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Spontaneous Spiral Wave Breakup Caused by Pinning to the Tissue Defect

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Cardiac failure is one of the leading causes of death in the modern industrial world [1]. Very often cardiac failure is preceded by the arrhythmia: irregular or unusually fast or slow rhythm of cardiac contractions [2]. A pattern of electrical activity of the heart, most commonly recorded as electrocardiogram (ECG) [3], may have some signs empirically selected by the medical doctors, such as, for example, elongation of the QT interval on the ECG [4]. These signs indicate that a person is subject to the risk of sudden attack of the potentially lethal arrhythmia, mainly related to the emergence of rotating spiral waves or reentry [5].

When propagating excitation fronts lose stability and break apart, the wave breaks give birth to rotating spiral waves [6]. In a series of our studies we intend to reveal some mechanisms potentially triggering cardiac arrhythmia, based on the rotating spiral wave origination.

In this particular work we present a mechanism of spiral wave initiation due to the specific features of the cardiac tissue defect, related to the boundary conditions on its border. There are known scenarios when anatomical or functional defects in cardiac tissue may provoke the spiral wave origination. They include unidirectional blockage while passing through the narrow gates [7], bent over critical curvature wave fronts [8], inhomogeneous recovery of the tissue [6, 9], etc. We show a scenario of spiral wave breakup on a small defect, which is inexcitable but permeable for ionic currents supporting the excitation wave. It was known before, that such a defect may provide so-called electrotonic load and should cause a decrease of the velocity of the excitation front near its border [10]. It was believed that such defects stabilize the rotating wave; however, instead of stabilizing it leads to the spiral breakup and subsequent multiplication of the rotating waves.

In this work we use modified Aliev–Panfilov model [11] with steps $t = 0.001$, $h = 1$.

$$\frac{\partial u}{\partial t} = D\Delta u + k(1-u)(u-a)u - uv, \tag{1}$$

$$\frac{\partial v}{\partial t} = \epsilon(ku(u-1-b) - v), \tag{2}$$

where diffusion coefficient $D = 4$, excitability $k = 8$, threshold $a = 0.05$, $b = 0.1$, $\epsilon = \epsilon_0 = 0.012$.

It was found, that spiral wave, pinned to an obstacle with the full flux boundary conditions, breaks up spontaneously (Fig. 1). First, wave rotated several times

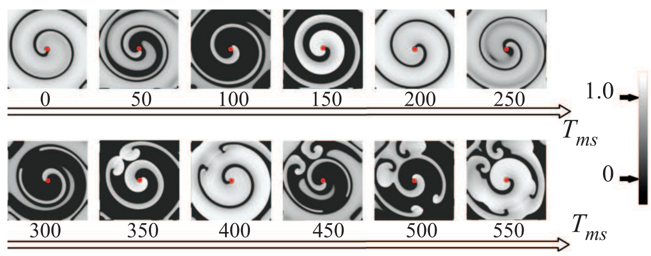

Fig. 1. (Color online) Spiral wave pinned to the defect with the radius $R = 15$. Flux through the border causes spiral wave breakup. Red circle shows ablated zone with Dirichlet boundary conditions. Greyscale shows membrane voltage (u), with light gray indicating depolarized tissue. Size of sample is 512×512

around the obstacle (0–3.3 s), and then the wave front of the spiral stumbled on its own refractory tail (on 3.3 s) which caused the wave breaks and the consequent spiral multiplication (3.3–3.6 s). With no-flux boundary conditions during the period of 20 s (or 200 full rotations) no spiral breakup occurred. Thus, one can conclude that the flux through the border provokes the spiral breakup.

We measured the period of rotation of the spiral wave in both cases. Generally, the rotation period is determined by the traveled path (perimeter of the defect) and the velocity of the wavefront near the border of the defect. Surprisingly, the period of rotation in the case of flux boundary conditions appeared to be lower, than in no-flux conditions, which means that the velocity of the wave near the defect was higher.

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The spiral breakup was reported to occur for the media with low excitability. We studied the range of parameters, where this effect may take place. First, we varied the threshold and the diffusion coefficient D, as it was done before for homogeneous media without an obstacle [12]. Then we changed the restitution parameter ϵ. Both plots show that the lower is the threshold, the wider is the range of radii or ϵ where spiral breakup occur. For the thresholds higher than 7 % of the action potential amplitude the spiral wave is stable for any other settings of the model. However, in low-excitable media spiral breakup occurs for a wide range of parameters.

One of the most important characteristics of the excitable medium is a maximal captured frequency, which is the highest frequency of stimulation, when all of the stimuli give rise to a wave. The decrease in the refractory period causes an increase in the maximal captured frequency. In Krinsky's work was shown [8] that refractoriness inhomogeneity is a fundamentally arrythmogenic factor. Indeed, in the proximity of the border with the flux boundary conditions, the wave train may propagate with higher frequency than far from the border. If the frequency is high enough, the wave breaks will appear far from the border, by the mechanism described in [8]. It also means that for sufficiently small perimeters of the defect propagation will be undisturbed near it while away of it wave breaks and spiral waves multiplication will occur.

To explain the shortening of the refractoriness period close to the border, we used a local Aliev–Panfilov model for one cell and described flux as leakage current ($I_{\text{flux}} = -d * u$).

$$\frac{\partial u}{\partial t} = -d * u + k(1-u)(u-a)u - uv, \tag{3}$$

$$\frac{\partial v}{\partial t} = \epsilon(ku(u-1-b) - v). \tag{4}$$

From the form of the isoclines near the border it is seen that the leakage would cause a rise of the threshold (first solution of $\frac{\partial u}{\partial t} = 0$), or minimum stimuli in other words, and the decrease of the refractory period. It will slow down the first wave which propagates in that zone. However, when the second wave propagates in a non-fully recovered medium (close to the refractory tail of the first wave) there would be an impact of the residual inhibitor. Thus, we consider this residual inhibitor as a constant in the equation and make substitution $u' = u - u_{\text{residual}}$. In this case the threshold will decrease in the case of the flux. As a result, the velocity of the second wave will increase.

Back to the wave, rotating around the defect, if the defect is small enough for the spiral wave (perimeter of the defect is less than the wavelength) the propagating spiral front will interact with the spiral wave refractory tail, causing multiple wave breaks.

It was shown that traumatic defects could be arrhythmogenic due to the flux through their border. The fluxes may generate a strong refractoriness inhomogeneity which in turn, could produce a spiral wave. No-flux Neumann boundary conditions are commonly used to model the cardiac tissue defects, assuming that the inner space of the defect is inexcitable and disconnected from the healthy tissue. This method is applicable while modeling nontraumatic natural anatomical defects, like veins. However, ischemic scars or fibrotic zones seem to be indeed inexcitable, but still connected with the tissue as the passive electrotonic load. Obtained results lead us to the conclusion that the boundary conditions may have great impact on the solution and the right choice of the flux, non-flux or partial flux is important for getting relevant model.

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