Nonlinear and nonstationary ECG analysis of spontaneous transition from polymorphic to monomorphic arrhythmia in a mathematical model of cardiac tissue dynamics

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Abstract — Dependence of ECG dynamics on behavior of the excitation vortex in the myocardium was investigated in computational simulation by the example of the autowave lacet. The lacet is transformation of the vortex motion from a two-periodic one into one-periodic circular rotation due to spontaneous deceleration of vortex drift The excitation vortex in two-dimensional excitable media (alias reverberator) can be described simplistically as a half of a plane wave curved around its break point. The break point is also called the tip of the reverberator. Reverberator behavior is commonly sketched in the terms of movement of its tip. Autowave reverberators are known to be main cause of different kinds of ventricular tachycardia. The lacet can lead in the heart to spontaneous transition from polymorphic to monomorphic tachycardia. In this work, it was demonstrated that the information revealed in ECG with the normalized-value analysis of electrocardiographic variability corresponds sufficiently with the drift velocity of the reverberator.

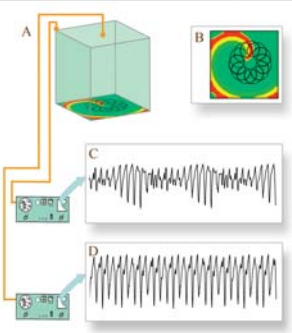

Fig. 1. Shape of ECG recorded in two different leads during experimental tachycardia in computational simulation. **A** — sketch of numerical experiments, **B** — excitation autowave (reverberator) and the trajectory of its tip, **C** and **D** — ECGs, registered upon the corner and upon the center of the excitable medium correspondingly. Both ECGs are in the same scale.

Mathematical model of cardiac tissue dynamics

Combination of computational simulation, which supply us with time series for subsequent analysis, and data processing was used. Fig. 1 is for the purposes of illustration of our computational simulation.

The most often used is the description of excitable media by nonlinear partial derivatives equations of reaction-diffusion type. The approach gives sufficiently accurate quantitative results that agree with experimental results.

The mathematical model of excitable medium by Aliev and Panfilov, which is a modified version of the popular FitzHugh-Nagumo model, was applied. Here are the equations of the Aliev-Panfilov model:

$$\begin{aligned} \frac{\partial u}{\partial t} &= \Delta u - ku(u-a)(u-1) - uv \\ \frac{\partial v}{\partial t} &= \varepsilon(u,v)(-v - ku(u-a-1)) \\ \varepsilon(u,v) &= \varepsilon_0 + \frac{\mu_1 v}{u+\mu_2}, \end{aligned} \qquad (1)$$

where $u(x; y; t)$ is a dimensionless function similar to the transmembrane potential in myocardial cells and $v(x; y; t)$ is a dimensionless function similar to a slow recovery current. The simulations were carried out in 2D excitable media (128 elements along each dimension) with no-flux boundary conditions. For calculation, we used a forward Euler numerical approximation (Δt = 0.01 t.u., $\Delta x = \Delta y$ = 0.50 s.u.). The location of the reverberator tip was defined as the point of intersection of particular values of the excitation and recovery state variables: u = 0.89; v = 0.50.

The ECG at each instant, $U(t)$, was computed with:

$$U(t) = \sum \left[\frac{\partial u}{\partial x}\frac{\partial}{\partial x}\left(\frac{1}{r}\right) + \frac{\partial u}{\partial y}\frac{\partial}{\partial y}\left(\frac{1}{r}\right) \right], \qquad (2)$$

where summation is done over all points of the 2D excitable medium, u is the value of the recorded variable, r is the distance from the current point to the recording point. The position of the latter is set by the coordinates (x, y) of its projection on the plane of the medium and the distance d to this plane. Two virtual ECG recorders were placed at d = 128. One of them was over the center of the medium ($x = y$ = 64), and the other was over its corner ($x = y$ = 0).

Data processing

Normalized-value analysis of electrocardiographic variability ('ANI-method' in Russian notation) was proposed for studying nonstationary time series obtained as observed value of some cyclic (quasiperiodic) process. The main idea of ANI-method is illustrated with Fig. 2. For example, the ANI-method could be useful for analysis of both normal and arrhythmic electrical cardiac activity. The current implementation of the ANI-method (**ANI-2003**) was developed for ECG analysis of experimental polymorphic ventricular arrhythmia and ventricular fibrillation. The ANI-2003 maps an ECG fragment onto two real indices (arbitrary units) as it is described by (3)–(5). The indices provide a quantitative representation of polymorphism, which is one of the qualitative ECG features of potentially life-threatening reentrant arrhythmias. Index V_1 represents an average evaluation of the unlikeness of data segments inside the studied fragment of the data series and the index V_2 is its variation.

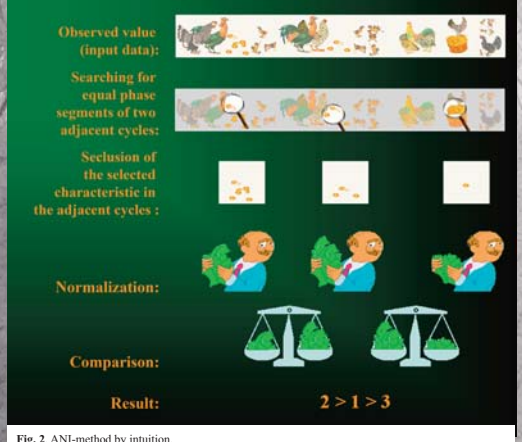

Fig. 2. ANI-method by intuition.

To calculate the indices, we compare an arbitrary segment of an data series with another segment, which is considered to be a reference sample. The comparison procedure is described with the functional:

$$R(t,T) \equiv \frac{1}{S(t)} \left[\int_t^{t+T_{SW}} (\varphi(\tau+T) - \varphi(\tau))^2 \, d\tau \right]^{1/2}, \qquad (3)$$

where T_{SW} is the sampling window width and $S(t)$ is the peak-to-peak amplitude of the signal in the sampling window corresponded to time t. T_{SW} is the constant value inside the studied fragment of the data series. It is important that the compared segments are assumed to correspond to similar intervals of two adjacent cycles, therefore we chose T_{SW} to be comparable with the shortest duration of the cycle.

The procedure of searching for the similar interval of the next adjacent cycle is executed in the time interval (scanning window, T_{ScW}) confined with the domain of anticipation of the next adjacent cycle. Therefore, for each instant t, it is admitted that the similar segments of adjacent cycles of the data series are away from each other in the time interval $T_0(t)$, called quasiperiod, such as

$$R(t, T_0(t)) = \min_{T_{SW} \le T < T_{ScW}} R(t,T). \qquad (4)$$

The comparison procedure is carried out at each moment of time yielding the local characteristic of the data series variability (instant variability index, I):

$$I(t) \equiv R(t, T_0(t)) \qquad (5)$$

To monitor the time series changes with time, we calculate the variability indices V_{1i} and V_{2i} for the segment in some fixed-width window, that is called the averaging window, T_{AW}. The V_{1i} and V_{2i} is produced from $I(t)$. V_{1i} is the average $I(t)$ inside some short time interval $t_i \le t < t_i + T_{AW}$, and V_{2i} is V_{1i} divided by the standard deviation of $I(t)$ inside the same interval. Shifting T_{AW} along the time axis, we obtain $V_1(t)$ and $V_2(t)$.

Basing on the definition of ventricular tachycardia, we chose $T_{AW} = 6T_{SW}$. For successive ECG fragments of fixed length, a sequence of the indices draws a trajectory in the index space. The trajectory drawn in (V_1, V_2) index space enables one to visualize the detailed ECG dynamics.

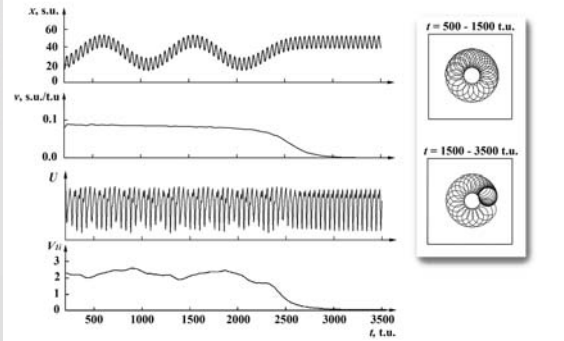

Fig. 3. The transition from polymorphic to monomorphic arrhythmia in the Aliev-Panfilov model (1) at a = 0.1803. From top to bottom: the dynamics of the x coordinate of the reverberator tip, the dynamics of speed, v, of the instant center of the autowave vortex, the ECG, U, and index of the ECG variability, $V_1(t)$. All the graphs have the same horizontal scale. Insertion on the right shows a trajectory of the reverberator tip. The trajectory is separated in two successive parts for the convenience of readers .

Results

The parameters in the equations (1) were adjusted by the autors of the model to accurately reflect the properties of the normal cardiac tissue (k = 8.0; μ_1 = 0.2; μ_2 = 0.3; ε_0 = 0.01; a = 0.150). In our simulations, the parameters of (1) were the same as indicated, except that the parameter a, which is similar to the threshold of excitation, was varied from 0.1500 to 0.2300. The dynamics of velocity of the reverberator drift as well as the ECGs were calculated for each parameter set, and each ECG was quantitatively evaluated by the ANI-2003.

Some of our results were presented formerly (Biophysics 2007, 52(2): 237–240; Chaos, Solitons & Fractals 2008, 36(1): 66–72; Chaos, Solitons & Fractals 2009, 40(1): 426–431).

In this work, the comparison the velocity of reverberator drift and ECG dynamics described with $V_1(t)$ shows (Fig. 3) that there is perfect coincidence between them.

Conclusion

In this study, we have shown that the technique for ECG analysis referred to as ANI-2003 could provide cardiologists with sensitive clinical tool for identifying life-threatening arrhythmias. In the heart, the autowave lacet, which is cardiac states conditioned by the bifurcation memory, requires to be distinguished from the other types of transition from polymorphic to monomorphic ventricular tachycardia. We demonstrated possibilities of the ANI-2003 for ECG diagnostics of spiral wave behavior like the autowave lacet. Should future studies confirm the existence of the lacet in the myocardium, the ANI-method shall be helpful in recognition of the autowave regime when visual analysis of ECG is insufficient.