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 drift. The heart is a transformation of the vortex motion in a two-periodic one into one-periodic circular rotation due to spontaneous deceleration of vortex drift. The excitation vortex in two-dimensional excitable media (data 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. This behavior can lead in the heart to spontaneous transition from polymorphic to monomorphic tachycardia. In this work, we demonstrated that the information revealed in ECGs with the normalized-value analysis of electrocardiographic variability corresponds sufficiently with the drift velocity of the reverberator.

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 a purpose 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 qualitative 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:

\[
\begin{align*}
\frac{\partial u}{\partial t} &= \frac{u}{1 - u} + \frac{v}{1 + v} - u + a(u - a)(u - 1) - \nabla^2 u, \\
\frac{\partial v}{\partial t} &= \epsilon (u - v) - k(u - a)(u - 1)
\end{align*}
\]  (1)

where \(a\), \(\epsilon\), \(k\) is a dimensionless function similar to the transmembrane potential in myocardial cells and \(u\), \(v\) is a dimensionless function similar to a slow recovery current. The simulation 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. The location of the reverberator tip was defined as the point of intersection of particular values of the excitation and recovery state variables: \(a = 0.89\), \(k = 0.150\). In our simulations, the parameter of (2) were the same as indicated, except that the parameter \(a\), which is similar to the threshold of excitation, was varied from 0.5 to 0.9. The 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 2009, 36(1): 66–72; Chaos, Solitons & Fractals 2009, 40(1): 426–431).

Results
The parameters in the equations (1) were adjusted by the authors of the model to accurately reflect the properties of the normal cardiac tissue (\(a = 0.4\), \(\epsilon = 0.2\), \(k = 0.3\), \(\epsilon = 0.01\), \(a = 0.150\)). 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 0.5 to 0.9. The 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 2009, 36(1): 66–72; Chaos, Solitons & Fractals 2009, 40(1): 426–431).

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 reverberator, which is cardiac state conditioned by the bifurcation memory, requires to be distinguished from the other type of transitions from polymorphic to monomorphic ventricular tachycardia. The authors of this study applied the ANI-2003 for ECG diagnostics of signal wave behavior like the autowave lacet. The simulation underlines the existence of the lacet in myocardium. The ANI-2003 shall be helpful in monitoring of the autowave regime when visual analysis of ECG is insufficient.