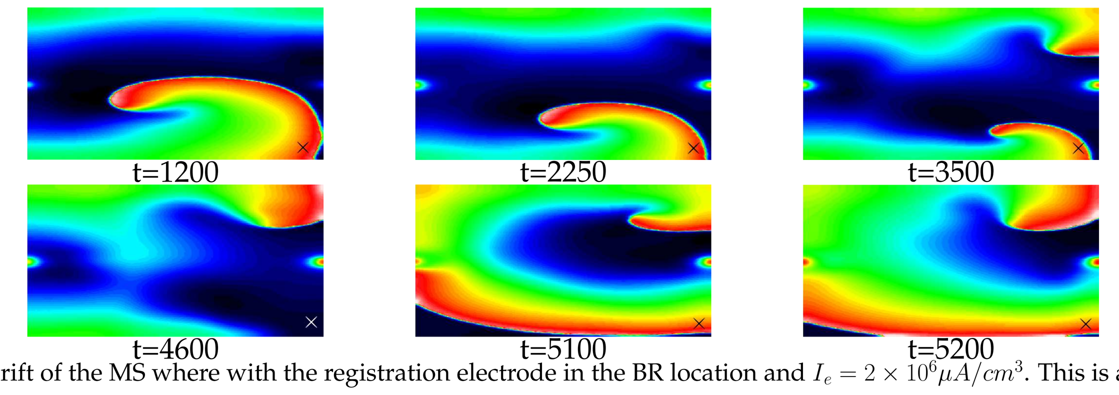

Fig3: Resonant drift of the MS where with the registration electrode in the BR location and $I_e = 2 \times 10^6 \mu A/cm^3$. This is an example of the case where an additional rotor is generated from the shocks, the feedback algorithm first 'pushes' the original spiral to the boundary (where it is terminated) and then does the same for the new rotor. This procedure continues until all rotors have been annihilated.

In the case when new wavefronts are formed, the different spirals sometimes collide and annihilate each other without reaching a boundary. The threshold for defibrillation (50% success) using a single shock with the same parameters was $I_e = 1.4 \times 10^7 \mu A/cm^3$. The results obtained from this series of experiments are below.

I_e	BL	BR	TL	TR
1×10^6	19169	5013	16763	10239
2×10^6	1297	6478	4880	9712
3×10^6	5930	2689	6474	4960
4×10^6	9820	3530	4160	2310
5×10^6	2060	560	2160	2670
6×10^6	2570	560	1100	1730
7×10^6	900	920	1300	3590
8×10^6	1660	340	720	1330

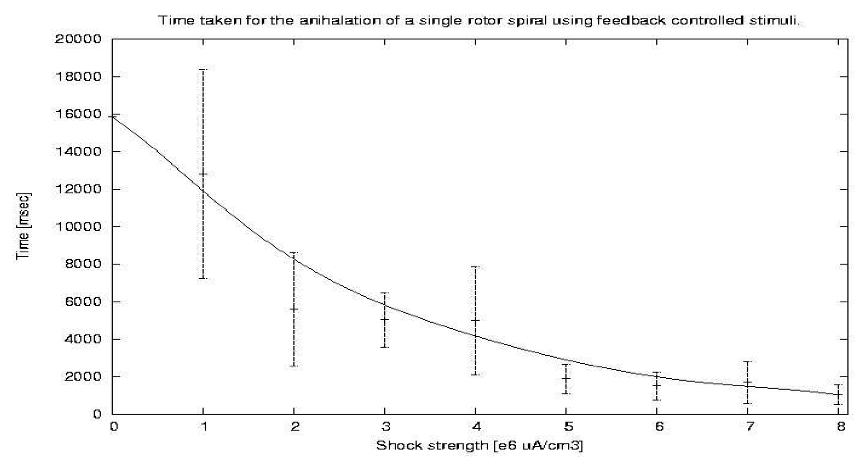

Fig4:Results from numerical simulations with MS.Time is in $msec$ and shock strength in $\mu A/cm^3$

5 RESULTS: Rigidly rotating spiral (RR)

The same scenarios which appeared for MS also exist for RR. For example, figure 5 shows an example where the original spiral is pushed towards the boundary but a new spiral wave is formed in the process. The feedback loop then concentrates on annihilating this new one.

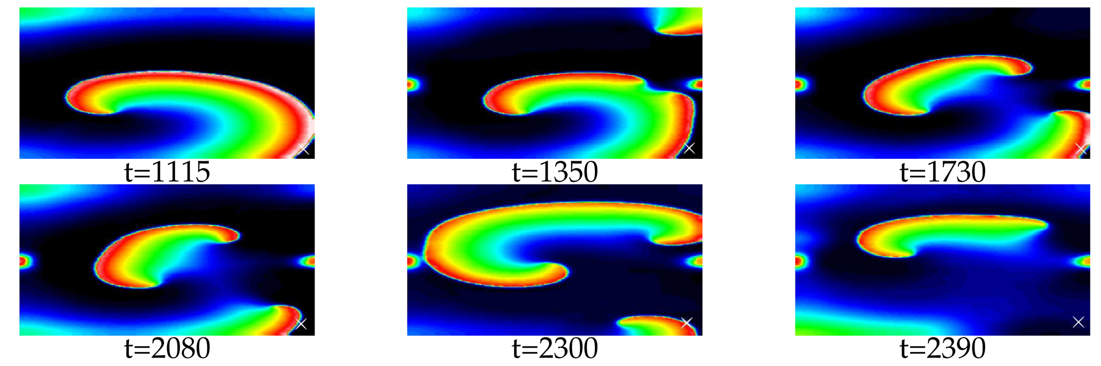

Fig5:Resonant drift of the RR where with the registration electrode in the BR location and $I_e = 7 \times 10^6 \mu A/cm^3$. This is an example of the case where additional rotors are created.

Complete termination of re-entry activity was not always evident. Here we saw that the feedback algorithm can get caught in a loop. That is where the original spiral has been terminated, but the stimulations produce new wavefronts which repeatedly trigger another stimulation

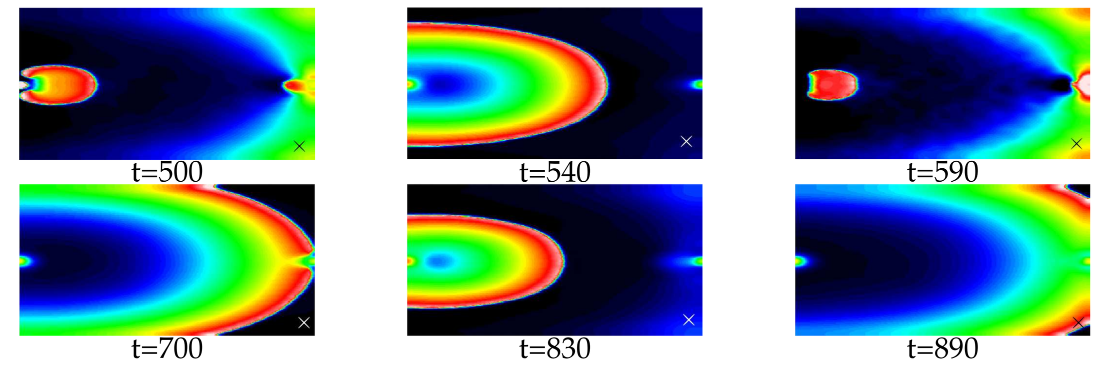

Fig6:Example of when the feedback loop will never terminate all re-entrant activity.

The table below shows the results which we have obtained using the feedback loop on RR. The threshold for defibrillation (50% success) using a single shock with the same parameters was $I_e = 1.8 \times 10^7 \mu A/cm^3$.

I_e	BL	BR	TL	TR
2×10^6	L_∞	L_∞	L_∞	L_∞
3×10^6	L_∞	21390	L_∞	L_∞
4×10^6	L_∞	12330	L_∞	17640
5×10^6	L_∞	19530	L_∞	30420
6×10^6	L_∞	3370	L_∞	21000
7×10^6	L_∞	3250	L_∞	8630
8×10^6	L_∞	790	L_∞	3210
9×10^6	L_∞	480	L_∞	3340
10×10^6	L_∞	400	L_∞	1610

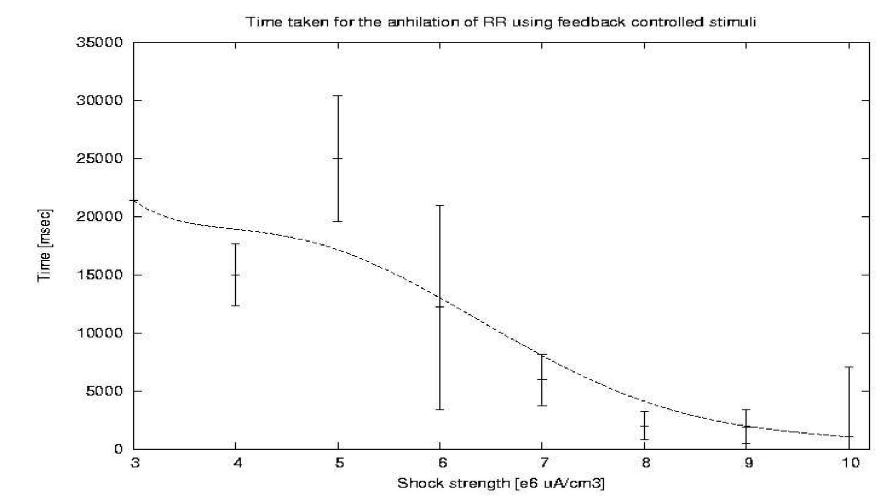

Fig7: Results from numerical simulations with RR.Time is in $msec$ and shock strength in $\mu A/cm^3$. L_∞ denotes the cases where the feedback controlled stimulations get caught in an infinite loop as in Fig.6

6 Discussion

The results so far show that in this bidomain model of stimulation, feedback controlled stimulations can indeed eliminate spirals at amplitudes much smaller than the single shock defibrillation threshold, but the success depends on a number of details which numerical experiments help to uncover (e.g. that the mutual orientation of the stimulating and registering electrodes can make or break the stimulation). We plan to investigate whether the shape of the time-profile of the stimuli, the shape of the stimulating electrodes, and/or a delay in re-activating the feedback loop after shocks will effect the algorithm.

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