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MAY SUPPRESSION OF THE SPATIO–TEMPORAL CHAOS IN CARDIAC TISSUE BE A METHOD FOR CONTROLLING THE FIBRILLATION PHENOMENON?

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Abstract: We describe a method involving a smart chaos suppression which may help to understand how to treat the most dangerous cardiac decease — fibrillation. On the basis of a Panfilov–Hogeweg model the cardiac excitation we consider the defibrillation problem. It is shown that suppression of fibrillative dynamics can be achieved by a low–amplitude local non-feedback stimulation.

keywords: Applications of dynamical systems in medicine

1. INTRODUCTION

Any abnormality in the cardiac rhythm is said to be arrhythmia. It can be developed by several reasons, the dominant of which is the change in the intrinsic properties of the excitable tissue. In this case the destruction of the excitation wave fronts is possible, and then the fibrillation phenomenon, which is fatal arrhythmia, may appear. The dominating hypothesis in the current theory of excitable media is that fibrillations occur due to the creation of numerous autowave sources, which are spiral waves or vortex structures (i.e., in fact, spatio–temporal chaos), in cardiac tissue. To suppress this spiral–wave activity and restore the natural cardiac rhythm, high–energy pulses (in the form of external or implantable defibrillators) are used.

However, as is known, this leads to unwanted side effects. For example, high–energy shock can cause the necrosis of myocardium or give rise to functional damage manifested as disturbances in atrioventricular conduction. The application of electrical pulses for the termination of fibrillations is also used in implantable cardioverter defibrillators (ICDs) initiating low–power electrical pacing pulses automatically when they detect dangerous activity. However, ICD actions are very painful, and they may occur even in the case of complex arrhythmias that are not necessarily associated with fibrillation. Thus, in the contemporary cardiology there is an urgent need in the elaboration of other ways of defibrillation.

The recent investigations of active media offer new opportunities for the electrical defibrillation: the amplitude of the external stimulation can be *essentially* decreased and the turbulent regime in excitable systems can be suppressed by a sufficiently weak non-feedback periodic external forcing applied globally [1, 2] or locally [3–8] (see also [9–11] and refs. cited therein). By these manners, it is possible to stabilize the turbulent dynamics and reestablish the initial cardiac rhythm, because such a strategy leads to the relaxation of the medium to the rest state.

In the present paper we show that suppression of spatio–temporal chaos in the excitable medium can be achieved by a weak local periodic excitation. The proposed method seems to be a quite applicable to real media and may at least help to develop new effective methods of defibrillation.

2. A SIMPLE MODEL OF CARDIAC TISSUE

During last 15 years a number of models of cardiac tissue has been tested. A part of them uses a system of partial differential equations of a diffusion type. As a quite general and at the same time sufficiently simple model of a diffusion type is a family of FitzHugh-Nagumo systems [12]:

$$\frac{\partial u}{\partial t} = \Delta u - f(u) - v, \quad \frac{\partial v}{\partial t} = g(u,v)(ku - v). \tag{1}$$

In order to obtain a more adequate decription, the Eqs. (1) are usually represented in a particular form of so-called Panfilov–Hogeweg modification [13], in which

$$f = \begin{cases} C_1 u, & u < u_1, \\ -C_2 u + a, & u \in [u_1, u_2], \\ C_3(u-1), & u > u_2, \end{cases} \quad g = \begin{cases} G_1, & u < u_2, \\ G_2, & u > u_2, \\ G_3, & \begin{matrix} u < u_1, \\ v < v_1. \end{matrix} \end{cases} \tag{2}$$

Here u and ν are activator and inhibitor variables, respectively. The parameter values are $C_1 = 20$; $C_2 = 3$; $C_3 = 15$; $u_1 = 0.0026$; $u_2 = 0.837$; $\nu_1 = 1.8$; $k = 3$; $G_2 = 1$. Parameters $G_1 \in [1/75, 1/30]$ and $G_3 \in [0.1, 2.0]$ are usually control ones. One of them, G_3, takes into account a relative relaxation period for small values of u and v. The other one, G_1, gives an absolute relaxation period for large values of v and intermediate values of u, that corresponds to the leading and trailing fronts of the wave.

In spite of its simplicity, this model describes real experimental data on a sufficiently good level, even the myocardium tissues of mammals [14].

Our analysis of the turbulent and regular dynamics of the system (1), (2) is based on the calculation of the number N of phase singularities [15]. The method is based on the fact that the tip of each spiral wave is a singularity for the phase field $\varphi(x, y, t) = \arctan 2\,(U((x, y, t) - U^*), V((x, y, t) - V^*))$. Then

$$N = \frac{1}{\pi}\oint \nabla\varphi dl$$

is the topological charge. It is not equal to zero only if such a singularity is located within the integration contour. In this case N is an integer, and its sign determines the chirality of the spiral wave.

3. SUPPRESSION OF TURBULENT DYNAMICS

With the applied point of view Eqs.(1), (2) qualitatively describe the electrochemical potentials of cardiac cells. Therefore, multiplicative and parametric perturbations of this system mean the change of the cell membrane capacitance, the intensity of the operation of ionic pumps or the conductivity of ion channels, etc. This is a very laborious problem. The implementation of additive stimuli $I_k(x, y, t)$ is much simpler: it is sufficient to introduce electrodes into tissue and to supply pulses through these electrodes. Here I_k symbolizes an external pacing which acts on elements of the medium with numbers $k = 1, 2, \ldots, N$ and spatial coordinates (x, y).

In our investigations, in contrast to the defibrillation by single pulses applied to the entire muscle or a quite large part of it, we added the external *periodic* stimuli to a point (2×2 nodes) of a medium. Their waveforms are rectangular pulse and saw–like stimulus. To select the stimulation frequencies we generated pacemakers in a quite small volume of the medium and determined the frequency of the target waves as a function of the internal pacemaker frequency. The medium response is higher at certain frequencies. Thus, it is especially pliable to periodic perturbations at these frequencies. The rest two parameters, the amplitude and duration of stimuli are usually optimized during numerical simulations of the system (1), (2) with the external stimulation $I_k(x, y, t)$.

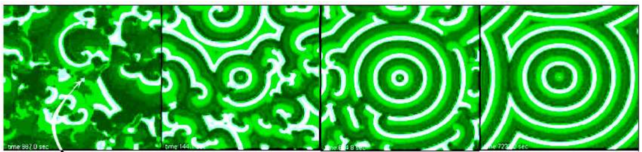

Figure 1 – Suppression of spiral–wave turbulence by external periodic stuimulations.

The result of the point excitation of the turbulent medium is shown in Fig.1. One can see that step-by-step target waves from the external source displace spiral waves and occupy the medium area. As a result, all the rotating waves are suppressed, the medium goes to a spatially homogeneous steady state so that the initial rhythm may be restored. However, such successful stabilization is not always possible. The analyzed system is very sensitive to initial conditions and the stimulus location. Recently, to solve this problem we proposed to use moving pacemakers [16]. We have revealed that in this case the effectiveness of the suppression does not crucially depends on the location of external sources.

4. CONCLUDING REMARKS

Thus, although the suppression effectiveness strongly depends on the stimulation frequencies and the amplitude, it was found that if these values are chosen by an appropriate way, the turbulent wave activity can be eliminated. This is a very important qualitative outcome, which gives us the hope to resolve the defibrillation problem. Therefore, the obtained results make it possible to predict the dynamics of active systems, depending on their parameter values. Moreover, using the proposed approach one can develop a quite general theory of the chaos suppression in distributed media by point excitations. However, majority of problems touched upon in the present paper remains to be carefully explored [17].

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