EC CLINICAL AND MEDICAL CASE REPORTS
Mini Review

# Spiral Structures in the Myocardium

**Alexander Chalyi* and Albina Kryshtopa**

*Department of Medical and Biological Physics and Informatics, Bogomolets National Medical University, Kyiv, Ukraine*

***Corresponding Author:** Alexander Chalyi, Professor, Head of Department of Medical and Biological Physics and Informatics, Bogomolets National Medical University, Kyiv, Ukraine.

**Received:** January 19, 2023; **Published:** February 27, 2023

## Abstract

This article is a continuation of our previous publication [1] and is devoted to the consideration of spiral waves (reverberators) in the myocardium, the cause of which is either mechanical inhomogeneity of the myocardium or its inhomogeneity in the refractory period. A direct consequence of the chaotic increase in the number of reverberators is tachycardia, possible fibrillation and sudden death. Understanding the processes leading to the multiple formation of spiral waves allows us to conduct a targeted search for drugs and non-drug methods to prevent the occurrence of fibrillations.

***Keywords:*** *Spiral Structures; Myocardium; Tachycardia*

## Introduction

For the first time, spiral structures in the myocardium were discovered in 1946 by the Mexican cardiologist Arthur Rosenblueth and the American mathematician Norbert Wiener, who is rightfully considered the «father of cybernetics» [2]. In that year, A. Rosenblueth told his friend N. Wiener about a dangerous heart disease - fibrillation, which very often leads to instant cardiac arrest. And together they created a model showing that when the mechanical homogeneity of the heart muscle - myocardium is disturbed (such heterogeneity occurs in the place where the vein flows from the heart), a spiral wave of electrical excitation of myocardial cells appears. This spiral wave is called a «reverberator». Subsequently, it was possible to prove that reverberators arise not only where mechanical inhomogeneity is disturbed, but also at points where inhomogeneity appears in some hidden parameter - the refractory period of the active medium (see below). Specifically, these points become sources of spiral waves (reverberators). A direct consequence of the multiplication of reverberators in the myocardium is tachycardia (a change in the normal rhythm of the heart, namely an increase in heart rate), and then fibrillation (chaotic heart pulsation). Understanding the mechanisms of the appearance of reverberators, it is possible to conduct a conscious search for drugs and other non-drug methods to prevent fibrillation.

## General properties of dissipative structures

Let us first consider the general characteristics of open systems, i.e. such systems that exchange matter, energy, and information with the environment [3]. Unlike equilibrium formations, which can be described and studied by known methods of thermodynamics and statistical physics, in non-equilibrium systems, various ordering processes occur and so-called dissipative structures can be realized (the term was introduced by Ilya Prigogine, the Belgian physicist and chemist, winner of the 1977 Nobel Prize in Chemistry). An example of conventional equilibrium structures is a liquid or a crystal that exists depending on temperature, pressure, and other external parameters. Dissipative structures are formed due to the flows of energy, momentum, mass through the boundaries of the system. Typical examples of dissipative structures are autowaves and auto-oscillations, which are realized in the form of (a) reverberators in the myocardium, (b) waves of electric potential change or, in other words, action potential (AP) propagation along the nerve fiber (axon), (c) self-oscillations during glycolysis and photosynthesis, etc.

Common to all these phenomena is the presence of the following similar features of the environments where they occur:

1. Media in which autowaves or self-oscillations propagate are active. In ordinary passive media where elastic, electromagnetic or thermal waves take place, the energy of the wave is transmitted from the source to distant points with attenuation. Unlike passive media, processes of energy accumulation and its release take place in active media with an appropriate excitation mechanism.
2. Active media have three different states of operation:
    - A state of rest, realized in the absence of external influences;
    - A state of excitation that occurs in the presence of an external influence;
    - A state of refractoriness that occurs after the disappearance of excitation and during which the system returns to a state of rest (if the system is in a state of refractoriness, it cannot be transferred to a state of excitation until it passes into a state of rest).
3. An interesting property of autowave processes, including reverberations in the heart muscle, is associated with the so-called synchronization effect. The essence of this effect is that if several sources of oscillations and waves with different frequencies act in an active medium, then the oscillations and waves with the maximum frequency are the most persistent. In other words, all vibrations with lower frequencies are suppressed by vibrations with higher frequencies.
4. The properties of autowaves in active media and waves in passive media are very different (See table 1). The last column of this table contains information about another type of ordered structures - solitons (solitary waves). At present, solitons have been discovered in objects of the inorganic world - in magnets, superconductors, the atmospheres of the Earth and planets. For organic living systems, solitons, in a certain approximation, can be considered the above-mentioned solitary waves of AP propagation along the axon. It is very likely that solitons were of great importance for the evolution of the Universe. It is fair to say that the science of solitons is rapidly developing in our time.

| Property | Autowaves in active media | Waves in passive media | Solitons |
|---|---|---|---|
| 1. Dissipation (loss of) energy | Great | Small | Absent |
| 2. Compensation energy losses | Present | Absent | Absent |
| 3. Speed conservation | Present | Absent | Present |
| 4. The principle of superposition | Absent | Present | Absent |
| 5. Annihilation upon collisions | Present | Absent (in general case) | Absent |
| 6. Interference | Absent | Present | Absent |
| 7. Diffraction | Present | Present | Present |
| 8. Reflection | Absent | Present | Present |

***Table 1:*** *Comparison of the properties of autowaves in active media, waves in passive media, and solitons.*

It should be noted that the biophysical mechanism of AP generation, the equivalent electrical circuit of the region of the axon excitatory membrane, as well as the corresponding differential equation describing the process of AP propagation along the axon, were proposed by Hodgkin and Huxley (See, for example [3]).

The result of these unique experimental studies and the creation of an appropriate consistent theory in 1948-1952 became the 1963 Nobel Prize in Physiology or Medicine, which was awarded to Alan Hodgkin and Andrew Huxley along with John Eccles "for their discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheric and central portions of the nerve cell membrane" [4].

### Autowave processes in the myocardium

A classic example of ordering with the emergence of dissipative structures in the form of spiral waves in chemically reacting media is the periodic redox reaction by Belousov-Zhabotynsky (BZh reaction) (See e.g. [3,5]). The topology (spatial arrangement) of reverberators is very interesting, which can be observed in a Petri dish, where the BZh reaction occurs. It turned out that spiral waves (reverberators) are quite stable structures. Moreover, they can be characterized by the so-called topological charge, which determines the number of arms emerging from a common center. Figure 1 shows one-, two-, and three-armed reverberators with topological charges of 1, 2, and 3, respectively. Interestingly, such spiral waves with topological charges greater than 1 have been observed in experiments with the BZh reaction performed by Valentin Krinsky and Konstantin Agladze [6,7]. In these and other experiments, it was found that the topological charge of the spiral wave in the active medium is conserved. Only when approaching the boundary of the active medium, the topological charge conservation law is violated, and the spiral wave can disappear at the boundary itself.

***Figure 1:*** *Reverberators with different topological charges.*

The interest in the BZh reaction is largely associated with the possibility of using it to simulate the processes of the emergence of autowave structures (reverberators) in the myocardium in a chemical reactor. In particular, it was found that the chaotic multiplication of reverberators is the cause of fibrillation of the heart muscle, which can cause myocardial infarction. Let's consider this question in more detail.

The effect of synchronization of autowaves, which was mentioned above, determines the reliability of the functioning of various organs and systems, including medical and biological objects. So, in the sinus node of the heart there is a pacemaker - a group of myocardial cells that have a coherent connection with each other. This ensures the operation of the pacemaker in an auto-oscillating mode, which sets the heart rate and propagation of the excitation wave in the atrium. If this pacemaker fails due to a certain local damage (for example, due to a microinfarction), then another pacemaker with a lower frequency starts to work. It turns out that in the myocardium there can be several such groups of cells operating in an auto-oscillatory mode with different frequencies. Suppose now that the pacemaker that had the maximum frequency and which, due to the synchronization effect, suppressed all other pacemakers, is out of order. Then his role is transferred to another pacemaker, having the maximum frequency among those staying intact. Of course, the heart rate decreases, but this cannot significantly affect the work of the heart.

In the experiments of Krinsky and Agladze, other interesting properties of spiral waves were observed. First, it was found that spiral waves with the same topological charge have the same frequency. Secondly, with an increase in the topological charge (the number of reverberator's arms), their frequency decreases. This automatically means, due to the synchronization effect, that spiral waves with a lower topological charge suppress spiral waves with a higher topological charge.

The described synchronization effect, according to which only sources of autowaves with the maximum frequency remain in active media, is of a great practical importance in medicine. Violation of the homogeneity of the myocardium in terms of the refractory period, that is, in terms of the recovery time of the resting potential on the cytoplasmic membranes of myocardial cells, as mentioned above, can cause chaotic reproduction of reverberators. This chaos causes, as a result, very dangerous cardiac arrhythmias - paroxysmal tachycardia and fibrillation.

As it was proved in the experiment, with paroxysmal tachycardia, a reverberator appears, which has a higher frequency (sometimes several times) than the frequency of the pacemaker in the sinus node of the heart. It is clear that the work of this pacemaker will be suppressed and there will be a sudden increase in contractions. The further process can develop according to the following scenarios:

- **Scenario 1:** Due to the heterogeneity of the heart muscle (myocardium), there may be a shift in the center of the spiral wave and its gradual extinction with the restoration of a normal heart rhythm from the pacemaker in the sinus node of the heart.
- **Scenario 2:** When a spiral wave passes through local areas of the myocardium with sharp changes in the refractory period, a rupture of the spiral wave may occur with subsequent reproduction. This process becomes chaotic if the rate of reproduction of the reverberators is greater than the rate of their decay. It is in this case that fibrillation occurs, leading to instant cardiac arrest.

As known, in such cases, special devices - defibrillators are used to restore heart contractions. As a result of applying to the heart muscle for hundredths of a second an electrical impulse of a defibrillator, which has the following approximate parameters: voltage $U \approx$ 5 - 6 thousand volts and current strength $I \approx 20$ A, all myocardial cells go into an excited state. This can lead to the desired result - the complete resumption of the pacemaker in the sinus node and the regular contraction of the heart muscle. To prevent significant damage to the heart cells due to the action of the defibrillator and the passage of a large current, causing a significant amount of heat to be released and essentially the moisture to evaporate from the myocardial cells, a safer method can be used. If an external source of waves is applied to the myocardium, having a higher frequency than the frequency of the reverberators, these reverberators will be suppressed and squeezed out of the myocardial region with pathological disorders of the refractory period. Thus, the properties of autowaves in an active medium provide fundamental grounds for the development of new effective methods for combating dangerous cardiac arrhythmias.

In conclusion, let us dwell briefly on another (also fairly common) example of the formation of dissipative structures in systems with chemical (biochemical) reactions, which underlie chemical signaling processes in collective amoeba colonies (like e.g. mushroom slime mold *Dictyostelium discoideum*). These amoebas are called social because they trend to the association (aggregation) in the corresponding spatial structures. It turns out that when the amoebas have enough food, they exist as separate and develop individually. A completely different situation occurs when food is over. Then the hungry amoebas begin spontaneously and in pulsed mode to allocate a special chemical substance - cAMP (cyclic adenosine monophosphate or glorin), which plays a role of morphogen that contributes to morphogenesis. As a result of the appearance of a heterogeneous spatial distribution of cAMP (in mathematical language - a gradient of the morphogen concentration), in the absence of food, amoebas aggregate, forming spiral structures similar to spiral autowaves (reverberators) in the myocardium. It means that such a chemical signalization of social amoebas (as well as viruses, by the way) is similar in a certain sense to the process of thinking, which is in fact typical not only for human beings!

## Conclusion

The similarity of the behavior of various systems in the organic, living world and the inorganic, inanimate world around us gives reason to talk about the synergy of all these open systems, seemingly different in nature. At the same time, the universality of the processes discussed above, such as the appearance of spiral formations - reverberators in the myocardium, amazing transformations in the BZh periodic chemical reaction, the formation of spiral structures in a colony of social amoebas - undoubtedly indicate that they are based on a common first principle of nature, which allowed the outstanding physicist Richard Feynman, 1965 Nobel Prize winner in Physics, to say these words: "The real glory of science is that we can find a way of thinking such that the law is evident" [8].

## Bibliography

1. Alexander Chalyi and Albina Kryshtopa. "Synergetic Approach to Teaching Natural Sciences in Medical Universities". *EC Clinical and Medical Case Reports* 5.6 (2022): 58-61.
2. N Wienner and A Posenblueth. "The Mathematical Formulation of the Problem of Conduction of Impulses in a Network on Connected Excitable Elements, Specifically in Cardiac Muscle". *Archivos del Instituto de Cardiología de México* 16.3-4 (1946): 205-265.
3. Medical and Biological Physics / Textbook for students of higher medical universities, Edited by A. Chalyi, 2nd edition, Khyga Plus, Kyiv (2004).
4. J Eccles., *et al*. "Nobel Lectures, Physiology or Medicine 1963-1930". Elsevier Publishing Company (1972).
5. AV Chalyi. "Synergetic Principles of Education and Science". Bogomolets National Medical University, Kyiv (2000).
6. VI Krynskii. "Fibrillation in Exitable Media". Problems of Cybernetics. Science (1968): 59-80.
7. VI Krynskii and AS Mikhailov. "Autowaves". Knowledge (1984).
8. RP Feynman., *et al*. "The Feynman Lectures on Physics". California Institute of Technology, Volume 1, Chapter 26 (2013).

**Volume 6 Issue 3 March 2023**