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Use of cardiometry and oculography in concealed information detection
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The article presents the results of an experimental study on the use of cardiometry and oculography to detect concealed information. It has been shown that a complex assessment of the person's emotional-cognitive state based on cardiometric and oculographic recording of reactions to specially selected stimulus material of visual and audial modality can be successfully used in concealed information detection.

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The aim of our study is to empirically verify the conceptual possibility of constructing a taxonomy of diverse domestic situations, which may become the basis for choosing the best ways to increase an individual stress resistance in a human subject.

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Founded and published by
Russian New University
Radio str., 22 Moscow Russia 105005
An official peer-reviewed journal

Current issue №14 (May 2019)

Frequency
2 issues/year

First issue
November 2012

Journal website administrator
Sergey Rudenko

Art & design
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Gustav M. Poyedintsev, the Russian Engineer and Mathematician, the developer of the mathematical equation concept to describe human hemodynamics, that has been verified and validated in practice and that has laid the groundwork for a new fundamental science: CARDIOMETRY
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Aleksandr S. Ognev, Professor, Doctor of Science in Psychology, the developer of a new research field: CARDIO-OCULOGRAPHY (CARDIO-OCULOMETRY)
Dear Reader!

The present issue of our journal is of very special nature. We are constantly analyzing not only the readers' focus of interest to the publications in our journal, but we are also tracing how cardiometry as a new science is realized by medical doctors and how they apply it in their practice. Undoubtedly, the mathematical fundamentals of hemodynamics are very difficult to understand not only by doctors, but even by mathematicians. Therefore, we have decided to collect in the first section of the present issue all the basic, previously published, mathematical concepts of hemodynamics as a complete collection part, in order to provide our readers with a convenient reference form. We think that this is an absolutely reasonable idea, since our journal always offers a thematic outline philosophy. We can see that it plays an important role in attracting the readers’ attention all over the world.

It should be stressed that actually cardiometry is a fast-developing scientific field. Therefore, another part of the present issue is devoted to cardiooculometry. By combining two devices, the eye tracker and the Cardiocode device, Russian Professor Alexander Sergeevich Ognev has obtained unique results: it has made it possible to find a relation between psychological responses/reactions and physiology. As a result, psychology has received a platform for its conversion to a natural science (!!!): the incredible dream has become true. A.S. Ognev has discovered a complete set of laws with deriving the respective axiomatic apparatus, which is capable of properly interpreting the observed phenomena. A refined logical analysis, based on the above laws and axiomatics, performed by him in the exquisite way, has made it possible to achieve in practice exclusive results that has never been done before. A.S. Ognev is the first who has transformed psychology into a natural science! His research works reveal the existing inadequacy of conventional approaches thereto by other scientific schools.

Undoubtedly, it is necessary to immediately present his latest advancements to our esteemed Readers. It is scheduled that in our next issues we will publish further results of his original research.

Your feedback is very much appreciated! Join us and enjoy inspiring ideas in breaking through the science barrier!

Sincerely yours,

Editorial Board
Cardiometry
The G. Poyedintsev - O. Voronova mathematical model of hemodynamics

Published with the support of RFBR (grant No. 18-29-02073)
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Aims
The objective is to demonstrate the features of an original mathematical model of hemodynamics, developed by Russian researchers G. Poyedintsev and O. Voronova.

Materials and methods
The proposed original mathematical model of hemodynamics is based on the laws of the fresh hydrodynamic theory of the "third" fluid flow mode.

Results
As a result of the application of the above mathematical model of hemodynamics, an advanced method for noninvasive measuring of a complete set of hemodynamic parameters with the use of the cardiac cycle phase durations, implemented by the Cardiocode device, have been elaborated.

Conclusion
The unique method for noninvasive measuring of a complete set of hemodynamic parameters, which has been developed on the basis of the above mathematical model of hemodynamics, is a promising source for considerable expanding of diagnostics capabilities.

Keywords
Hemodynamics, Biophysics, Cardiocode, ECG, Human hemodynamics mathematical model by G. Poyedintsev – O. Voronova

Introduction
As a matter of fact, the circulatory system in a human is the most efficiently working hydraulic system. Therefore, the key to the proper understanding of the laws of its performance and control should be sought in the field of hydrodynamics.

Conventionally, it is believed that the blood flow is laminar within the entire cardiovascular system and shows a turbulent structure in the aorta mouth. An additional point to emphasize is that the laminar blood flow shall obey the Poiseuille’s law. However, in a number of research papers, factual evidence data contradicting this statement are presented. An analysis of these data allows concluding that the Poiseuille law cannot be applied to the motion of blood in the vessels, since from these standpoints it is impossible to explain the highest efficiency of the circulatory system performance and the blood flow structuring. Classical hydrodynamics is not capable of offering an adequate solution to this problem [1, 2].

The situation has changed in a revolutionary way after the discovery of the unknown “third” mode of the real fluid motion, which differs from the two known regimes, namely, the laminar (Poiseuille) flow regime and the turbulent flow one, in substantially less losses due to friction and in a specific wave-like flow pattern [1÷3]. The pattern of this mode has been used to describe the motion of blood in vessels in vivo. This approach has been found to be fruitful: a beginning has been made in creating a new general trend in the studies of the circulatory system in human individuals [4-7].

Aims
To build a mathematical model of human hemodynamics based on the concept that the blood flow in blood vessels is organized in the "third" fluid flow mode.

Materials and methods
The original studies in the field of hydrodynamics, which led to the development of the theory of the "third" mode of fluid flow, were carried out in the 1970s by the Russian researcher G. M. Poyedintsev (1929÷2006). Using the axiomatic method, an analysis of the prerequisites to derivation of the classical equations of viscous fluid motion (the Navier-Stokes
equations) was completed by the researcher. This has made it possible to correct the system of the applied axioms and, on its basis, create an original mathematical model of the real fluid motion in a pipe, which is capable of adequately describing the laminar and turbulent flows. Moreover, the obtained solutions have shown that, at the onset of the motion in a pipe, a real fluid is featured by elevated fluidity and has a specific flow pattern, which exists for some small fractions of a second. In case of the two-phase fluid, similar to human blood, the flow structuring is observed in the initial phase of the fluid motion from its quiescent state.

In Figure 1 herein we can identify the positions of erythrocytes in the blood stream at each instant of time from the onset of the flow in a pipe, from the fluid quiescent state up to the flow transformation into the Poiseuille-type flow. While at the initial stage, at the flow beginning (in the "third" mode), the specific alternate annular layers formed by blood elements and plasma are observed, the laminar regime (positions E and F in Figure 1) demonstrates another pattern: all the blood elements are concentrated and collected in the middle of the flow. At the same time, the blood elements touch each other, forming a dense mass. A result of this process can be an aggregation of erythrocytes and hemolysis. To avoid such pathological consequences, it is necessary to control the flow structure, in order to maintain the same number of the concentric layers with time, as it is the case with the above described process.
Following this original conceptual idea, our researchers have succeeded in finding the method of maintaining the above fluid flow mode type in a pipe with a standing wave axisymmetric velocity profile under a static pressure within an unlimited time span [1, 2].

It can be realized under the conditions of a pulsating mode only. The most efficient is the fluid motion in the pulsating mode in an elastic pipe, and the fluid velocity and the pipe radius should change at each impulse according to some strictly defined laws as indicated below:

• the instantaneous velocity of the fluid flow motion in the elastic pipe changes under an impulse load according to the law as follows:

\[ U_1 = U_0 \left( \frac{t_2 - t}{t} \right)^{0.4} \]  

(1)

• the instantaneous radius of the elastic pipe lumen during its expansion varies according to the following law:

\[ r_1 = r_0 \left( \frac{t}{t_0} \right)^{0.2} \text{ where } t_0 \leq t \leq t_1 \]  

(2)

• the instantaneous radius of the elastic pipe lumen during its contraction varies according to the law as given below:

\[ r_0 = r_0 \text{ where } t_0 \leq t \leq t_2 \]  

(3)

• the maximum velocity of the fluid flow motion in the elastic pipe under an impulse load is equal to:

\[ U_0 = \frac{37.5gt_0[(5e-2)^3-27]}{[(5e-2)^3-243]} \]  

(4)

Here:

\[ g = \left( \frac{t_1}{t_0} \right)^{0.2} = \left( 1 + \frac{\Delta t_1}{t_0} \right)^{0.2} \]  

(5)

\[ \alpha = \left( \frac{t_2}{t_0} \right)^{0.2} = \left( 1 + \frac{\Delta t_1 + \Delta t_2}{t_0} \right)^{0.2} \]  

(6)

\[ \beta = \frac{2(e-1)}{\alpha - e} \]  

(7)

t – current time; \( t_0 \) – the time of the pressure increase in the supply system to the level of pressure in the elastic pipe; \( \Delta t_1 \) – time of expansion of the elastic pipe under an impulse load; \( \Delta t_2 \) – time of contraction of the elastic pipe under impulse load; g is the gravitational acceleration (g = 9.81 m / s).

By applying the laws of the above described by equations (1) ÷ (7), we can derive formulas for calculating the volume parameters of the fluid flow, namely:

\( Q_1 \) – is the volume of fluid entering the elastic pipe from the supply system during its expansion;

\( Q_2 \) – is the volume of fluid entering the elastic pipe from the supply system during its contraction;

\( Q_3 \) – is the volume of liquid filling an increment in the elastic pipe inside volume within the time of its expansion. This volume is ejected during the pipe contraction due to its elastic properties. That is, the elastic pipe functions as a peristaltic pump.

Thus, an original mathematical model of an optimal hydraulic system for the transportation of multiphase fluids, similar to blood, in the most economically efficient "third" mode, has been built.

Afterwards, a complete set of signs, which characterizes this hydraulic system in the most accurate way, has been revealed in the human circulatory system performance. This has reinforced the statement that blood moves in the blood vessels not in the Poiseuille, but in the most economically efficient "third" mode, when and where the flow has an axis-symmetric “layered” structure and when and where the blood cells move with a velocity exceeding the average flow velocity value [1, 2].

Results

The developed mathematical model of the optimal hydraulic system performance has been adapted to describe the processes, which take place in the human circulatory system. Let us represent our algorithm for solving the given problem in more details.

• The original mathematical model of the optimal hydraulic system [1] has been used as a theoretical basis. The model contains the mathematical laws of the fluid flow in the third flow mode, which represents the fluid flow in the elastic pipe and which is described by equations (1) ÷ (7). In doing so, the formulas for determining the systolic and diastolic volume parameters of the central hemodynamics in a human with the use of the cardiac cycle phase durations have been derived.

• Electrocardiography is used as a method for identifying the specific phase structure of a cardiac cycle [3].

The initial data for calculating the volumetric parameters of human hemodynamics are actual durations of ECG waves and segments, namely, as listed below:
QRS – the duration of the complex from the Q wave onset to the S wave end; 
RS – the duration of the complex from the R wave peak to the S wave end; 
QT – the duration of the Q-T interval (from the Q wave onset to the T wave end);
PQ – the duration of the P-Q segment (from the P wave end to the Q wave onset); 
TT – the duration of the cardiac cycle, measured from the end of the T wave to the end of the next T wave.

SV is a stroke volume (ml); 
MV is a minute volume, (l / min); 
PV1 and PV2 are volumes of blood entering the heart ventricle in the phase of the early diastole and the atrial systole, respectively (ml); 
PV3 and PV4 are volumes of blood ejected by the heart ventricle in the phase of rapid and slow ejection, respectively (ml); 
PV5 is a volume of blood pumped by the ascending aorta, which works as a peristaltic pump, during the systole phase (ml).

Let us briefly describe the algorithm for determining the systolic volume parameters of hemodynamics using the cardiac cycle phase durations.

• It is assumed that the sectional area of the blood vessel at the level of the ascending aorta is involved in the calculations.
• $S_0$ is an aortic sectional area (cm$^2$) to be determined according to an applicable nomogram or by any other generally accepted method.
• Duration $t_0$ is equal to: $t_0 = RS$ (s)
• The systole duration (including $t_0$) is equal to: $t_2 = QT – QRS + RS$ (s)
• The heart rate is calculated as follows: $HR = 60 / TT$ (beats per min)
• Dimensionless parameters and functions thereof are computed as indicated below:
  \[\alpha = \left(\frac{t_1}{t_0}\right)^{\frac{1}{2}}\]  
  \[\beta = \frac{2(e^{-1})}{a-e}\]  
  \[f_1(e, a, \beta) = \frac{5}{12}e^2(2+\beta)(a' - e') - \frac{5}{8}e\beta(2+\beta)(a' - e')^2 + \frac{1}{4}e\beta^2(a' - e')^3\]  
  \[f_2(e) = e^5 - \frac{5}{3}e^3 + \frac{2}{3}\]  
• The maximum velocity of blood flow under impulse: $U_o = \frac{36787.5f_t}{(5e - 2)^2 - 243}$ (cm/s)

Now let us take a brief look at an algorithm for deriving the diastolic volume parameters of hemodynamics.

• The diastole is considered as two successive systoles, during which the blood is ejected from the atrium into the ventricle (the early diastole and the atrial systole).
• Durations $t_{01}$ and $t_{02}$ are determined theoretically provided that the blood structure pattern at the moment of transition from the phase of the early diastole to the atrial systole is properly maintained. Evidence exists that this will be fulfilled subject to the following condition:
  \[t_{01} = t_{02}\]
• The duration of the early diastole period (including $t_{01}$) is equal to: $t_{12} = TT - QT - PQ$
• Dimensionless parameters and functions thereof are as calculated below:
  \[\alpha_1 = \left(k_{11} \frac{t_{01}}{t_{01}}\right)^{0.2} = \frac{3\alpha_1 + 2}{5}\]  
  \[\beta_1 = \frac{2(e_{1} - 1)}{\alpha_1 - e_1} = \left(k_{12} \frac{t_{01}}{t_{01}}\right)^{0.2}\]
• Maximum velocity \( U_{01} \) for the early diastole period and \( U_{02} \) for the atrial systole is computed as given below:

\[
U_{01} = \frac{3678.5 t_{01} \left( 5 \varepsilon_i - 2 \right)^3 - 27}{\left( 5 \varepsilon_i - 2 \right)^3 - 243} \text{ (cm/s)}
\]

Velocity \( U_{01} \) is calculated using the same formula at \( \varepsilon = \varepsilon_i \).

• The value of time interval \( t_{01} \) is determined based on a certain condition. To calculate it we take value \( t_{01} \) subject to the following equation:

\[
SSV - t_{01} \left( U_{01} \left( \varepsilon_i^3 - 1 + f_i \left( \varepsilon_i, \alpha, \beta \right) - f_2 \left( \varepsilon_i \right) \right) + U_{02} \left( \varepsilon_i^3 - 1 \right) \right) = 0
\]

• The RV1 blood volume, entering the heart ventricle in the phase of the early diastole, expressed as a percentage of the filling volume, is found as given below:

\[
RV1 = \frac{100 U_{01} \left( \varepsilon_i^3 - 1 + f_i \left( \varepsilon_i, \alpha, \beta \right) - f_2 \left( \varepsilon_i \right) \right) + U_{02} \left( \varepsilon_i^3 - 1 \right)}{U_{01} \left( \varepsilon_i^3 - 1 + f_i \left( \varepsilon_i, \alpha, \beta \right) - f_2 \left( \varepsilon_i \right) \right) + U_{02} \left( \varepsilon_i^3 - 1 \right)} \text{ (%)}
\]

• The RV2 blood volume, entering the heart ventricle in the phase of the atrial systole, expressed as a percentage of the filling volume, is calculated as follows:

\[
RV2 = 100 - RV1 \text{ (%)}
\]

• Provided that a balance between the blood input volume during the diastole and the blood output volume during the systole is kept, it may be assumed that the condition of the equal volumes in the filling and the ejection is met. Then, knowing the stroke volume SV value, it is possible to determine absolute (in ml) values of diastolic phase volumes PV1 and PV2:

\[
PV1 = SV \cdot RV1 / 100 \text{ (ml)}
\]

\[
PV2 = SV \cdot RV2 / 100 \text{ (ml)}
\]

In the process of research, the relative phase volumes of blood (RV1 + RV5) to express a percentage of the absolute value of each phase volume to the stroke volume SV, have been also calculated and analyzed. The hemodynamic parameters, the values of which are expressed as a percentage of the stroke volume, are pronounced markers of the contribution of each phase process to the formation of cardiac output.
Abstract

This paper offers some results obtained in our studies on the motion of individual formed elements in blood with due regard of a pulsatile flow of the plasma in the blood vessels. An analysis of the process of the motion of the blood particles having different shapes in a pressure wave variable field of the pressure wave has been completed herein.

Keywords

Blood formed elements, Motion, Pressure wave variable field, Human circulatory system, Physical models of motion of formed elements

Imprint


Introduction

Circulating blood represents a suspension comprised of the plasma as the blood liquid component and formed elements suspended therein, which are as follows: erythrocytes, leukocytes and thrombocytes, the sizes of which range up to 10 micrometers. Hemodynamic processes, which occur in different phases within a cardiac cycle, determine the respective blood flow volumes, which are considered to be one of the major criteria for an assessment of the cardiovascular system performance. Electrical potential traced as an electrocardiogram controls the blood flow in the blood vessels in order to provide all required parameters of hemodynamics. From an analysis of an electrocardiogram, which can be interpreted as a sequence of simple sinusoidal signals [1], it may be deduced that the blood flow is managed under smoothly changing energetic processes in each cardiac cycle, which show their maxima and minima, from their growing till their decaying. An actual frequency of these processes is dictated by the heart rate and cannot exceed 5 Hz that refers to 300 heart beats per minute. A knowledge of biophysics processes of blood circulating flows, considering motion of the formed elements in a pulsatile blood flow, is of crucial importance.

A set of the respective blood volumes and associated dynamic fluctuations thereof are considered to be a valuable diagnostics parameter for assessing of hemodynamic processes is. A simulation of the hemodynamic process on the basis of empirical equations by G.M.Poyedintsev – O.K.Voronova [2] according to their concept of elevated fluidity regime, existing in the circulatory system, has made it possible to bring an analysis of volumetric parameters of a cardiovascular cycle to a new higher level [3]. However it should be noted that many factors of biophysics, responsible for the motion of blood as a suspension, comprising the liquid plasma and the formed elements suspended therein, are still not clearly understood. There is still a poor understanding of how the blood laminar flow process is organized: erythrocytes, leukocytes and thrombocytes, circulating in blood vessels, are non-spherical in their shape. So, it is supposed that the blood elevated fluidity phenomenon, determined by pulsations by the blood vessel walls, should be accompanied by oscillations of the blood formed elements. Considering the above, an attempt is made in our paper to analyze the process of the motion of the blood elements in a variable field of a pressure wave.

Materials and methods

The construction of our fresh theory of the motion of the blood formed elements is based on a solution of a number of physics-related problems. Following this way, it should be stressed that the key problem within the context is an investigation of the behavior of individual particles and the system of these smallest particles in a variable field of pressure. The solution of this problem allows discovering applicable laws and regularities of the major physical mechanism of the laminar flow of the elements in a variable pressure field. The formed elements, which are suspended in the liquid medium, under the action of the oscillations, are
involved into different types of the motion. And the viscosity of the medium plays a significant role therein.

The laws, regularities and general rules of the motion of a single spherical fluid element in a viscous medium are quite sufficiently treated in papers by G. G. Stokes, L.D. Landau, E.M. Lifshits [4] and other researchers. In monographs by N.A. Fuks [5], a theory of the behavior of an individual particle in a viscous medium under the action of different forces is comprehensively studied. Based on the key results of this theory, the description of the behavior of individual particles and their system in a variable pressure field will be discussed herein below.

The formed particles, residing in a field of periodical mixing in a viscous medium, are subjected to external forces, resistance forces and forces of interactions between the particles. As a result of the collective action of the above forces, a motion of the particle relative to the medium is initiated. By the external forces we usually mean gravity, electrostatic forces etc. Those forces, acting on a particle, exerted by a resting medium (in case of the particle motion) or a moving medium, are usually not ranked as the external forces. They are referred to as the forces of the resistance. In cases, when the particles are involved in an oscillatory movement in a variable pressure field, the resistance forces should be regarded as the acting ones, so that they may be taken into account as the external forces.

The force, exerted by the medium, which acts on a single particle, can be computed from a solution to the Navier-Stokes equation. For a spherical solid particle having radius R, the solution to the Navier-Stokes equation:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{1}{\rho_c} \nabla p + \nu \nabla^2 \mathbf{V}$$  \hspace{1cm} (1)

for a viscous incompressible medium, in case of an arbitrary function of time for medium velocity $U(t)$, leads to formulation of an expression for time-variable force $F$, acting on the particle, as given below:

$$F = 6\pi \eta RV + \frac{4}{3}\pi R^3 \rho \frac{dV}{dt} + \frac{2}{3}\pi R^3 \rho \int_0^t \frac{dV}{dt} \sqrt{t-t_i} \, dt$$  \hspace{1cm} (2)

where $V = (U - U_p)$ is velocity of flow past a particle, $U_p$ is velocity of the particle, $\eta$ is a coefficient of the dynamic viscosity of the medium; $\nu = \eta/\rho_c$ is a coefficient of the kinematic viscosity, $\rho_c$ is density of the medium; $g$ is gravitational acceleration; $t_i$ is typical time at the inverse Fourier transform of the function $V(t)$; $p$ pressure.

The formula (2) holds for small Reynolds numbers $Re = 2R |V|/\nu$. The first term in the right side expresses the Stoke's force of the resistance at a constant velocity of the motion, equal to the instantaneous value of flow past at a given instant. The second term represents the Archimedes force, or the buoyant force. The third and the fourth terms are the forces of the resistance, which are associated with an energy consumption required to initiate the motion of the medium itself. In this case, the third term corresponds to the force of inertia for a potential flow past a medium. It can be interpreted as a mass added to the particle, that is equal to one half liquid displaced by the particle itself. The fourth term is associated with an energy input to initiate the motion of the medium areas, adjacent to the particle, due to the mechanism of the internal friction (viscosity).

Under the oscillatory motion of the medium, the velocity of the medium $U_p$ and, consequently, the flow past velocity are functions of time. However temporal variations in the velocity will not alter the pattern of the viscous motion of the particle, provided that the condition of the quasi-stationarity [6] is met:

$$\frac{\partial \mathbf{V}}{\partial t} \cdot \nu \mathbf{V} \approx \frac{\mathbf{V} \cdot \nu \mathbf{V}}{\nu} = 1$$  \hspace{1cm} (3)

where $\omega = 2\pi f$ is a circle frequency.

The condition of the quasi-stationarity is very crucial for studies on issues associated with effects made by oscillations on liquid dispersed media, and it is fulfilled for the heart pulse frequencies.

In addition, we should mention that there may be some other factors and properties of the particles capable of influencing the nature of the motion of these smallest components, the sizes of which are in the range of few microns, as follows: their non-sphericity, fluctuating lability, etc. The actions and effects thereof can be taken into account by introducing the respective correction coefficients. But it is often the case, when they are ignored to a rough approximation.

The motion of the blood formed elements in a variable pressure field can be defined by a system of parameters derived from the solution of the equation of the motion.
The differential equation of the motion of an individual particle in a viscous medium can be written on the basis of the basic law of dynamics as follows:

$$m_p \frac{dU_p}{dt} = m_p g + \frac{4}{3} \pi R^3 \rho_c \frac{dU_p}{dt} - F,$$

where $m_p = \frac{4}{3} \pi R^3 \rho_p$ is mass of the particle, $\rho_p$ is density of its matter.

As compared to the other constituents in (4), the action of gravity on the micron-sized particles is negligible, so that it may be ignored. Upon such simplification, the formula (4) becomes an equation of one-dimensional motion of the particle, and all values included therein can be written as the scalars.

Upon substitution of (2) into (4), taking into account the signs of the acting forces and normalizing on the $t_0$ basis, the equation of the motion takes the form as follows:

$$\left(1 + \frac{\rho_c}{\rho_p}\right)\frac{dU_p}{dt} + \frac{3 \rho_c}{2 \rho_p} \frac{dU_p}{dt} - \frac{1}{\tau} (U_i - U_p) -$$

$$- \frac{9 \rho_c^2}{2 \pi \rho_p^3} \int_0^t \frac{1}{\sqrt{1 - \frac{t_i}{t}}} dU_p = 0$$

(5)

where $\tau = \frac{m_p}{6 \pi \eta R} = \frac{2 R^2 \rho_p}{9 \eta}$ is time of relaxation of the particle.

Due to smallness of the $\rho_c/\rho_p$ relation between the density of the blood plasma and that of the matter of the formed particle, we may neglect the respective terms in the equation (5). The influence produced by the integral member in (5) is also insignificant. As a result, for our analysis of the behavior of the aerosol particles in a field of periodically varying forces, the following approximate equation obtained from (5) is applied for displacements:

$$\frac{d^2x_p}{dt^2} + \frac{1}{\tau} \frac{dx_p}{dt} = \frac{1}{\tau} \frac{dx}{dt}$$

(6)

where $x_p$ and $x$ are current values of displacements of the particle and the medium, respectively.

From (6), by substituting the harmonic function of the medium displacement, the parameters of the oscillatory motion of the formed particles can be easily found, which are fully suitable for applications in practice.

If we set $U_i = U_0 \cos \omega t$, then for a steady-state regime we have

$$U_p = U_0 n \cos (\omega t - \phi)$$

$$V = U_0 m \sin (\omega t - \phi)$$

(7)

where $n = \cos \phi = 1/(1 + \omega^2 \tau^2)^{1/2}$ is a coefficient of entrainment, $m = \sin \phi = \omega \tau (1 + \omega^2 \tau^2)^{1/2}$ is a coefficient of flow past, $\phi$ is a phase shift due to inertia of the particle, which is referred to oscillations of the medium and defined by the following equation:

$$\tan \phi = \omega \tau$$

The obtained parameters are appropriate for the case $Re << 1$. Under the viscous conditions of flow past, at $Re > 0.5$, due to the inertia action exerted by the medium, the actually operating force differs to some extent from the Stokes’ force value. The influence of the medium inertia on the operating force can be taken into account by the Oseen’s correction [7].

An effect of the applications of the Oseen’s correction on the parameters of the oscillatory motion of an individual particle is analyzed further herein.

When considering various aspects of the theory of the motion of particles of this sort, some problems arise, the solutions of which imply the fact that the shape of the particle plays a significant role, for instance, when finding a field of erythrocytes flow past. In such cases, the real non-spherical particles should be replaced by the corresponding physical models.

It is evident that an extended ellipsoid of revolution (Figure 1a) and the flattened one (Figure 1b) may be judged to be the adequate physical models of the real formed particles. At sufficiently large ratios of their axes, the ellipsoids of revolution may be treated as the adequate physical models of the particles both of flat and extended shapes, and in case when there is a relatively small difference in the sizes of their axes, the ellipsoids of revolution take the form similar to a spherical one.

For the extended ellipsoid of revolution and the flattened one, we have succeeded in obtaining relatively compact expressions for the force of the resistance, the component of the velocity of flow past in a sound field etc. In this connection, it should be noted that difficulties associated with the mathematics, which appear in formulating the above expressions, discourage applying a unified physical model of the real formed elements, namely, an arbitrary three-axes ellipsoid of revolution.

Depending on the nature of the motion in the stationary viscous medium, a non-spherical particle may have different orientations. When the free settling rate is small (the purely viscous regime of flow past), the non-spherical particles are oriented in an arbitrary way with reference to the direction of their motion [6]. Sufficiently large-scale particles retain their initial orienta-
Figure 1. Physical models of the formed elements of non-spherical shape. Legend: a – an extended ellipse of revolution; b – a flattened ellipse of revolution.

The orientation, while small-sized particles have to take all possible orientations due to the Brownian motion. The absence of a definite orientation can be explained by the fact that the torque, applied to the particles of irregular shapes, under the purely viscous regime of flow past, is equal to zero [6].

When the Reynold’s number Re reaches values of the order of 0.05-0.1, the character of the motion changes. In doing so, the non-spherical particles seek to take such a position, which provides for perpendicularity of their highly developed edges and faces to the direction of the motion [6]. As a Re value grows, such orientation of the non-spherical particles becomes more and more clearly defined. It is precisely the torque, the value of which is now other than zero, that is responsible for the orientation of the particles under the conditions.

As the degree of the orientation increases, the ability of the particles to move falls off that it is especially noticeable in the direction of their motion. It results in the fact that the non-spherical particles, the developed edges and faces of which are oriented perpendicularly to the direction of the motion, are executing a zigzag or a spiral motion when settling. This effect is most pronounced at the plate-shaped particles.

The orientation of the extended and flat-shaped particles is observed in flows showing velocity gradients directed perpendicularly to the flow. When the polar axis of an ellipsoidal particle is in the velocity variation plane, the velocity gradient induces flipping of the extended ellipsoid of revolution to position the polar axis thereof in the direction of the flow, and flipping of the flattened ellipsoid of revolution to position the equatorial axis of the latter in the direction of the flow, correspondingly [7-15]. The above phenomena were experimentally reproduced in colloid solutions and suspension media. It should be mentioned that the behavior of the formed elements in flows showing velocity gradients remains to be explored.

Small nanometer-scale particles, which represent a majority, are practically fully entrained by the medium oscillations. In this case, their orientation depend on a Re number value. At Re values, which are below a certain critical value, the ellipsoid particles are oriented in the same manner as it is the case with the particles fully entrained by the oscillatory movement. At Re number values exceeding the critical value, the particles show the orientation as those particles, which do not participate in the oscillations of the medium.

In case with the purely viscous regime of flow past, at the Reynolds number Re << 1, for a non-spherical body, the force of the resistance is expressed by the Stokes formula, but with another coefficient. The form of this coefficient was obtained by Oseen in his work [5]. If we denote the semi-major axis of the ellipsoid of revolution by C, the ratio of the major axis to the minor axis by N, and the dynamics viscosity of the medium by η, then the resistance of the medium to the motion of a single ellipsoid element in a sound field can be expressed by the following formula:

\[ F = 6 \pi k CV \]

where \( k \) is a form factor of a particle.

At \( N \to 1 \) the expression (10) transforms to the known Stokes formula for the force of the resistance of the sphere in the viscous medium.

Conclusions

Our analysis of the computations obtained according to the above mentioned formulated expressions has shown that the shape of the formed elements in blood significantly influences the values of the entrainment and flow past coefficients. The orientation of the elliptical particles in a variable pressure field exerts a weak effect on the entrainment and flow past coefficients. As to the erythrocytes, which are shaped as flattened ellipsoids of revolution, observed is a decrease in the coefficient of entrainment and an increase in the past flow coefficient with a growing inclination angle with reference to the blood flow \( \theta \). More significant changes in the coefficients of entrainment and flow past are reported to be for the particles showing higher axes ratios. The formulated theoretical reasoning
and the obtained computation data are supported by the known experimental studies of the motion of the blood formed elements in the blood vessels.

**Statement on ethical issues**
Research involving people and/or animals is in full compliance with current national and international ethical standards.

**Conflict of interest**
None declared.

**Author contributions**
All the authors read the ICMJE criteria for authorship and approved the final manuscript.

**References**
The new analytical solution of the 3D Navier-Stokes equation for compressible medium clarifies the sixth Millennium Prize problem

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Abstract
The limitations of capabilities of the existing mathematical weather prediction (including forecasting for weather-sensitive individuals) cannot be duly realized nowadays due to the fact that till now there is no proof of the existence and uniqueness of smooth solutions of the three-dimensional (3D) Navier-Stokes equation (in any finite period of time).

We have obtained a new analytical solution of the Cauchy problem of this equation in an unbounded space, which has finite energy for any values of time.

Keywords
Hydrodynamics, Compressibility, Viscosity, Turbulence, Vortex waves

Imprint
Sergey G. Chefranov, Artem S. Chefranov. The new analytical solution of the 3D Navier-Stokes equation for compressible medium clarifies the sixth Millennium Prize problem; Cardiometry; No.10 May 2017; p. 18–33; DOI:10.12710/cardiometry.2017.10.1833; Available online: www.cardiometry.net/issues/no10-may-2017/analytical-solution-of-the-navier-stokes-equation

Introduction
1. The proper understanding of many processes in nature and engineering systems is closely connected with the existence of the fundamental and applied problem of turbulence, which remains unsolved for more than a century due to the absence of exact analytical nonstationary smooth vortex solutions of the Navier – Stokes (NS) equation. The development of the statistical approach to its solution gave a lot of interesting results, but at the same time led to a new, still unsolved, problem of the closure in the description of different moments of the vortex field, an approximated solution of which was proposed by Kolmogorov A.N., Geizenberg V. et al. [1].

In order to solve the problem of turbulence, in its turn, it is required to properly understand the mechanism of the appearance of randomness due to instability of a deterministic continual dynamic system described by the NS equation. In this case, the problem of the appearance and development of turbulence is linked to the problem of self-organization of coherent structures emerging from chaos and to the associated issues of nonrandom randomness in an individual life of a human and in life spans of living species treated in the context of the Sinai billiards [2].

However, till the present, an analytically smooth on the whole time axis nonstationary solution of the three-dimensional (3D) NS equation has not been found and even the corresponding theorem of the existence and uniqueness of such solution has not yet been proven [1].

Actually, up to date in hydrodynamics only a few exact solutions are well known, but, however, none of them is nonstationary and at the same time is defined in an unbounded (or with periodic boundary conditions) space [1–4]. Only weak nonstationary solutions describing, for example, dynamics and interactions between singular vortex objects in the two-dimensional (2D) and three-dimensional (3D) ideal incompressible medium are known [3, 5, 6]. At the same time, for the 3D ideal medium flows there are some conceptual ideas on a possibility of the existence of nonstationary solutions of the Euler – Helmholtz (EH) equation only on an unbounded interval of time $0 \leq t < t_0$ (see [1, 3, 6, 7] and the references given therein). This time value for incompressible medium is determined exclusively by the 3D effect of vortex filament stretching, which may lead to an explosive unbounded growth of the enstrophy (the integral of the squared...
vorticity over space) in finite time $t_0$ [1, 3, 6, 7]. On the other hand, known are the exact stationary modes of flows of the viscous incompressible medium in the form of the Burgers and Sullivan [3] vortices for which this, potentially dangerous with respect to appearance of singularity, effect of the vortex filament stretching is accurately compensated by the effect of the viscosity. For these solutions, however, a convergent integral of energy over the entire unbounded space does not exist.

2. As a result, for almost two hundred years (since 1827–1845), open remains the issue on the existence of smooth nonstationary divergent and divergent-free solutions of the 3D NS equation in an unbounded (or with periodic boundary condition) space and on an unbounded interval of time [8–12]. And the significance of this problem is determined not only by mathematical, but also by practical interest, owing to both the fundamental and applied problem of predictability in hydrometeorology and other related fields that might be the case with the applications of the methods utilized for the NS equation computational solution [9, 10].

Therefore, in 2000 the problem of the existence of a smooth nonstationary vortex solution of the 3D NS equation on an unbounded interval of time was included by Clay Mathematics Institute into the list of the seven fundamental Millennium Prize problems under number six [8, 9, 11, 12]. However, at the same time, in [8] it is proposed to consider this problem solution not for the full NS equation [4], but only for the equation, derived from it in assumption that the divergence of incompressible medium velocity field is equal to zero. Evidently, such a definition a priori assumes that for divergent flows (having a nonzero velocity field divergence) the full NS equation obviously cannot have smooth solutions on an unbounded time interval. Actually, in [12] written is the following: “The Millennium Prize problem refers to incompressible flows, as it is known that the compressible ones behave disgustingly”. Thereupon, an example of appearance of the shock wave in compressible medium when an object moves therein with a velocity higher than the velocity of sound in this medium is given in [12]. However, it is clear that the viscosity forces do not allow for real singularity for any flow characteristics, that, as a result, does not exclude a possibility of the existence of smooth divergent solutions of the full NS equation.

3. Up to date, as we know, a direct proof of impossibility of the existence of smooth divergent solutions of the full NS equation has not been obtained yet, and therefore the problem formulation in [8] allows in full a generalization for the case of divergent compressible medium flows that is the matter under consideration in this paper.

Actually, in the present paper on the basis of the theory [13] found is a new analytical nonstationary vortex solution of the full 3D NS equation which because just to the finiteness of the viscosity forces (which are modeled by adding of the velocity field of the random Gaussian delta correlated in time to the velocity field [10]) remains smooth for any arbitrary large periods of time. At the same time, the NS equation solution may be extended in Sobolev space $H^q(R^d)$ for any $q \geq 1$ and $t \geq t_0$, where $t_0$ – is a minimum time of singularity (collapse) appearance for the corresponding exact solution of the EH and Riemann – Hopf (RH) equations in case of zero viscosity. The norm in Sobolev space $H^q(R^d)$ is determined in the form [14]:

\[
\|u\|_{H^q(R^d)} = \left( \sum_{j \leq q} \int |\beta|^2 \left[ qHR \right] \right)^{1/2} \tag{B.1}
\]

Let us note that in [14] formulated is a local theorem of the existence of a 3D EH equation solution of the divergent-free ideal incompressible fluid flow. According to this theorem, a smooth EH equation solution exists if the initial velocity field $u_0$ belongs to the Sobolev space $H^q(R^d)$ when $q \geq 3$, and the very solution corresponds to the class

\[
u \in C \left([0, t^*]; H^q \right) \cap C \left([0, t_0]; H^{q-1} \right),
\]

where the norm is determined in (B.1). At the same time, for the considered herein exact EH and RH equation solution in case of the divergent ideal compressible medium flow there exists the possibility for extension of this solution for times $t \geq t_0$ only in Sobolev space $H^q(R^d)$. And there is no possibility for its extension in Sobolev space $H^q(R^d)$ by time $t \geq t_0$ when $q = 1$ is instead of the condition $q \geq 3$ of the theorem in [14].

The finite value of the velocity field divergence corresponds to the obtained NS equation analytical solution, that indicates an inconsistency of the above “quasi evident” a priori assumption on the absence of smooth divergent 3D vortex solutions of the full NS equation.

The noted method for taking into account the viscosity is a particular example of turbulence modeling, when instead of a random force a random velocity field is entered [15]. In [15], however, treated is only the spatially
inhomogeneous large-scale random velocity field and excluded is the drift part of this velocity which depends only on time. At the same time, just the averaging over the random velocity field, which depends only on time, provides the proper modeling of the effective viscosity (in assumption that this velocity is Gaussian and delta – correlated in time) in the present paper. Besides, it is important that this method for modeling the viscosity effect does not change the structure typical for viscosity force \( F_v \), which is entered into the NS equation and, as an example, for the incompressible medium, having the form

\[ F_v = \nabla \mu \Delta u \quad [3]. \]

Actually, it is well known [15], that the existence of a NS equation solution is proven in case if to the conventional viscosity force added is a member which is proportional to a higher derivative (of the velocity of flow \( u \)) of the form

\[ \Delta^\alpha \nabla u, \alpha \geq \frac{5}{4} \]

(see [16,17]) and which is responsible for changes of the viscosity force structure typical for the initial NS equation.

Besides, it is shown that an elimination of the singularity of the solutions of the EH, RH and NS equations takes place even in case of an introduction of a sufficiently great coefficient of external friction \( \mu \), satisfying the condition (5.3) and corresponding to the substitution

\[ \nabla \mu \rightarrow -\mu \]

in the NS equation.

The new solution of the 3D NS equation is found under the condition of the zero total balance of normal stresses caused by pressure and the viscosity of the compressible medium divergent flow that, as shown in paragraph 2 hereof, corresponds to the sufficient condition of positive definiteness of the integral entropy growth rate. It allows reducing the NS equation solution to the solution of the 3D analog of the Burgers equation, and then to the solution of the 3D RH equation and its generalization for the case of taking into account the viscosity force (the external friction or the above effective friction related to the random velocity field).

Let us also note that in general case the vortex solutions of the 3D RH equations coincide with the 3D EH equation solutions for describing the ideal compressible medium vortex flows with the nonzero velocity field divergence [10, 13].

In fact, all real media are more or less compressible, and their flows should be described just by the divergent solutions of the full NS equation. On the other hand, the divergent flows for a conditionally incompressible medium may also correspond to the presence of distributed sources and drains, modeling of which is successfully used in relativistic and non-relativistic hydrodynamics [18–21].

4. Let us notice that in [22] obtained is also an exact solution of the 3D RH equation, which describes, however, only in terms of the Lagrangian variables, an explosive evolution with time for the matrix of the first derivatives of the velocity field. It does not provide a possibility for obtaining on its basis an exact solution of the 3D EH equation for the vortex field, as it has been performed in [13] in the Eulerian representation of the solution. At the same time, the present paper shows that the obtained in [13] exact solution of the 3D RH equation for the velocity field (see formula (3.7) below) in the Lagrangian representation gives for the evolution of the matrix of first derivatives of the velocity field an expression (3.14), which exactly coincides with the formula given in [22] (see formula (30) in [22]).

Also found are new analytical solutions for the evolution of vortex intensities and helicity of the Lagrangian fluid particle in the 1D and 3D cases. In [23] considered is the similar in structure form of the EH equation solution (see formula (23) in [23]) on the basis of an application of a combination of the Eulerian and Lagrangian descriptions in the representation of the vortex lines. However, it does not permit to explicitly describe the peculiarities (including the enstrophy singularity) of the evolution with time for vorticity. The discovered herein description of the evolution vorticity in the Lagrangian representation for the 2D and 3D case (see (4.4) and (4.5)) may be considered as a concretization of the obtained in [23] form of the EH equation solution for the case of the inertial fluid particles motion.

Besides, herein specified is a new necessary and sufficient criterion for the realization of the explosive singularity (collapse) in a finite time (see (3.11), (3.12)) for the nonviscous RH and EH equation solutions in the 1D, 2D and 3D cases. At the same time, in [22] given is an integral criterion in the form of (3.13) (see formula (38) in [21]), which determines only the sufficient condition for the realization of a solution collapse. Besides, for example, for the case of the ini-
tial divergent-free velocity field, the
collapse is possible only according to
the necessary and sufficient criterion
(3.12), but it cannot be established
from the criterion (3.13). At the same
time, from the completed in [22] con-
sideration of the explosive mode for
the 3D RH equation solution made is
a conclusion about impossibility of ex-
tension of this solution by an infinite
time in the Sobolev space $H^2(R^3)$, that
differs from the above mentioned re-
sult indicated herein.

In the 2D case we have an exact corre-
spondence between the criterion (3.11)
and the similar criterion given in [24]
(see formula (9) in [24]) in connection
with the solution of the problem of flame
front propagation (generated by self-sustained exothermic chemical re-
action) on the basis of a simplified ver-
sion of the Sivashinsky equation [25]:

$$\frac{\partial f}{\partial t} - \frac{1}{2} U_s \left( \frac{f}{U_s} \right)^2 = \gamma_0 f \quad (B.2)$$

In the equation (B.2), the function
$$x_i = f(x_1, x_2, t)$$
determines the flame front represen-
ting the boundary between combus-
tion agent ($x_1 > 0$) and combustion
products ($x_1 < 0$), where $U_s$ and $\gamma_0$
are constant positive values character-
izing the front propagation veloci-
ty and the combustion intensity, re-
spectively. With $\gamma_0 = 0$ the equa-
tion (B.2) coincides with the Hamilton – 
Jacobi equation for a free non-rela-
tivistic particle. The proposed herein
exact RH equation solution (3.7) in
the 2D case (to be more exact, in its
modification, taking into account the
external friction with the coefficient
$\mu$ and the formal equality $\mu = -\gamma_0$)
gives the exact equation solution
(B.2). At the same time, the solution
(3.7) describes the potential flow of
the form
$$f = -U_s \nabla \phi.$$  

5. An important result of the present
paper is obtaining of the closed de-
scription of the with-time evolution
of enstrophy and any higher vortex field
moments, as well as the velocity field
in the 2D and 3D cases. It is achieved
on the basis of the corresponding an-
alytical solution of the EH, RH and
NS equations both for the case of the
zero viscosity and the case with tak-
ing into account the external friction
or the effective viscosity. As a result,
not approximately, as usual, but exact-
ly solved has been the problem of the
closure in the theory of turbulence,
which remained unsolved for a long
time, despite multiple attempts for
searching at least for its approximate
solution [1]. Herein we have succeed-
ed in finding the solution due to es-
tablishing a relatively simple and clear
dependence on the initial condition
for the obtained exact EH and RH
equation solution for the velocity field
(3.7) and the vortex field ((4.1) and
(4.2)), which is absent, for example,
in the well known exact Burgers equa-
tion solution, obtained with the use of
the nonlinear Cole – Hopf transfor-
mations.

In particular, due to this fact, based
on the exact solution (4.2), obtained
an estimate for the integrals of the vorticity field in the 3D case
close to the moment of solution sin-
gularity:

$$\Omega_{3(2m)} = \int d^3x \omega^{2m} \approx O(1) \quad \text{and} \quad \Omega_{3(m)} = \int d^3x \omega^m \approx O(1),$$

when $m = 1, 2, 3...$. Thus, the following
inequality is evident:

$$\Omega_{3(2m)}^2 / \Omega_{3(m)}^2 \gg 1; \quad (B.3)$$

It demonstrates a strong intermittency
of the vortex field in the vicinity of sin-
gularity.

Let us note, that usually the inequality
$$\Omega_{3(2m)} > \Omega_{3(m)},$$
actually, is regarded to be true under a
strong vortex intermittency [15], but
in the past it was impossible to derive
it from the exact solution of the clo-
sure problem in the theory of turbu-
lence, as it was done, when obtaining
the estimation (B.3).

6. In conclusion hereof, based on an
analysis of the exact closed solution
of the enstrophy balance equation
(5.6) and the rate of integral kinet-
ic energy change in (6.1)–(6.4), dis-
cussed is a possibility of the existence
of not only divergent, but also smooth
divergent-free NS equation solutions
on an unbounded time interval.

1. The Navier-Stokes (NS) and Euler-Helmholtz (EH)
equations

The equation of the motion of the compressible medium may be writ-
ten as follows [4]:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{\eta}{\rho} \Delta u_i - \frac{1}{\rho} \frac{\partial}{\partial x_i} \left( u_j - (\zeta + \frac{\eta}{3})(\frac{\partial u_j}{\partial x_j}) \right);$$

$$\Delta = \frac{\partial^2}{\partial x_k \partial x_k} \quad (1.1)$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k} (\rho u_k) = 0 \quad (1.2)$$
It follows from the form of the second member in the right side (1.1) that for the viscous compressible divergent flow the normal stresses are determined not only by pressure, but also by the velocity field divergence. In (1.1), (1.2) \( u_i \) – is a velocity of medium; in repeated indices implied is a summation from 1 to \( n \) (where \( n \) – is dimensionality of space, and later treated will be the cases, when \( n = 1, 2, 3 \)), \( a \), \( p \), \( \rho \), \( \eta \), \( \zeta \) – is a pressure, a density, the constant coefficient of the viscosity and the constant coefficient of the second viscosity of medium, respectively [4].

For the incompressible medium with a constant density \( \rho = \rho_0 \) from equation (1.1), in the 3D case (when \( n =3 \)) after curl operation from left and right sides, the following Euler – Helmholtz (EH) equation is obtained:

\[
\begin{align*}
\frac{\partial \omega}{\partial t} + u_i \frac{\partial \omega}{\partial x_i} &= \frac{\omega_k u_k}{\partial x_k} - \omega_i \text{div}\vec{u} + \nu \Delta \omega_i \\
= & \omega_i \text{div}\vec{u}
\end{align*}
\]

(1.3)

In (1.3) \( \omega = \text{rot}\vec{u} \), and \( \nu = \eta \rho_0 = \text{const} \) – is a coefficient of molecular kinetic viscosity.

For the case of the compressible medium, the equation (1.3) also takes place, but only if \( \eta \rho = \text{const} \) and the curl from the second member in the right side (1.1) is equal to zero. In particular, it occurs in the case if the second member in the right side is equal to zero (1.1) that corresponds to the zero total balance of the normal stresses produced by pressure and viscosity of the divergent medium flow.

In [13] obtained is an exact vortex solution of the 3D Riemann-Hopf (RH) equation (which coincides with (1.1) when vanishing the right side (1.1)) in case of arbitrary, smooth, vanishing at infinity, initial conditions. It coincides with the exact EH equation solution (1.3) for the compressible nonviscous medium (when in (1.3) the last member in the right side is equal to zero). At the same time, in [13], in particular, it is demonstrated that the obtained smooth solution may exist only on a bounded interval of time \( 0 \leq t < t_0 \) (where the value \( t_0 \) is determined further from equation (3.11)).

Further (in paragraph 3 herein) it is demonstrated that for any arbitrarily small value of the effective viscosity (introduced instead of the last member in the right side (1.3)) obtained can be an exact solution of the equations (1.1) – (1.3) which exists even on an unbounded time interval.

2. Energy and entropy balance equations

1. Usually, when considering the system of four equations (1.1), (1.2) for five unknown functions, introduced is an additional condition of a relation (an equation of the medium state) between density and pressure in order to make equal the number of the equations and the number of the unknown functions. The representation of the equation of state for a nonequilibrium vortex flow needs to be specified. Instead of this, for the closure of the system (1.1), (1.2) usually utilized is an approximation of the velocity zero divergence for the incompressible medium, that is reasonable, in particular, in case of relatively lower (if to compare with sound velocity) medium motion velocities.

Let us derive a similar equation, which closes the system (1.1), (1.2) for the compressible medium divergent flow and which will substitute the condition of equality to zero of the velocity field divergence for the incompressible fluid flow.

For this purpose, we obtain the energy and entropy balance equations which follow from (1.1), (1.2) as well as from the conventional thermodynamic relations [26]. In case of a single-component medium, these relations have the following form [26] (see (14.3), (15.6) and (15.7) in [26]):

\[
\begin{align*}
\varepsilon &= Ts - \frac{P}{\rho} + \Phi \quad (2.1) \\
-sdT + \frac{dp}{\rho} &= d\Phi \quad (2.2) \\
d\varepsilon &= Tds + \frac{P}{\rho}d\rho \quad (2.3)
\end{align*}
\]

In (2.1) – (2.3) \( T \) – is a temperature, \( \varepsilon, s, \Phi \) – are internal energy, entropy and thermodynamic potential or the Gibbs free energy (units of medium mass), respectively [26]. At the same time, the equation (2.3) immediately follows from the equation (14.3) in [26], and it exactly coincides with the equation (15.7) and (15.6) in [26], respectively at any \( \Phi \). For the considered single-component medium under condition of the constant amount of the particles therein, we assume below that in (2.1) and (2.2) \( d\Phi = 0 \) and \( \Phi = \Phi_0 = \text{const} \).

The equation (2.3) is further used in the following form (see also [4] on page 272):

\[
\frac{\partial \varepsilon}{\partial t} = T \frac{\partial \varepsilon}{\partial t} + \frac{p}{\rho^2} \frac{\partial \rho}{\partial t} \quad (2.4)
\]

2. Based on the equations (1.1), (1.2), we may obtain the equation of the balance of the integral kinetic energy

\[
E = \frac{1}{2} \int d^3x u^2 \quad \text{as follows:}
\]

\[
\frac{dE}{dt} = -\eta \int d^3x \left( \frac{\partial \varepsilon}{\partial x_i} \right)^2 + \int d^3x \left[ p - (\zeta + \frac{\eta}{3}) \text{div}\vec{u} \right] \text{div}\vec{u} \quad (2.5)
\]
For the incompressible viscous medium, the divergent-free flow formula (2.5) exactly coincides with the formula (16.3) in [4], and it serves as its generalization for the case of the compressible viscous medium flows. To derive the equation (2.5) it is enough to scalarly multiply the equation (1.1) by the vector \( \rho \mathbf{u} \), multiply the equation (1.2) by the scalar \( \frac{\mathbf{u}^2}{2} \), add the obtained expression and integrate over the entire space.

Let us notice, that in case of an ideal (nonviscous) medium, from (2.5) it follows that integral kinetic energy is an invariant only for the divergent-free flows, and for the divergent flows as an invariant should be only the total integral energy

\[
E_s = \int d^3x \left( \rho \frac{\mathbf{u}^2}{2} + \rho e \right),
\]

conservation of which is assumed to be for the viscous medium, too [4].

Let us derive an equation of the total energy balance for the viscous compressible medium and the corresponding equation of entropy balance, on the basis of the equations (1.1), (1.2), (2.1) and (2.4). As opposed to the derivation given in [4], let us immediately use the equation (2.1) written taking into account the above equality \( \Phi = \Phi_0 = \text{const} \). As a result, considering (2.1), we have the following from (2.4):

\[
\frac{\partial}{\partial t}(\rho e) = T \frac{\partial}{\partial t}(\rho s) + \Phi_0 \frac{\partial \rho}{\partial t} \tag{2.6}
\]

In the equation (2.6), the second member in the right side, taking into account (1.2), is convenient to represent in the form

\[
\Phi_0 \frac{\partial \rho}{\partial t} = -\text{div}(\Phi_0 \rho \mathbf{u}) .
\]

At the same time, from (1.1), (1.2) and (2.6) we obtain the following total energy balance equation:

\[
dt E_s + \int d^3x \left( \rho \frac{\mathbf{u}^2}{2} + \rho e \right) = -\frac{\partial}{\partial t} \left( \rho \frac{\mathbf{u}^2}{2} + \rho e \right) + \int d^3x u_i \left( \rho \frac{\mathbf{u}^2}{2} + \Phi_0 \right) + p - \left( \zeta + \frac{\eta}{3} \text{div} \mathbf{u} \right) \text{div} \mathbf{u} - \eta \frac{\partial}{\partial x_i} \left( \frac{\mathbf{u}^2}{2} \right) + \text{div} \left( \frac{\partial}{\partial t} \left( \rho \mathbf{u} \right) + \frac{\partial}{\partial x_i} \left( \rho u_i u_j \right) + \Phi_0 \frac{\partial \rho}{\partial t} \right) \tag{2.7}
\]

As in [4], from (2.7), taking into account the requirement of equality to zero of the time-related derivative of the integral total energy

\[
\frac{d}{dt} E_s = 0 ,
\]

we can write the following entropy balance equation:

\[
\frac{\partial}{\partial t}(\rho s) = \frac{B}{T} , \tag{2.8}
\]

where expression \( B \) is given in (2.7).

The energy and entropy balance equations (2.7), (2.8) do not coincide with the equations given in [4] in the formula (49.3) and (49.4), respectively. However, from the balance equation (2.7) we may obtain exactly these equations (49.3), (49.4) and the given in [4] integral entropy balance equation (49.6) as well. For this purpose, in (2.7) we should use instead of the equation (2.6) its equivalent representation

\[
\frac{\partial}{\partial t}(\rho e) = (\epsilon + \frac{p}{\rho} \frac{\partial p}{\partial t} + \rho T \frac{\partial s}{\partial t}) \tag{applied in [4] without taking into account (2.1), but assuming the equality \( \Phi = \Phi_0 = \text{const} \).} \tag{2.9}
\]

It is more significant that, in addition thereto, to provide the coincidence of (2.7) with (49.3) in [4], the pressure gradient in (2.7), according to [4], should be expressed in the form of

\[
\frac{\partial p}{\partial x_i} = \rho \frac{\partial}{\partial x_i} (\epsilon + \frac{p}{\rho} - \rho T \frac{\partial s}{\partial t}) ,
\]

which follows from the thermodynamic relation (2.3) (if to add member \( dp/\rho \)). to the left and right side (2.3)). Such thermodynamic representation for the pressure gradient which enters into (2.7) (and in (1.1)), corresponds to the conventional representation of pressure, which completely describes normal stresses for the compressible and incompressible medium only in case of the zero viscosity. It does not correspond to that new representation of pressure, which appears just in case of description of the viscous compressible hydrodynamics in (1.1) due to appearance of additional normal stresses, proportional to the velocity field divergence (see [4] page 275).

This statement on incompletely adequate representation of the pressure gradient (in formulas (2.7) and (1.1)) on the basis of the application of the thermodynamic relation (2.3) is further confirmed by the obtained in next clause fundamental relation (2.10) between the rates of with-time change of the integral entropy and the integral kinetic energy. Actually, the relation (2.10) immediately follows from (2.5) and the integral entropy balance equation, written just in the form of (2.9) on the basis of (2.8). On the other hand, this relation (2.10) obviously cannot be obtained from (2.5) and the integral entropy balance equation in the form given in [4] (see (49.6) in [4]).

4. From the entropy balance equation (2.8), the integral entropy balance equation

\[
S = \int d^3x \rho s
\]
in the given below form follows (for simplicity's sake, herein as well as in (2.7) and (2.8) we do not use members, which describe flows generated by the temperature gradient):
\[ \frac{d}{dt} S = \eta \left[ d^3 x \frac{1}{T} \left( \frac{\partial u}{\partial x_i} \right)^2 \right] - \int d^3 x \frac{1}{T} \text{div} \left[ p \left( -\zeta + \frac{\eta}{3} \text{div} \mathbf{u} \right) \right] \]  

The balance equation (2.9), as already noted in the previous clause hereof, significantly differs from the integral entropy balance equation given in [4] (see formula (49.6) in [4]).

From (2.9) and (2.5), in case of constant temperature \( T = T_0 \) in (2.9), it immediately follows that the given fundamental relation is exactly satisfied:

\[ T_0 \frac{dS}{dt} = - \frac{dE}{dt} \]  

(2.10)

(it is also given in [4] page 422) between the rate of the mechanical energy change and the rate of the integral entropy growth.

The expression for the rate \( dE/dt \), given in formula (79.1) in [4], is not derived immediately from (1.1), (1.2), as it is done for the equation (2.5), but entered only on the basis of the relation (2.10), resulting from the presented in [4] integral entropy balance equation (49.6). At the same time, it is clear, that it is just the formula (2.5) for value \( dE/dt \) that provides a generalization of the formula (16.3) in [4] for the case of the compressible medium divergent flows, and it is not the formula (79.1), as stated in [4] without substantiation of derivation (79.1) on the basis of the Navier – Stokes equation (1.1) and the continuity equation (1.2).

Thus, it is evident from (2.5) and (2.9), that the negative definiteness of the integral kinetic energy dissipation rate and the corresponding positive definiteness of the integral entropy growth rate are possible in the compressible medium divergent flows only under condition of vanishing the second member in the right side (2.5) and (2.9), when the following relation is satisfied:

\[ p = (\zeta + \frac{\eta}{3}) \text{div} \mathbf{u} \]  

(2.11)

The equation (2.11) demonstrates that the rate of decrease in the divergent flows integral kinetic energy in (2.5) is determined by only viscous dissipation, as it is the case with the divergent-free flows (see (16.3) in [4]). When satisfying the equation (2.11), the positively determined value of the rate of the integral entropy growth in (2.9) is found to be significantly less than the growth rate of the integral entropy given in formula (49.6) in [4]. Actually, in (49.6) there is a member present, which is proportional to the second viscosity coefficient, and in (2.9) such a member is absent under condition (2.11). The relative decrease in the kinetic energy dissipation rate in (2.5), if to compare with the expression (79.1) in [4], corresponds to the said entropy growth rate decrease in (2.9) under condition (2.11). At the same time, at least a similarity to the minimum entropy production by I. Prigogine (see in [10]) takes place.

Thus, for the compressible medium divergent flows formulated is an additional equation (2.11), which closes this system (1.1), (1.2), based on the requirement of the positive definiteness of the integral entropy growth rate in (2.9) and the negative definiteness of the integral kinetic energy dissipation rate in (2.5). Therefore, the equation (2.11) for the compressible medium divergent flows must substitute the condition of the nondivergency, usually applied for the closure of the system (1.1), (1.2) in case of the incompressible medium approaching.

3. A new divergent solution of the NS equation

1. The condition (2.11) defines an exact mutual compensation between the normal stresses of pressure and the normal viscous stresses of the compressible divergent flow. As a result of such compensation, vanishing is the second member in the second side of equation (1.1). At the same time, the equation (1.1) exactly coincides with the n-dimensional generalization of the Burgers equation:

\[ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{\eta}{\rho} \Delta u_i \]  

(3.1)

In this case, the system (1.2), (3.1) is already closed and describes the evolution of the density and the medium inertial motion velocity field with decaying available, which should be attributed only to the action of the shearing viscous stresses, corresponding to the nonzero right side of the equation (3.1).

If in (3.1) the viscosity coefficient is equal to zero, from (3.1) we obtain the n-dimensional RH equation, for which in [13] obtained is an exact vortex solution, considered further and generalized for the case of taking into account the external friction or the effective viscosity. Let us notice that, as opposed to the given here-in and in [13] consideration of the vortex solutions, previously studied was only a vortex-free solution of the equation (3.1), which corresponds to the potential flow and which is obtained when using the modification of the nonlinear Cole – Hopf transformation [27, 28].

Suppose that in (3.1) carried out is the substitution \( u \rightarrow u + V(t) \), where \( V(t) \) is a random Gaussian delta-correlated with-time velocity field, for which the following relations take place:
\[ \{ V(t) V_j(\tau) \} = 2 \nu \delta_\theta \delta(t-\tau) \]
\[ \{ V_j(t) \} = 0 \]  
(3.2)

In (3.2) \( \delta_\theta \) – is the Kronecker symbol, \( \delta \) – is a delta function of Dirac – Heaviside, and the coefficient \( \nu \) characterizes the viscosity force effect. In general case, it may depend on time, describing the effective turbulent viscosity, but also it might coincide with the constant coefficient of the kinematic molecular viscosity, when the considered random velocity field corresponds to molecular fluctuations. Let us consider only the case, when the said coefficient in (3.2) is constant, but at the same time remains sufficiently great in value, so that we have the following inequality which allows neglecting the member in the right side (3.1):

\[ \nu \gg \frac{\eta}{\min(\rho)} \]  
(3.3)

where \( \min(\rho) \) – is an absolute minimum of the medium density value in space and time.

The substitution in (3.1) with an introduction of the random velocity field, as already mentioned in Introduction hereof, corresponds to the applied in [15] method for obtaining the stochastic NS equation not at the expense of the random force application, but by adding the random velocity to the velocity of that field, which enters into the conventional deterministic NS equation. Herein, as opposed to [15], considered is the case, when such random velocity field depends only on time (in [15] such velocity field is called a drift part of the large-scale inhomogeneous random field) and its accounting is equivalent to an introduction of the volume viscosity force, which coincides in its structure with the conventional friction force in the NS equation.

From the equation (3.1), upon averaging with due consideration of (3.2), under condition (3.3), we write the following equation:

\[ \frac{\partial \{ u \}}{\partial t} + \nu \Delta \{ u \} = -\nu \Delta \{ u \} \]  
(3.4)

where the angle brackets correspond to the operation of averaging over the random Gaussian field \( V(t) \).

When deriving the equations (3.4) from (3.1), (3.2) except inequality (3.3) used is the following relation (which is a consequence of the Furutsu – Novikov formula [29-31]):

\[ \{ V_i \frac{\partial u}{\partial t} \} = -\nu \Delta \{ u \} \]  
(3.5)

The equation (3.4), also without condition (3.3), may correspond to the equation (3.1) as well, if together with (3.5) the following equalities hold

\[ \{ u \} = u \]
\[ \{ u_j \frac{\partial u}{\partial x_j} \} = u_j \frac{\partial u}{\partial x_j} \]  
(see [31]) and if in (3.1) the substitution

\[ \eta \rho \to \min(\eta \rho) = \nu \]

is carried out before. Such disconnecting of the correlations is possible in case of an exact disintegration of the time scales related to the large-scale inertial motions and the motions with the typical scale of the viscous dissipation [23].

2. Instead of approximate solving (see [32]) the problem of closure when considering the equation (3.4) in order to find the average velocity field \( \{ u \} \), let us use the initial equation, from which evidently explicit is just the equation (3.4). This initial equation has the form of the RH n-dimensional equation [10, 13, 22]:

\[ \frac{\partial u_j}{\partial t} + (u_j + V_j(t)) \frac{\partial u_j}{\partial x_j} = 0 \]  
(3.6)

If to apply the curl operation to the left side of the equation (1.3.6), we obtain just the Helmholtz equation (1.3), where only the member \( \nu \Delta \omega \) should be deleted and where the substitution \( u \to u - \nabla a \) should be carried out.

The equation (3.6), as shown in [14], has the following exact solution for the case of an arbitrary dimensionality of the space \( (n = 1, 2, 3, \text{etc.}) \):

\[ u_j(x,t) = \int d^3 r_{0} u_{j0} (r_{0}) \frac{1}{\det \hat{A}} \]  
(3.7)

where

\[ \hat{A} = A_{nm} = \delta_{nm} + \frac{\partial u_{nm}}{\partial x_m} \]

\( \det \hat{A} \) – are determinants of the matrix \( \hat{A} \), and \( u_{j0} (x) \) – is an arbitrary smooth initial velocity field. The solution (3.7) satisfies the equation (3.6) only at times for which with any spatial coordinate values the value of the matrix \( \hat{A} \) determinant is positive, i.e.\( \det \hat{A} > 0 \). Therefore everywhere we shall take it into account, and, respectively, the modulus sign when writing \( \det \hat{A} \), will not be used, unless otherwise specified.

The solution (3.7) only in case of the initial velocity field potentiality is a potential vortex-free one and corresponds to the zero vortex field for all subsequent time moments. On the contrary, it is the vortex one and determines the vortex field evolution in case of a nonzero initial vortex field (see the next paragraph herein). Further, let us discuss the vortex solutions only (3.7). Let us note, however, that in [24] obtained is just the potential solution of the 2D RH equation (3.6) (at \( B = 0 \)).
in (3.6) in the Lagrangian representation, which exactly follows from (3.7) at \( n = 2 \), as already mentioned in Introduction hereof in connection with the possibility of description of the Sivashinsky equation (B.2) solution, using the potential solution (3.7). For the 1D case with \( n = 1 \) we have

\[
\det \dot{A} = 1 + t \frac{du_{01}}{dx_1}
\]

in (3.7), and the solution (3.7) exactly coincides with the solutions given in [33, 34]. The solution (3.7) is found if applied has been an integral representation for the implicit solution of the equation (3.6) in the form of

\[
u_1(x,t) = u_{01}(x - B(t) - tu(x,t))
\]

with the use of the delta-function and the following identities [13]:

\[
\delta(\xi - x + B(t) + tu(\xi,t)) = \delta(\xi - x + B(t) + tu_0(\xi)) \det \dot{A};
\]

\[
\frac{\partial \delta(\xi - x + B(t) + tu(\xi))}{\partial x_i} \equiv \frac{\partial \delta(\xi - x + B(t) + tu_0(\xi))}{\partial x_i};
\]

\[
\delta(\xi_1 - x + B(t) + tu(\xi_1)) = \delta(\xi_1 - x + B(t) + tu_0(\xi_1)) \equiv \frac{\partial \delta(\xi_1 - x)}{\partial x_i} \det \dot{A}
\]

where \( \dot{A} \) is the matrix inverse to the matrix \( A \).

After averaging over the random field \( B(t) \) (with Gaussian density of probabilities distribution) from (3.7) we can obtain the following exact solution of equation (3.4) (and the equation (1.1) under the condition (2.11)):

\[
\{u_1\} = \left\{ d^2\xi u_{01}(\xi) \right\} \det \dot{A} \frac{1}{(2\pi \nu t)^{n/2}} \cdot \exp \left[ -\frac{f(x - \xi - tu_{01}(\xi))^2}{4\nu t} \right]
\]

The averaged solution (3.10), as opposed to (3.7), is already arbitrarily smooth in any unbounded span of time change, and not only just under the condition of positivity of the matrix \( \dot{A} \) determinant.

3. Without taking into account the viscosity forces, when in (3.7) \( B(t) = 0 \), the smooth solution (3.7), as already noted, is determined only under the condition \( \det \dot{A} > 0 \) [13]. It corresponds to the bounded interval of time where the value of the bounded minimum time of the existence of the solution \( t_0 \) is computed from the solution of the following algebraic equation of order \( n \) (and further minimization of the obtained expression, which depends on spatial coordinates, by these coordinates):

\[
\det \dot{A}(t) = 1 + t \frac{du_{01}(x)}{dx_i} = 0, n = 1
\]

\[
\det \dot{A}(t) = 1 + t \text{div} u_0 + t^2 \det \dot{U}_{012} = 0, n = 2
\]

\[
\det \dot{A}(t) = 1 + t \text{div} u_0 + t^2 (\det \dot{U}_{012} + \det \dot{U}_{013} + \det \dot{U}_{023}) + t^3 \det \dot{U}_0 = 0, n = 3
\]

where \( \det \dot{U}_0 \) is the determinant of the 3D matrix \( U_{000} = \partial u_{00}/\partial x_0 \) and

\[
\det \dot{U}_{012} = \frac{\partial^2 u_{01}}{\partial x_1 \partial x_2} - \frac{\partial^2 u_{01}}{\partial x_1 \partial x_2}, \quad \frac{\partial^2 u_{01}}{\partial x_2 \partial x_1}, \quad \frac{\partial^2 u_{01}}{\partial x_1 \partial x_2} 
\]

is the determinant of the similar matrix in the 2D case for variables \( (x_1, x_j) \). At the same time \( \det \dot{U}_{012} \) are the determinants of the matrices in the 1D case (for the variables \( (x_1, x_j) \) and \( (x_p, x_j) \), respectively.

Let us notice, that in the 2D case (3.11) exactly coincides with the collapse condition, obtained in [24] in connection with the problem of front flame propagation, studied on the basis of the Sivashinsky equation (B.2).

For an exact coincidence it is necessary to substitute

\[
t(t) = \frac{U_1(\exp(\gamma_\psi t) - 1)}{\gamma_\psi}
\]

in (3.11).

In the 1D case at \( n = 1 \) from (3.11) we have the minimum time for singularity appearing

\[
t_0 = \frac{1}{\max \left( \frac{du_{01}(x_1)}{dx_1} \right)} > 0.
\]

In particular, at the initial distribution

\[
u_0(x_1) = a \exp(-\frac{x_1^2}{L_1^2}), a > 0
\]

we obtain

\[
t_0 = \frac{L_1}{a\sqrt{2}}
\]

for the value

\[
x_1 = x_{1\text{max}} = \frac{L_1}{\sqrt{2}}.
\]

At the same time, the singularity realization itself may take place only with positive values of the coordinate \( x_{1j} > 0 \), when the equation (3.11) has a positive solution for the time value.

It means that the singularity (collapse) of the smooth solution never occurs in case when the initial velocity field is other than zero only at negative values of the spatial coordinate \( x_{1j} < 0 \). The value of the wave breaking time \( t_0 \) is computed similarly at \( n > 1 \), too. Thus, for (3.11) in the 2D case (with the initial velocity field under the zero divergence) for the initial function of the flow in the form

\[
\psi_0(x_1, x_2) = a_2 \sqrt{L_1 L_2} \exp(-\frac{x_1^2}{L_1^2} - \frac{x_2^2}{L_2^2}), a > 0,
\]

the minimum value of the time of the existence of the smooth solution is equal to

\[
t_0 = \frac{a_2 \sqrt{L_1 L_2}}{2a}.
\]
The indicated minimum time of the existence of the smooth solution in the treated example is realized for the spatial variable values corresponding to ellipse points
\[
\frac{x^2}{L_1^2} + \frac{x^2}{L_2^2} = 1.
\]

According to (3.11), the necessary condition of the singularity realization is the condition of the existence of the real positive solution of the quadratic (at \(n = 2\)) or cubic (at \(n = 3\)) equation in relation to time variable \(t\). For example, in the case of the 2D flow with the zero initial divergence of velocity field \(\text{div} u_0 = 0\) the necessary and sufficient condition for the singularity (collapse) solution realization in finite time according to (3.11) is the following:
\[
\text{det} U_{012} < 0 \quad (3.12)
\]

For the considered above example from (3.12), the inequality
\[
\frac{x^2}{L_1^2} + \frac{x^2}{L_2^2} > \frac{1}{2},
\]
follows, in case when it is satisfied for \(n = 2\) there is a real positive solution of the quadratic equation in (3.11), for which found is the given above minimum value of the collapse time
\[
t_0 = \frac{e^{\sqrt{L_1 L_2}}}{2a} > 0.
\]

On the contrary, if the initial velocity field is defined in the form of the finite function with a carrier in the domain
\[
\frac{x^2}{L_1^2} + \frac{x^2}{L_2^2} \leq \frac{1}{2},
\]
the inequality (3.12) breaks down, and appearance of the singularity in a finite time becomes impossible, and the solution remains smooth for an unbounded time even without taking into account the viscosity effect.

The condition of the existence of the real positive solution of the equation (3.11) (see, for example, (3.12)) is necessary and sufficient for the realization of singularity (collapse) of the solution as opposed to the sufficient, but not necessary integral criterion, proposed in [22] (see formula (38) in [22]) and written in the following form:
\[
\left(\frac{dI}{dt}\right)_{t=0} = -\int d^3x \text{div} u_0 \det^2 \hat{U}_0 > 0; \quad I = \int d^3x \det^2 \hat{U} \quad (3.13)
\]

Actually, according to this criterion, proposed in [22], the solution collapse is impossible for the case when the initial velocity field is divergent-free, i.e. \(\text{div} u_0 = 0\). At the same time, however, violation of the criterion (3.13) does not exclude a possibility of the solution collapse by virtue of the fact that criterion (3.13) does not determine the necessary condition for the collapse realization. Indeed, in the considered above example (when determining the minimum time of the collapse realization
\[
t_0 = \frac{e^{\sqrt{L_1 L_2}}}{2a}
\]
for the 2D compressible flow, the initial condition corresponds just to the initial velocity field with \(\text{div} u_0 = 0\) in (3.11) at \(n = 2\).

4. On the basis of the solution (3.7) it is possible, with the application of (3.8) and the Lagrangian variable \(a\) (where
\[
\frac{r}{x} = \frac{r}{x}(t, a) = \frac{r}{x} + \frac{r}{tu_0(a)}
\]
for the 2D compressible flow, the initial condition corresponds just to the initial velocity field with \(\text{div} u_0 = 0\) in (3.11) at \(n = 2\).

4. An exact solution of the EH and Riemann-Hopf (RH) equations

1. The velocity field (3.7) is in conformity with the exact solution for the vortex field having the form [13] in the 2D and 3D cases as follows:
\[
\omega(x, t) = \int d^2\xi \omega_0(\xi) \delta(\xi - \frac{r}{x} + B(t) + tu_0(\xi)) \quad (4.1)
\]

2. On the basis of the solution (3.7) it is possible, with the application of (3.8) and the Lagrangian variable \(a\) (where
\[
\frac{r}{x} = \frac{r}{x}(t, a) = \frac{r}{x} + \frac{r}{tu_0(a)}
\]
and
\[
\frac{r}{x} = \frac{r}{x}(t, a) = \frac{r}{x} + \frac{r}{tu_0(a)}
\]
for the 2D compressible flow, the initial condition corresponds just to the initial velocity field with \(\text{div} u_0 = 0\) in (3.11) at \(n = 2\).

4. The solution (3.15) coincides with the formula (14) in [22] and describes a catastrophic process of the collapse of a simple wave in a finite time \(t_o\) the estimation of which is given herein above on the basis of the equation (3.11) solution when applying the Euler variables.
(4.2), (3.7) corresponds to the following exact expression for helicity:

$$H = \omega_\lambda u_\lambda = \left( \int d^2 z' u_{\lambda z'} \frac{\partial}{\partial z'} \left( \frac{r^2}{2} \right) \right) \cdot \delta(\xi - x + B(t) + tu_\lambda(\xi))$$

The representations for the 3D vortex (4.2) and velocity (3.7) fields exactly satisfy the 3D Helmholtz equation (1.3), where, as mentioned above, it is necessary to remove the last member in the right side (1.3) and enter the random velocity field \( \hat{V}(t) \) for describing the viscosity forces. It may be verified by the direct substitution of the solution (4.2) and (3.7) into (1.3). For this purpose, when considering the nonlinear members, it is necessary to use the equality

$$\delta(\xi - x + B(t) + tu_\lambda(\xi)) = \delta(\xi - x + B(t) + tu_\lambda(\xi)) = \delta(\xi - x + B(t) + tu_\lambda(\xi)) = \delta(\xi - x + B(t) + tu_\lambda(\xi)),$$

and the following identities: (3.8), (3.9) and

$$\omega_{\lambda m}(\xi) = A_{\lambda m}^\dagger(\omega_{\lambda z'} + t\omega_{\lambda z')}) \frac{\partial}{\partial z'}.$$

After averaging in (4.1) and (4.3) over the random Gaussian field \( B(t) \) taking into account (3.2), we obtain expressions where under integral sign in (4.1)–(4.3) the delta-function is substituted by an exponent with the normalizing multiplier as it is the case with (3.10). Only after the said averaging provided is the existence of not only the averaged vortex and helicity field values, but also the corresponding highest derivatives and higher moments in any time span. In particular, it takes place when for the entrophy value (the integral of the vorticity square over the entire space) and higher moments of the vortex field, for which the explicit analytical expressions are obtained in an elementary way in the next paragraph without solving any closure problem.

2. In the Lagrangian variables, the expressions, which correspond to the Eulerian vortex (4.1), (4.2) and helicity (4.3) fields, may be presented in the following form (in case when \( B(t) = 0 \):

$$\omega_{\lambda}(\hat{u}, t) = \frac{\omega_{\lambda m}(\hat{u}, t)}{\det \hat{A}(\hat{u}, t)} \quad (4.4)$$

$$\omega_{\lambda}(\hat{u}, t) = \frac{\omega_{\lambda m}(\hat{u}, t) + t\omega_{\lambda m}(\hat{u}, t) \frac{\partial \omega_{\lambda m}(\hat{u}, t)}{\partial \omega_{\lambda m}}}{\det \hat{A}(\hat{u}, t)} \quad (4.5)$$

$$H(\hat{u}, t) = \frac{\omega_{\lambda m}(\hat{u}, t) + t\omega_{\lambda m}(\hat{u}, t) \frac{\partial \omega_{\lambda m}(\hat{u}, t)}{\partial \omega_{\lambda m}}}{\det \hat{A}(\hat{u}, t)} \quad (4.6)$$

where

$$\det \hat{A} = \det (\delta_{im} + t\omega_{\lambda m}(\hat{u}, t))$$

From (4.4) – (4.6) it follows that for the Lagrangian fluid particle the vortex value singularity in the 2D and 3D cases, as well as the helicity singularity, take place at \( t \to t_0 \) when \( \det \tilde{A}(\hat{u}, t) \to 0 \) and the finite time value of the existence of the corresponding smooth fields is determined by the Lagrangian analog of the condition (3.11). At the same time, it follows from (4.5) u (4.6) that the 3D effect of vortex filaments stretching leads to not only an explosive, but a weaker power-raise-related increase in the vortex and helicity values as opposed to the catastrophic process of the vortex wave collapse in a finite time \( t_0 \) just for the divergent flow of the compressible medium.

Let us notice that in [23] (see formula (23) in [23]) obtained is the representation of the EH equation solution (1.3) (at zero viscosity) in the following form:

$$\omega_{\lambda} = \frac{\omega_{\lambda m}(\hat{u}, t) \delta R(\hat{u}, t)}{\partial \omega_{\lambda m}} \quad (4.7)$$

In (4.7) \( J = \det (\omega_{\lambda} / \partial \omega_{\lambda m}) \) is the Jacobian transformation to the Lagrangian variables \( \hat{u} \). At the same time, \( \omega_{\lambda m}(\hat{u}) \) is a new Cauchy invariant (coinciding with the initial vorticity) which is characterized by the zero divergence

$$\frac{\partial \omega_{\lambda m}(\hat{u})}{\partial \omega_{\lambda m}} = 0 \quad \text{and} \quad x_i = R(\hat{u}, t) \text{ and} \quad \frac{dR}{dt} = V_n(R, t),$$

where \( V_n \) is the velocity component being normal to the vorticity vector so that for the component we have \( \text{div} V_n \neq 0 \).

As opposed to (4.1) and (4.2), the expression (4.7) does not give an explicit representation for the EH equation solution, since in (4.7) no definite relation for the Jacobian \( J \) and the vector \( R \) is provided. At the same time, there exists a structural correspondence between (4.7) and (4.1), (4.2), and for case of the Lagrangian fluid particles motion due to inertia, at least, for the Jacobian in (4.7) may be used the explicit representation \( J = \det \hat{A} \), where

$$\det \hat{A} \text{ is determined from (3.11).}$$

5. Equation of enstrophy balance and due consideration of external friction

1. Disregarding the viscosity force (i.e. without averaging in (4.1) and (4.2) over the random field \( B(t) \) from (4.1), (4.2) it follows that the enstrophy values conforming with them in the 2D and 3D cases allow for an exact closed description and take on the form [14]:

$$\Omega_3 = \int d^2 x \omega_{30}(x, t) = \int d^2 \xi \omega_{30}(\xi) / \det \hat{A} \quad (5.1)$$
\[ \Omega_3 = \int d^3 \omega \left( \mathbf{A}, t \right) \]
\[ = \int d^3 \xi \left( \omega_{\mu} + t \omega_{\nu} \right) \frac{\partial \omega_{\mu}}{\partial \xi_{\nu}} / \det \mathbf{A} \]  
(5.2)

To obtain the expressions indicated in (5.1) and (5.2) above, there has been no necessity to solve the closure problem which usually exists in the theory of turbulence. In our case, we succeed in avoiding this problem due to a comparatively simple representation of the exact solution of the Helmholtz nonlinear equation utilized for the description of the vortex flow of an ideal compressible medium.

The expressions (5.1) and (5.2) tend to approach infinity in a finite time \( t_\gamma \), determined from the solution of the algebraic equation (3.11) and subsequent minimization of this solution with the use of the space coordinates.

Using the exact solution of the EH equation in the form of (4.1) and (4.2), we can obtain a closed description of the with-time evolution not only for enstrophy, as it was the case with (5.1) and (5.2), but also for any other higher moments of a vortex field.

For example, in the 2D case, from (4.1), taking into account (3.8), we will obtain:

\[ \Omega_{2i} = \int d^2 \omega \omega_i = \int d^2 \xi \omega_i \frac{\omega_i}{\det \mathbf{A}} \]
\[ = \int d^2 \xi \omega_{2i} \frac{\omega_{2i}}{\det \mathbf{A}} \]
\[ m = 1, 2, 3, ... \]

In Introduction hereof, presented has been the estimation (B.3) for a relation of different moments in the 3D vortex field that was obtained on the basis of the expressions of the similar type from (4.2) and (3.8).

To obtain (B.3), utilized is also the estimation \( \det \mathbf{A} \equiv O(t_o - t) \), which is realized in the limit \( t \to t_o \). The quantity of the collapse minimum time \( t_o \) is computed in this case on the basis of (3.11).

2. Let’s take into account the external friction now. For this purpose, in the equation (1.3) we should replace \( i \omega \omega_i \to i \omega \omega_i \). In doing so, from the expressions (3.7),(4.1) and (4.2) we can obtain an exact solution, which is found from (3.7), (4.1) and (4.2) by carrying-out the substitution of the time variable \( t \) for a new variable

\[ \tau = \frac{1}{\mu} \exp \left( \frac{-t}{\mu} \right) \]  
[13].

Changes of the new time variable \( \tau \) take place now within the finite range from \( \tau = 0 \) (for \( t = 0 \)) to \( \tau = 1 / \mu \) (at \( t \to \infty \)). It leads to the fact that in case, when under the given initial conditions the following inequality

\[ \mu > \frac{1}{t_o} \]  
(5.3)

holds, then the value \( \det \mathbf{A} > 0 \) in the denominator (5.1) and (5.2) cannot go to zero at any moment of time, since the necessary and sufficient condition for realization of the singularity is no longer met for any instant of time (3.11), where the substitution \( t \to \tau(t) \) should be made.

Subject to the condition (5.3), the solution of the 3D EH equation is smooth in an unbounded span of time \( t \). The corresponding analytical divergent vortex solution of the 3D NS equation (where the relation (2.11) for pressure should be taken into account and where carried out should be the substitution of the first term in the right side (1.1)

\[ \frac{\eta}{\rho} \Delta u_i \to -\mu u_i; \mu = \text{const} \]

also remains smooth at any \( t \geq 0 \) subject to the condition (5.3). We should also notice that when the values of parameters are formally coinciding \( \mu = \gamma_0 \) (see the Sivashinsky equation (B.2)), the equality \( \tau(t) = b(t) \) takes place subject to the condition that the singularity has been realized (3.11) with \( n = 2 \) and in accordance with the solution of the Sivashinsky equation in [24].

3. It should be noted that for flows of the nonviscous (ideal) incompressible fluid with the zero divergence of the velocity field an explosive growth of enstrophy is characteristic of the 3D flows only, and enstrophy for the 2D flows should be viewed as an invariant. A different situation arises with the divergent flows of the compressible medium under consideration herein.

Actually, for the divergent flows of the nonviscous medium, the equations of enstrophy balance in the 2D and 3D cases, which follow from the EH equation (1.3) (at \( v = 0 \) in (1.3)), hold true as given below:

\[ \frac{d \Omega_3}{dt} = -\int d^3 \xi \omega^2 \mu \]  
(5.4)

\[ \frac{d \Omega_2}{dt} = 2 \int d^2 \xi \omega^2 \omega_i \frac{\partial u_i}{\partial \xi_k} - \int d^2 \xi \omega_i \mu \]  
(5.4)

It can be seen from (5.4) that in the 3D case the evolution of enstrophy \( \Omega_3 \) with time is determined not only by the effect of stretching of vortex filaments (by the first term to the right), but also by the second term as well, determined by the finiteness of the value of the velocity field divergence. As to the 2D flow, the with-time evolution of enstrophy \( \Omega_2 \) occurs only, if the flow velocity field divergence is other than zero.
In order to solve (3.7), the value of the divergence of the velocity field is of the form [13]:

\[
\frac{\partial u_k}{\partial x_i} = (5.5)
\]

\[
= \int d^2 \xi (\frac{\partial}{\partial t} \delta (\xi - \hat{x} + B(t) + u_\xi (\xi))).
\]

An integral over the entire unbounded space from the right side (5.5) is equal to zero by virtue of the fact that the identities (3.9) hold and subject to the condition of becoming zero at infinity for the initial velocity field. As a result, for the solution in question, the equality \( \int d^2 \xi u^i \delta (\xi - \hat{x}) = 0 \) takes place, which is responsible for the fulfillment of the law of conservation of full mass of fluid and an exact mutual integral compensation of intensities of the distributed sources and drains.

For the 3D case in (5.4), based on (3.7), (3.8), (3.9), (4.2) and (5.5), we can formulate exact expressions for the first term and the second one in the right side (5.4), which describe the contribution to a growth rate of enstrophy as against the process of a wave collapse in the divergent flow. Its expression under integral sign is proportional to the value \( O (1/\det \hat{A}) \). It is evident that it makes a relatively lesser contribution to the rate of an explosive growth of enstrophy as against the second term in (5.6), the expression of which under the integral sign is proportional to the value \( O (1/\det \hat{A}) \) and which exists only for the case with the divergent flows with a nonzero divergence of the velocity field.

Since, as noted above, taking into account the viscosity (in particular, under due consideration of the external friction, when the condition (5.3) is met) leads to a regularization even of divergent solutions of the NS equation, it might be expected that it is also possible for solutions with the zero-divergence. As for them, a similar regularization, probably, would be possible because of a comparatively weaker (in the above mentioned sense) effect of stretching of the vortex lines as against the process of a wave collapse in the divergent flow. This issue will be also treated in the next paragraph herein.

4. From (2.11) and (5.5), upon averaging the Gaussian probability distribution for random field \( B_\xi (t) \) we obtain with due account of (3.2) the following representation for pressure

\[
\langle p \rangle = \frac{\rho_0}{3}.
\]

\[
\cdot \int d^2 \xi (\frac{\partial}{\partial t} \delta (\xi - \hat{x} + u_\xi (\xi))) \cdot \frac{1}{(2\pi \nu)^{\frac{1}{2}}} \exp \left[ -\frac{(\xi - \hat{x} + u_\xi (\xi))^2}{4\nu t} \right].
\]

An expression for the density conforming with the equations (1.2) and (3.6) takes the form [12]:

\[
\rho = \int d^2 \xi \rho_0 (\xi) \frac{1}{(2\pi \nu)^{\frac{1}{2}}} \exp \left[ -\frac{(\xi - \hat{x} + u_\xi (\xi))^2}{4\nu t} \right].
\]

6. On the existence of divergent-free solutions of the NS equation

The found smooth divergent solution of the NS equation (1.1) in the form (3.10), (3.7), as stated above, by virtue of the fact that there is its analytical representation for arbitrary smooth initial conditions is just the proof that the solution of the NS equation really is existent and unique. It is of importance that in order to model the viscosity effect, it is precisely the random Gaussian delta-correlated with-time velocity field that has been introduced for that purpose, that leads to an effective viscosity force, which is structurally exactly in conformance with the viscosity force in the NS equation, as distinct from the derivatives treated in [16, 17], which are higher than the Laplacian, in computation of the viscosity force in the NS equation.

Let us perform a comparative analysis of integral values for the divergent
and divergent-free flows which characterize the evolution of the integral kinetic energy with time, the finiteness of which in [8] is the major criterion supporting the evidence of the existence of a solution of the NS equation.

For this purpose, let us consider the equation of the balance of the integral kinetic energy (2.5) on the condition (2.11) that has replaced the assumption of the zero divergence of the velocity field and that provides the closure of the system of the equations (1.1), (1.2) for the case of the divergent flows of the compressible medium. In doing so, from (2.5) we can write an expression as given below

$$\frac{dE}{dt} = -\eta F;$$

$$F = \int d^3x \left( \frac{\partial u}{\partial t} \right)^2$$  \hspace{1cm} (6.1)

The equation of the balance (6.1) in its form is exactly coincides with the equation of the balance of the integral kinetic energy for the divergent-free flow of incompressible fluid, as indicated in [4] (please, see formula (16.3)). Unlike the formula (16.3) from [4], there is in the formula (6.1) just the divergent velocity field, which has the nonzero divergence and which describes the motion of the compressible medium. In this case, for the divergent flow, the functional F in (6.1) is connected with enstrophy

$$\Omega_3 = \int d^3x (rotu)^2$$

by the following relationship:

$$F = \Omega_3 + D_3;$$

$$D_3 = \int d^3x (divu)^2$$  \hspace{1cm} (6.2)

As this takes place, for the divergent solution of the NS equation, the right side (6.2), with other conditions being equal, obviously exceeds the value of the functional $F = F_o = \Omega_3$ for the solution with the zero divergence of the velocity field.

For the obtained exact solution, the expression for enstrophy $\Omega_3$ in the right side (6.2) takes the form (5.2), and for the integral of the square of the divergence from (5.5) and (3.8) we arrive at an expression as given below:

$$D_3 = \int d^3x \left( \frac{\partial det A}{\partial t} \right)^2 / det A$$  \hspace{1cm} (6.3)

From comparison of (6.3) and (5.2) it follows that in the vicinity if the singularity of the solution at $t \to t_0$ (see (3.11)) the values of the first and the second terms in the right side (6.2) are of the same order of magnitude.

Besides, for functional $F$ in (6.1) let us make upper estimate with the use of the Koshi-Bunyakovsky inequality as follows:

$$F^2 = \left[ \int d^3x (rotu)^2 \right]^2 \leq \int d^3x \left[ \int d^3x (rotu)^2 \right] = \int d^3x \left[ (rotrotu)^2 + (graddivu)^2 \right]$$  \hspace{1cm} (6.4)

According to (6.2) – (6.4), the divergent flows, with other conditions being equal, demonstrate obviously a higher value of functional $F$ as against the divergent-free flows, for which the ad-dend in the square brackets in the right side is absent (6.4).

From the preceding, it is clear that a conclusion must be made that the smooth divergent-free solutions of the NS equation are existent because of the fact of the proven existence of the divergent smooth solutions of the NS equation on an unbounded time interval with due consideration of the effective viscosity or external friction subject to the condition (5.3).

Conclusions

Therefore, in (3.10), (5.7) and (5.9) represented is the analytical solution of the NS equation (1.1) and the equation of continuity (1.2) for the divergent flows which have a non-zero divergence of the velocity field (5.5). From (3.10), boundedness of the energy integral in the 3D case

$$E_\infty = \frac{1}{2} \int d^3x \left( \frac{\partial det A}{\partial t} \right)^2 / det A$$

obviously follows, too, that meets the main requirement, when formulating the problem of the existence of a solution of the NS equation [8]. Besides, satisfied is the requirement specified in [8] for unbounded smoothness of solutions for any time intervals, when describing velocity and pressure fields.

We should notice that for the found solution of the equation (3.7) even without averaging (for example, in the case $\tilde{B}(t) = 0$) the energy integral

$$E_\infty = \frac{1}{2} \int d^3x \left( \frac{\partial det A}{\partial t} \right)^2 / det A$$

remains finite for any finite moment of time, while at the limit $t \to \infty$ energy also tends to approach infinity in a power raise manner as $O(t^\alpha)$ (refer to (3.11)). In this case, the solution (3.7), (4.2) can be extended by any finite time $t_\infty \geq t_1$ in the Sobolev space $H^p(R^3)$. It means that for the case with the ideal (nonviscous) medium the flow energy meets the requirement specified in [8] to prove the existence of the solution of the NS equation.

At the same time, however, the integral of enstrophy in (5.2) demonstrates an explosive unbounded growth (in a finite time $t_\infty$ determined from (3.11)), when

$$\Omega_3 \equiv O \left( \frac{1}{t_\infty - t} \right)$$

in case with the unique positive real root of the equation (3.11). By this it is meant that the obtained exact solu-
tion of the EH equation in the form (3.7) and (4.2) cannot be further extended in the Sobolev space $H^q(R^3)$ by a time $t \geq t_0$, i.e. even at $q = 1$ when defining the norm (B.1). Only considering the viscosity makes possible to avoid the said singular behavior of enstrophy and higher moments of a vortex field which is to say that there is a possibility of extending the solutions of the EH and NS equations for any $t \geq t_0$ in Sobolev space $H^q(R^3)$ even at any $q \geq 1$.

In [7], under formulating the problem of the existence of a solution of the 3D NS equation, it has been offered to impose restrictions to considering only cases of solutions with the zero divergence of the velocity field. Therewith in [7] noted is importance of treatment of those particular 3D flows, for which the effect of stretching of vortex filaments in a finite time may lead to a limitation on the existence of solutions of the NS equation in the small (im Kleinen) only.

The reached conclusion that there are smooth divergent solutions of the 3D NS equation at the expense of considering even small viscosity bears witness to an admissibility of a positive solution of the problem of the existence of smooth divergent-free solutions on an unbounded interval of time as well. Really, as it has been established in (5.6), the effect of stretching of vortex filaments makes a considerably lesser contribution to the realization of the singularity of the solution than the effect of collapse of a vortex wave in the divergent compressible flow. This possibility is suggested by the inequality (6.4) as well as the equality (6.2), which determine the value of rate of change in the integral kinetic energy.

It should be also stressed that the exact solution of the EH and RH equations found in [13] gives a closed description of the with-time evolution for enstrophy and any higher moments of the vortex, velocity, pressure and density fields. The possibility of a closed statistic description for modes of turbulence without pressure (modeled with the linear 3D RH equation (3.6)) was mentioned first in 1991 in [13]. We should note that the paper by A.M. Polyakov [35] published in 1995 develops for the 3D RH equation with a random white-noise type force (Delta-correlated with time) a general theoretical field approach to the theory of turbulence and establishes a relationship between the breakdown of the Galilean invariance and intermittency. With this, however, only for 1D case found was a concrete solution of the problem of the closure in the form (refer to formula (41) in [35]) of an explicit expression for distribution of probability $w(x, y)$ of the value of velocity difference $u$ at points being at a distance $y$ from each other.

This paper offers a fresh approach capable of considering also exactly pressure on the basis of which an analytical solution of the full NS equation for a flow of the viscous compressible fluid has been found. In doing so, actually, the main problem of the theory of turbulence has been resolved [1], when the precise representation for a joint characteristic functional of the velocity and density fields (the pressure field in this case is uniquely defined from (2.11)) is provided. In the past, it was generally accepted that the main problem of the theory of turbulence in case with the compressible fluid could not be solved, and in [1] in this connection it was stated: "Unfortunately, this general problem is too difficult, and at present an approach to finding a full solution thereof cannot be seen." (please, refer to [1] P.177).

Utilizing the proposed exact solutions of the EH, RH and NS equations, modeling of turbulent modes can be provided, including modeling performed on the basis of the method of randomization of integrated problems of hydrodynamics offered by E.A. Novikov [36] and developed in [10]. For this purpose, we must introduce a probability measure on ensemble of realization of the initial conditions, which should be treated in this case as random functions.

The possibility established herein that a solution of the NS equation is existent is based on the fresh nonstationary analytical solution of the said equation that was said in the past to be unreachable [9, 13]. Following this way, it has been discovered that for the existence of the solution in an unbounded span of time it is just the viscosity that is required to be taken into account for this purpose. On the other hand, the issue on stability of the obtained solution should be treated on the basis of the available results which bear witness to a possibility of some destabilizing effects of the viscosity which may lead to a dissipative instability [37–40].

By this means, detected has been the mechanism of the appearance of the limitation in predictability and forecasting of a wind velocity field and impurity fields (affecting human health under the variable climatic factors of the environment) that can be realized, for example, with the numerical solution of the NS equation (for the divergent flows of compressible medium).

This mechanism is connected the truncation $\lambda$, typical for the high wave
numbers or small scales that corresponds to entering of the external friction with the coefficient

\[ \mu = \frac{\nu}{\lambda^2}. \]

In this case, from the condition (5.3) it follows that only with selection of a sufficiently small scale of the truncation

\[ \lambda < \lambda_0 = \sqrt{\nu t_0^2} \]

(where the value \( t_0 \)) is computed in (3.11)) it is possible to avoid the explosive loss of the smoothness of the solution and the loss of predictability in a finite time \( t_0 \) even at the exactly defined initial data of the numerical forecasting based on the solution of the NS equation for compressible medium.

At the same time, actually the initial data are defined not accurately, but with a certain inevitable error. This may lead to breaking down the condition \( \lambda < \lambda_0 \) and loss of predictability in a finite time. In this regard, fascinating and intriguing is the relationship, as noted in [2], between the nonrandom randomness of the Sinai billiards, the problem of predictability based on the NS equation solution and another problem of relative longevity of biological species closely related by their initial physical and physiological parameters (raven and crow etc.) that has been known since the Sir Francis Bacon’s time.

**Conflict of interest**

None declared.

**Author contributions**

The authors read the ICMJE criteria for authorship and approved the final manuscript.

**Acknowledgment**

We would like to give due recognition to E.A. Novikov for his kind interest herein and highly appreciated suggestions here-to, to E.A. Kuznetsov for his attentive attitude, useful discussions and information about the relevant reference papers [15, 22–24] and to Mr.N.A. Ingomarov and V.V. Lebedev for their constructive criticism.

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The ECG in a new capacity: the most informative source of data on aerobic and anaerobic processes in the cardiac muscle fiber tissue cells

Published with the support of RFBR (grant No. 18-29-02073)
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Abstract
The article is devoted to a novel noninvasive measurement of parameters of metabolic processes in the cardiac muscle fiber cells upon an original ECG processing. Theoretically substantiated is an original method of the ECG cardiac cycle phase analysis, which allows measuring the concentration of oxygen, lactate and phosphocreatine in arbitrary units in the cardiac muscle fiber cells in each cardiac cycle. The results of practical applications of the above cardiometric method for assessing the conditioning in a high-performance swimming athlete are discussed herein. Recommendations for a widespread use of the method in practice are discussed herein, too.

Keywords
Cardiometry, Cardiometric method, Cardiac muscle fiber tissue cell metabolism, Lactate, Phosphocreatine, Oxygen, Cardiac cycle phase analysis, ECG

Imprint

Introduction
A noninvasive measurement of the metabolic characteristics in cardiac heart muscle fiber tissue cells has always been treated as a challenging research line for experts. First of all, it is due to the fact that the lactic acid (lactate) amount indicator is highly informative and shows the degree of the cardiac fatigue. However, at present, the only achievement is measuring the blood lactate concentration. Searching for a correlation between the lactate concentration in blood or in the cardiac muscle fiber cells and an ECG curve has resulted in the development of a novel method for deriving lactate amount parameters from the ECG upon specific processing of the latter. The concept of this method has been designed and applied by Russian researcher S. Dushanin [1]. It is based on processing of a standard three-lead ECG curve, when each lead, according to S. Dushanin, delivers unique data on the oxygen, lactate and phosphocreatine levels. Our studies have shown that the novel cardiometric method of ECG recording and processing, developed by us, is capable of delivering of the above mentioned metabolic characteristics [2-6] in a simple-to-record way with a high degree of accuracy. The cardiometric method has been thoroughly explored, and it has been effectively using in an integrated diagnostics of the cardiovascular system performance.

Aims
The aim of the present study is to describe and discuss applications of the noninvasive cardiometric method, which provides measuring of the metabolic parameters derived from the ECG upon its specific processing.

Materials and methods
In a cardiac cycle, the atrial systole phases can be divided in two groups: group one is classified by the contraction of the cardiac muscle fibers during the aerobic process, while group two is featured by the anaerobic process.

On an ECG curve, conceptually the aerobic processes should be related to the Q – R and the R – S intervals, while the anaerobic processes should be linked to the S – L and L – j segments thereon.

Considering the lines of energetics, the aerobic process demonstrates the greatest power. The energy supply is organized due to oxidation of fatty acids. It is precisely the aerobic process that is responsible for the contraction of the cardiac muscle fibers up to the level of the constant tension. In doing so, the blood motion in the ventricles can be maintained, even when the valves are closed. An action potential initiates the Na’
entry into a cell. This is an aerobic process. In spite of the relatively high energy consumption, the aerobic process is properly provided with all metabolism components [7-9].

The aerobic process is followed by the anaerobic process, which takes place in tension phase S – L. In the context of the energetics, the anaerobic process is characterized by splitting of the carbohydrates. It exhibits a very high consumption of the energy and cannot be maintained for a long time. Upon entering the cells, the Ca$^{++}$ ions initiate one more muscle contraction, but it occurs against the background of the permanent residual tension. It is similar to the Q – R – S complex. In this case, in the course of the anaerobic process, the lactic acid products (lactates) are formed [10, 11].

The Na$^+$ and Ca$^{++}$ ions, upon entering a cell, create the conditions for the K+ exit in phase L – j of the rapid ejection. This is an anaerobic process (the same case as we have in the previous phase). The shape of this ECG curve segment is similar to the QRS complex except for the amplitude of these oscillations: the amplitude is very low. In terms of the energetics, this process is weaker than the previous one. To ensure the process in the next cardiac cycle, the phosphocreatine must be restored in the diastole within the same cardiac cycle. Therefore it characterizes the remaining level of the phosphocreatine [12].

The Na$^+$, Ca$^{++}$, and Ca$^{++}$ ions, upon entering a cell, create the conditions for the K+ exit in phase L – j of the rapid ejection. This is an anaerobic process (the same case as we have in the previous phase). The shape of this ECG curve segment is similar to the QRS complex except for the amplitude of these oscillations: the amplitude is very low. In terms of the energetics, this process is weaker than the previous one. To ensure the process in the next cardiac cycle, the phosphocreatine must be restored in the diastole within the same cardiac cycle. Therefore it characterizes the remaining level of the phosphocreatine [12].

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The amplitude of the first order derivative R1 (when measured from the leading edge of the Q – R interval augmentation) can be treated as an indirect marker of the actual condition of the aerobic processes in the cardiac muscle fiber cells of the interventricular septum. The higher the amplitude of the derivative, the more efficient is the muscle performance. So, the amplitude of the first derivative K1 of the R – S interval indirectly shows the state of the aerobic processes in the cardiac muscle fiber cells.

The amplitude of the derivatives of these phases of the ECG differ in their informative values despite the fact that the aerobic processes occurring in the cells in the interventricular septum and the myocardium are identical. The interventricular septum starts contracting the first, and, while contracting, it is “pulling” the relaxed myocardium, and in the circumstances no resistance is available. But the contraction of the myocardium takes place, while the interventricular septum is kept constrained. Following this way, the difference in the metabolic consumptions of the above muscle types can be determined using the ratio as follows:

\[ W_1 \text{(aerobic, oxygen)} = \frac{R_1}{K_1} \]

Our investigations have shown that the relatively normal range for this ratio is 0.5 to 0.85 arbitrary units.

For the anaerobic process, incorporating the lactate production, the following ratio is applicable:

\[ W_2 \text{(anaerobic, lactate)} = \frac{R_2}{K_2} \]

In this case, the processes are running against the background of the permanent cardiac muscle tension due to pressure applied by blood available within the ventricles. The normal range for this ratio is 3 to 7 arbitrary units.

Figure 1. An example: a real ECG curve and the first order derivative thereof. On the amplitude derivatives: R1 and K1, R2 and K2, R3 and K3 correspond to interventricular septum and myocardial muscle contraction rates with reference to different phases, depending on the aerobic, anaerobic and phosphocreatine reactions, respectively.
In the anaerobic process, after the intracardiac pressure (applied on the muscle by the blood) is relieved, but the muscle tension remains steady, we deal with the following: phase L – j represents the remaining state corresponding to residual level of the phosphocreatine: W3 (anaerobic, phosphocreatine) = R3 / K3.

The normal values for this ratio are from 2 to 4 arbitrary units. Our studies have demonstrated that the oxygen level makes an effect on the QRS complex amplitude. Both the top and the bottom components of the above complex strongly depend on the respiration performance (see Figure 2 herein). But the amplitudes of the S - L and L - j phases remain unchanged.

The proposed new method of the assessment of the energy characteristics is highly sensitive; another advantage thereof is that it is capable of measuring the energetics of the heart in each cardiac cycle in most accurate manner. As to applicability of the method, the respective diagram for each process provides the maximum volume of information and is best suitable for an
<table>
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<th>Phosphocreatine</th>
<th>Oxygen</th>
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<td>328,54</td>
<td>1,95</td>
<td>0,59</td>
</tr>
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a)  

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b)  

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<tr>
<td>25.11.2008 18:01:35</td>
<td>24,50</td>
<td>2,93</td>
<td>0,52</td>
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c)
Figure 4. The CARDIOCODE Software screenshots, produced according to the cardiometric method, deliver parameters of hemodynamics and data on metabolic processes, measured noninvasively in a European swimming champion during the conditioning and after completion of the training process.

Table 1. The results of three measurements of the cardiac muscle metabolic characteristics in the athlete immediately after physical exercise versus one measurement three months upon completion of the training process (arb.u.)

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<td>18.02.2009 17:14:16</td>
<td>4.33</td>
<td>42.51</td>
<td>0.49</td>
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</table>

It has been already noticed that for the aerobic process, an arbitrary value of the myocardium contraction energy, W1, is found within the range 0.5…0.85.

For convenience, the aerobic process values can be classified into the following subgroups:
1. Values (0.7…0.85): this aerobic process range is typical for individuals undertaking regular physical activity.
2. Values (0.6…0.65): the aerobic process range is typical for medium-scale physical activity by a human.
3. Values (0.5…0.55): the given aerobic process range is typical for minimum physical activity by a human individual.

The intermediate values should be interpreted as borderline cases.

Results

The method has proved itself as the most informative and best suitable in high-performance sports practice. Figure 4 herein shows an exemplary case: there are
parameters of hemodynamics and data on metabolic processes measurement in a European swimming champion both during the conditioning and after the completion of the training process. The data are presented in a summarized tabulated form below (see Table 1 herein).

Conclusions
1. The offered novel noninvasive method of measurement of metabolic parameters, based on ECG processing, is an easy-to-use and a highly effective practical tool.
2. The given method appears to have considerable promise for a wide use in practice due to its capability to effectively supplement the classical diagnostics of the cardiovascular system performance.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest
None declared.

Author contributions
All the authors read the ICMJE criteria for authorship and approved the final manuscript.

References
Visit by Vladimir Zernov and Mikhail Rudenko to the Institute of Theoretical & Experimental Biophysics, RAS

Our Editor-in-Chief and Deputy Editor have visited the Institute of Cell Biophysics at the Russian Academy of Sciences (Pushchino, Moscow Region) on the 27th of February 2019 in order to discuss some frontier research issues with Prof., M.D. Eugene I. Maevsky, who is the Head of the Lab for Biological System Energetics and the Research Director of the above RAS Institute. The 3-hour friendly discussion has been devoted to some significant results obtained upon completion of original scientific investigations focused on cell metabolism. It was enjoyable to remember the time of establishing and developing the Research Institute: this unique research institution has been a leader in fundamental biophysics research in the former Soviet Union, and the discoveries made by its researchers have made possible to identify and interpret the mechanisms responsible for energy transformation in a cell under different conditions found in a human organism. One of the discussion themes has addressed the coordination of the cooperation of the above researchers in creating a new book to describe the principles how a healthy heart works. The book will cover some sports medicine aspects: it should not only offer knowledge & expertise in explaining biophysics and biochemistry in an athlete’s organism, but also provide a detailed description of how to apply it in practice.

Vladimir Zernov, Mikhail Rudenko and Eugene Maevsky have addressed the topics of applications of resonance to improve adaptation responses by a human organism. In this connection, separately treated has been an issue on actions and effects produced by resonance on DNA that induces genome expressions.
Justification for measurement equation: a fundamental issue in theoretical metrology

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Abstract
A review and a critical analysis of the specialized literature on justification for the measurement equation and an estimation of a methodical error (uncertainty) of the measurement result are presented in the paper, and some prospects for solving of the issue are discussed herein.

Keywords
Error, Uncertainty, Measurement equation (model equation), Physical and mathematical model, Algorithm

Imprint
Aleksandr V. Prokopov. Justification for measurement equation: a fundamental issue in theoretical metrology; Cardiometry; No.3; November 2013; p.58-68; doi: 10.12710/cardiometry.2013.3.5868 Available from: www.cardiometry.net/no3-november-2013/justification-for-measurement-equation

Introduction
Statement of the problem and analysis of publications
In recent years the measurement equation (model equation) has become an object enjoying close attention by researchers in metrology in many countries throughout the world. The measurement equation in metrology is interpreted [1, 2] as a functional relationship linking the quantity intended to be measured (measurand) with the quantity values immediately measured, as well as other quantity values which are essential for the measurement procedure under consideration. The measurement equation is required for solving many metrological issues, particularly for development of new measurement methods and measuring instruments, including an analysis of measurement result accuracy.

The problem of measurement modeling is widely represented in scientific programs of the UK’s National Physical Laboratory (NPL) devoted to the development of mathematical models and software for metrology applications [3], and issues on modeling measurement equations have a significant place in papers by German [4 - 6], Russian [2, 7 - 10] and Ukrainian [11 - 18] metrologists. It should be noted that most papers give an analysis of the already known models to select the best suited measurement equations. At the same time, the general principles of justification for the equation of measurement and an estimation of a methodical error (uncertainty) of measurement result are still insufficiently treated.

In the specialized literature on the subject, an extreme complexity of the issue on derivation (justification) of the measurement equation is emphasized; among other things, it is suggested that some specific approaches relating basically to arts rather than science should be required to derive the measurement equation [2]. It is also argued [8] that the measurement equation is one of the components of a priori knowledge obtained not by the procedures known from the point of view of metrology, but produced by methods used in some allied sciences. Perhaps that is the reason why there are no instructions in the Guide [1] on how to justify the measurement equation for metrological analysis. Instead, such unusual for scientific and technical literature recommendations as to rely on "critical thinking", "intellectual honesty" and "professional skill" are used therein.

It should be noted that the authors of the Guide to the Expression of Uncertainty in Measurement [1] are aware of the necessity to improve this document. A few years ago, a special working group WG1 was established under the Aegis of the International Bureau of Weights and Measures (BIPM). One of the main tasks of this Group is to prepare specific Supplements to the Guide, including a separate Supplement (JCGM 103) dedicated to the measurement procedure modeling and methodology of the measurement equation justification [19].

Thereby it confirms the fact that the problem of a rigorous justification for an algorithm of obtaining the measurement equation remains highly topical, and the given problem is a subject of the theory of measuring which should be referred to the fundamental issues in metrology.
The aim of this paper is to review and criticize the existing publications on the measurement equation justification and estimation of a methodical error (uncertainty) of the measurement result as well as discuss some promising ways for solving this problem.

Summary and outlines

The developments [4-6, 11-18], where the main aspects of the above problem are analyzed and general outlines for obtaining the measurement equation are provided, can be considered as a remarkable step on the way of finding the proper solution to the above issue. In the papers [4-6], for example, an outline of this sort consists of five successive stages which are as follows:

I. Description of the measurement, identification of significant quantities (including the measurand and influence quantities) and applied method of measurement.

II. Analysis of the measurement, its decomposition into separate elements, graphical representation of the cause-and-effect relations between the elements for a certain ideal (not exposed to external influences) measurement within the scope of the standard modeling components.

III. Consideration of all distortions, effects of an incomplete knowledge of quantities and external factors capable of affecting the ideal measurement. Graphical and mathematical interpretation of the cause-and-effect relations for the real (exposed to external influences) measurement. Use of corrections for taking into account distortions (external influences).

IV. Identification of reciprocal influence of quantities, introduction of correlations.

V. Transformation of mathematical relations which describe the cause-and-effect relationship for obtaining the model equation.

It should be pointed out that the operations necessary for the mathematical formulation of the problem are not specifically treated in the above mentioned publications.

In articles [11–18] an algorithm of obtaining the measurement equation is represented by seven stages as given below (you can find below the description of the algorithm for the case with the only one quantity to be measured to simplify the matter, and for the case with measuring more than one quantities the procedure should be similar):

I. Selection of a measurement object and preliminary identification of its properties and attributes which are essential for formation of a data signal carrying information relevant to the quantity value to be measured (unknown quantity value). Concretization of the said quantity.

II. Preliminary identification of physical processes which may influence the data signal and lead to a change in the latter during signal traveling from the object of measurement to the measuring device including traveling of the signal within the measuring device.

III. Formulation of a set of equations (with appropriate initial and boundary conditions) to describe the physical processes responsible for forming the data signal and influencing the latter during traveling of the signal from the measurement object to the measuring device including traveling of the signal within the measuring device (the mathematical formulation of the problem).

IV. Analysis of the initial equations. A quantitative assessment of influence of individual physical effects and processes on characteristics of the data signal during transmission of the signal from the measurement object to the measuring device, including transformation of the signal in the measuring device. Simplification of the mathematical formulation of the problem based on elimination of some physical effects and processes, which are insignificant for a given level of accuracy, from consideration. Evaluation of an error (uncertainty) caused by the said negligible effects and processes.

V. Selection and justification of the methods for solving the simplified equations for solving the problem which allow establishing the relationship between the unknown quantity (the measurand) and the immediately measured quantity values. Generally, this relationship may contain known constants, parameters with fixed values as well as some additional unknown parameters which consider, as an example, an influence of some external factors and which are to be determined separately.

VI. Solution of the equations solving the problem, analysis of the established relationship and transforming it to get the most convenient form for derivation of the measurement equation. In this case, two variants should be considered as follows: a) additional unknown parameters are represented as corrections provided they are empirically calculated in an independent way; b) the established relationship is used to formulate a set of equations that allows determin-
ing the quantity to be measured (the measurand) and some additional unknown parameters provided that they are instrumentally determined.

VII. Derivation of the measurement equation and estimation of methodical error (uncertainty) of the measurement result. Reducing the measurement equation to a standard form relating to direct, indirect, collective, joint or system measurements.

Let us consider a possible block diagram of the case of practical implementation of the above algorithm of the measurement equation justification [11 - 18] and estimation of the methodical error (uncertainty) of the measurement result for an exemplary indirect measuring. As before, we assume that there is only one unknown quantity value (while this algorithm is valid to another case with more than one quantity values, where the singular form of “quantity value” should be replaced by its respective plural form). The block diagram is given herein below, where the numbers denote actions, and the Roman letters signify the conditions of execution of these actions, namely:

1 – identifying of the measurement object, the quantity to be measured and the values to be measured immediately;
2 – listing of effects that are essential for the formation of the functional relationship between the quantity to be measured and the values to be immediately measured;
3 – based on an analysis of the literature on the subject, availability for relations connecting the immediately measured quantity values and the quantity to be measured (and their accuracy evaluation) should be defined;
4 – formulating of the equations for the physical effects and processes with their initial and boundary conditions that reflect the measurement problem specificity (mathematical formulation of the problem);
5 – using of the relations already available in the literature on the subject for justification of the equation of measurement, and the estimation of their accuracy should be applied to the evaluation of the methodical error (uncertainty) in the measurement;
6 – completing an analysis and an assessment of contributions of the individual physical effects and processes to the formation of the relationship between the desired quantity to be measured and the immediately measured quantity values, specifying the list of the effects and simplifying the original problem statement;
7 – solving the problem and obtaining the relations between the quantity to be measured and the immediately measured quantity values. Assessing of accuracy of the obtained relations on the basis of an analysis of the simplifications made before, when formulating and solving the problem;
8 – formulating of a set of equations necessary for determination of additional unknown parameters and the desired quantity to be measured with the obtained relations, which are presented for various values of the recorded parameters and the corresponding immediately measured quantity values (for the same values of the quantities to be determined as well as additional unknown parameters). Finding the equation of the measurement as a result from solving the above set of equations. Assessing of the methodical error based on the evaluation of the accuracy of the relations, as given above, which describe the relation between the desired quantity to be measured and the immediately measured quantity values;
9 – obtaining of the measurement equation using the derived relations where the additional unknown parameters, determined by computation, play the role of corrections. Methodical error should be estimated based on the assessment of the relation accuracy, as given above, which describe the relation between the desired quantity to be measured and the immediately measured quantity values, taking into account errors for establishing the corrections;
10 – transforming of the derived relations into the measurement equation. Utilization of the error caused by the inaccuracy of the relations as the methodical error of the measurement equation.

A – relations are not available;
B – relations are available, but without estimation of accuracy;
C – relations are available with estimation of accuracy;
D – accuracy does not comply with the specified requirements;
E – accuracy complies with the specified requirements;
F – the obtained relations contain not only the known constants, the recorded parameters, the desired quantity to be measured and the immediately measured quantity values, but also some additional unknown parameters (taking into account, for example, external environment influence), which should be determined separately;
G – the derived relations contain the known constants, the recorded parameters, the desired quantity to be measured and the immediately measured quantity values only;
H – additional unknown parameters are determined with instrumentation;
J – additional unknown parameters are determined by calculation using supplementary data.

From the above algorithm description, it follows that in those cases when the relevant data are available in the literature, some steps of the algorithm may be skipped. Among the other things, it should be noted that the wording used to define the actions prescribed by the algorithm cannot be considered in isolation from the wording describing the conditions of execution of these actions.

Conclusions
The review and the critical analysis of the literature dedicated to the solution of the problem of justification for the equation of measurement and the estimation of the methodical error (uncertainty) of the measurement result have been conducted herein. It has been shown that the mathematical formulation of the problem within the context of the approach presented in [11 - 18] is based on the application of rigorous formulations of physical laws (laws of nature) with the relevant boundary and initial conditions, considering the specificity of the given measurement task. The algorithm proposed in the present paper can be utilized for derivation of the measurement equations necessary for the development of new measurement methods, as well as for the development of measuring instruments to implement such methods, including analysis of the measurement result accuracy.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest
None declared.

Authors contributions
All the authors read the ICMJE criteria for authorship and approved the final manuscript.

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Cardiometry laws and axioms. Cardiometry laws

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Law No.1
The blood moves in vessels in elevated fluidity mode (so called “third condition” in contrast to the laminar and turbulent conditions), characterized by low friction of flow resulted from the ring-shaped combination of the blood and dry blood elements.

Conclusions:
1) The heart and vessels anatomy is aimed at this mode of current set-up and support
2) Cardiac cycle consists of ten phases, each performing a definite function in process of the hemo-dynamics setting-up and maintaining
3) The function quality depends on the amplitude and rate of the appropriate cardio-vascular system muscles contraction
4) Maintaining the normal hemodynamic parameters ensures the function of compensatory mechanism that maintains the CVS muscles activity by combination of increased activity of some muscles with simultaneous decrease in activity of the neighbouring muscles.

Law No.2
Cardiac nodes SA and AV, as well as the aorta baroceptors BA, nervous centers are baroceptors that generate the nervous impulses (response pulses) when the pressure of blood is applied to them.

Conclusion:
Pressure applied to the baroceptor is the only source required for generation of the nervous impulse (response pulse) for starting the CVS muscles contraction mechanism.

Law No.3
SA node ensures the closing of the atrioventricular valves.

Conclusion:
If the atroventricular valves fail to close at the end of each auricular systole phase, the residual pressure is built up in the atrium that has effect on the SA node. This surely will cause the repeated auricular contraction that will be represented on the ECG in the form of the second P wave (atrial arrhythmia basis)

Law No.4
AV node controls three mechanisms of the bloodstream structure preparation in vessels:
1) Control of the diastolic pressure in aorta (carotid artery)
2) Formation of turbulent bloodflows preceding the aortic valve (carotid artery) opening
3) Aortic valve (carotid artery) opening.

Conclusion:
1) with intensive physical activity the phase L – j generation may be repeated up to 7 times.

Law No.5
BA- baroceptors of aorta (carotid artery) retain the bloodstream structure and maintain the elevated fluidity mode of blood flow in vessels

Conclusion:
The aorta expansion amplitude regulates the flow resistance.

Law No.6
The amplitude of ECG phases corresponds to the cardiac muscles contraction amplitude.
The following parameters are analyzed:
– atriums contraction amplitude (P)
– IVS contraction amplitude (R).
– myocardium contraction amplitude (S)
– IVS contraction amplitude when electromechanical interface takes place (phase S-L maximum)
– aortic dilatation amplitude.
Law No.7
Q – R – S phase functioning is an aerobic process and requires the use of oxygen, without lactate accumulation in myocards.

Conclusion:
The oxygen quantity is assessed based on the following ratio: rate of IVS contraction in Q – R phase – to – the rate of myocardium contraction in R – S phase.

Law No.8
Phase S – L functioning takes place at presence of electromechanical interface in anaerobic process with the lactate accumulation in myocards.

Conclusion:
The lactate quantity is assessed based on IVS contraction speed in phase S – L – to – myocard contraction speed in the same phase against the background of the total tension of all cardiac muscles that took place in the previous phase and persists up to end of the systole. But it is required to take into account the effect of the pressure applied to them by the volume of blood contained in the cardiac ventricles.

Law No.9
Phase L – j functioning is effected by electromechanical interface. The remainder of the creatinephosphate comes out and supports the ATP energetic support function in the next cardiac cycle.

Conclusion:
The creatinephosphate quantitative assessment is made based on the IVS contraction rate in L – j phase – to – the rate of myocardium contraction in the same phase, but against the background of total tension of all cardiac muscles that took place in the previous phase and persists up to end of the systole, without taking into account the effect of the pressure applied to them by stroke volume of blood.

Application of laws in axiomatics
Axiomatics is method of science formation used in all natural science. The axiomatics objective is to prove that the observed phenomenon represents the varity. Further on, the proved phenomenon is used in the function of the logical ratiocination for further conclusions. Both the basic laws and the following
derived laws, phenomena and statements are considered to be axioms and accepted a priori and are not in doubt. As the evidentiary material is generated and accumulated, the theorems are formed that enable to apply the theory to practice.

The axioms noncontradiction is a main criterion for making decision to use it. There is a rule that determines the statements and conclusions noncontradiction in theorems that have been formulated based on the axioms accepted in the given science. Moreover, the further theorems shall prove the correct choice of the formerly accepted ones without additional proving.

All natural science is based on the principles of axiomatics. This is the principle of knowledge the truth. The cardiometry is based on the principles of axiomatics.

To be certain in correction of the cardio signals interpretation, it is necessary to determine at least three manifestations of their form alternation caused by the same process. At that, they should not contradict one another, on the contrary, they shall confirm the underlying cause of the process. This is the basis for precise detection of the cause of deviation from norm.

Example. In case of IVS minor contraction represented on the ECG by low amplitude of R wave, also the changes in the other phases shall be present. They are caused by the compensation mechanism meant for maintaining the hemodynamics parameters in norm. So, the S wave contraction amplitude shall be increased. If not, the pressure rise in aorta will be below normal value, that is diagnosed based on the rheogram made in the rapid ejection phase. The only conclusion that can be made is: the quality of muscles is too low to build up the pressure in ventricle. This results in low ejection of blood into aorta. At that, T wave amplitude may be increased thereby decreasing the blood flow resistance. As a consequence, the hemodynamics parameters will be normal, but the heart and vessels functioning will tend to pathological zone. The conclusion is as follows: it is necessary to recuperate the myocard metabolism, in particular the IVS contraction function shall be normalized.

The analysis of the subjective symptomatology is also very important. Three symptoms of health variations having the same cause can be identified through simultaneous analysis of ECG, RhEO and personal symptoms.
Coincidence of renal artery stenosis and coronary artery stenosis

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Aims
The aim of this study was to investigate the prevalence of renal artery stenosis in patients with severe coronary artery disease or stenosis of the left main coronary artery.

Materials and methods
This cross-sectional study was performed on 264 patients with a history of severe hypertension who were candidates for coronary artery angiography in Yazd Afshar Hospital. During coronary angiography, renal angiography was performed on all of the patients. At the same time, we investigated the renal artery stenosis and its association with a history of diabetes mellitus, high body mass index (BMI), hyperlipidemia, and other cardiovascular risk factors. Renal artery stenosis was defined based on luminal narrowing: mild (50%), moderate (75%), and severe (75%) decrease in luminal diameter. Collected data were analyzed by SPSS software (version 18.0).

Results
Among 264 patients, 54.92% were males and 45.08 % were females with the average age of 58.0±8.6. 83.71% of the patients had coronary artery disease and included 52.94% hyperglycemic, 63.39% diabetic, and 29.86% smokers. Prevalence of the renal artery stenosis (equal to or more than 50%) was 38.25% in all patients, including 43.56% in men and 56.44%, in women, which shows a significant difference (P=0.04). Prevalence of co-morbidity of coronary artery disease and renal artery stenosis for 1-vessel, 2-vessels, and 3-vessels disease was 34%, 57.14%, and 54.17%, respectively, that showed a significant difference (P<0.01).

Conclusion
Our findings showed a high prevalence (38.25%) of renal artery stenosis in hypertensive patients with coronary artery diseases. Accordingly, we suggest that simultaneous renal angiography after coronary angiography in hypertensive patients may help to find patients with renal artery stenosis and subsequently better management of these patients.

Keywords
Renal artery stenosis, Coronary artery stenosis, Hypertension, Coronary artery angiography, Renal angiography

Introduction
Renal atherosclerotic stenosis is the most prevalent disease of renal artery that plays an important role in developing and intensifying hypertension and renal atrophy [1, 2]. The prevalence of this disease in society is not completely clear but it has been estimated that 5-10% of hypertensive patients and approximately 17% of hypertensive patients with type 2 diabetes suffer from this disease [3,4].

In recent years, the association between coronary artery disease and the prevalence of renal artery stenosis has been studied a lot. Some studies have mentioned a strong relationship between coronary artery disease and the prevalence of renal artery stenosis [11] and some have investigated coronary artery disease risk factors that can lead to renal artery stenosis. However, the results of these studies are very different and sometimes antithetic. According to the difference in prevalence of heart disease risk factors in various societies, it seems that predictive risk factors of renal artery stenosis in heart disease are also different in various societies [12]. As a result, this study is aimed at investigating this relationship and predicting the future of the society of Iranian hypertensive patients.
Materials and method

This cross-sectional study was performed in angiography center in the cardiac ward of Yazd Afshar Hospital during the second half of the year 2010. The studied population include the patients with history of hypertension who were candidates for coronary artery angiography by an informed consent. The subjects of this study were selected by convenience and sequential sampling method from among the patients eligible for participating in the study. Diagnosed hypertension under treatment, two measurements of systolic blood pressure of higher than or equal to 140 mm Hg and diastolic blood pressure of higher than or equal to 90 mm Hg, and the written consent were the inclusion criteria. The patients who lacked appropriate hemodynamic conditions during angiography were excluded. Before angiography, a collection form containing demographic data, diabetes, and smoking, in addition to examining blood pressure, height and weight were recorded by conductors. Their blood pressure was taken twice and those with blood pressure higher than or equal to 140/90 mm Hg were included in the study. During coronary angiography, renal angiography was performed, non-selectively through abdominal aortography and selectively through renal artery injection of 10 cc contrast material in both kidney arteries. According to severity stenosis of renal artery from origin to bifurcation, patients were categorized into three groups of mild stenosis (50%), moderate stenosis (50-75%), and severe stenosis (more than 75%). Subsequently, two cardiologists expressed their observations and artery diameter stenosis as well as renal artery stenosis rate were based on their observations. At least 50% of diameter stenosis of the coronary artery (LCX, RCA, and LAD) or one of their main branches was considered as coronary artery stenosis. Left main coronary artery stenosis (LM) was considered as 2-vessels stenosis. This study protocol has been approved by Yazd Cardiovascular Research Center’s committee on human research.

Qualitative data were expressed through percentage and quantitative data were illustrated by mean and standard deviation. Qualitative variables were compared by Chi-square test or Fisher’s exact test and quantitative variables were compared by Student’s t-test. Version 18 of SPSS software was used for statistical analysis and a P-value of less than 0.05 was considered as significant probability.

Results

264 patients, consisting of 145 (%54.92) men and 119 (%45.08) women, with hypertension who were candidates for coronary artery angiography were studied. The number of patients with coronary artery disease was 221 (83.71%).

The mean age of patients was 57.0 ± 8.6. Minimum and maximum ages were 31 and 87, respectively. The mean age was 58.9±9.3 for patients with renal artery stenosis and 55.9±7.5 for patients without renal artery stenosis. According to Student’s t-test, mean age was not significantly different between two groups (p=0.09).

Of 264 patients studied the prevalence of renal artery stenosis (narrowing of the diameter equal to or more than 50%) was 114 (43.1 which was respectively 43.56% (44 patients) and 56.44 % (57 patients) in men and women (p<0.001) (Table2). Among 264 studied patients, 114 (43.1%) had renal artery stenosis, including 44 men (43.56%) and 57 women (56.44%) (P<0.001) (Table 2).

Coincidence of renal artery stenosis and coronary artery stenosis was 45.7 % (101 of 221 patients) Based on chi-square test the mean age of men and women was significantly different (P = 0.04).

Diagram 1 shows the severity of renal stenosis in CAD patients. 45.7% of patients had renal artery stenosis. The majority of them had mild and moderate stenosis.

Among 221 patients, a total of 100 (45.25 %) were involved in 1-vessel coronary artery disease, 34 of them (34%) had simultaneous renal artery stenosis. In addition, 49 patients (22.17%) had two-vessel involvement. Among them, 28 cases (57.14%) had simultaneous renal artery stenosis. 72 patients (32.58 %) had three-vessel involvement that 39 (54.17%) of them had simultaneous renal artery stenosis.

Discussion and conclusion

In the present study, the prevalence of renal artery stenosis in hypertensive patients undergoing coronary angiography was 43.18% that was estimated 43.56% and %56.44 in men and women, respectively. In the study of Edalatifard et al. in 2010 [17], the prevalence of renal artery stenosis was %25.3, which is less than that of the present study. In the study of Ebrahimi et al. [18] in 2005 on patients who were candidate for coronary angiography in Mashhad, 31% of hypertensive patients had renal artery stenosis and coronary
artery disease. The results of this study were close to ours. Comparing to other similar studies, the results of Ebrahimi et al. [18] and the results from this study show an increase in the prevalence of renal artery stenosis in patients with coronary artery disease. This could be due to investigation of the prevalence of renal artery stenosis in hypertensive patients.

Also in this study, renal artery stenosis of more than 50% was observed in 45.7% of patients with coronary artery disease which is higher than those of the studies of Edalatifard et al. (17.1%) and Ebrahimi et al. (%21) [17,18]. This partly reflects the increasing prevalence of renal artery stenosis in hypertensive patients. In the aforementioned studies, the prevalence of renal artery stenosis in patients with coronary disease confirmed by angiography was higher than other procedures (28-39 % vs. 9-14.5% in Edalatifard study). Similar results were obtained in the present study, and this indicates the close relationship of atherosclerosis in coronary and renal artery. In several studies, in addition to characterization of the prevalence of renal artery stenosis, an attempt has been made to identify risk factors and predictors of disease. In the study of Alhaddad in 2001, coronary artery stenosis was considered as an important factor in the prediction of renal artery stenosis [19]. In Aqel’s study (2003), besides the age and renal function, peripheral vascular disease is mentioned as a predictor of renal artery stenosis instead of coronary heart disease. In 28% of patients, over 50% of renal artery stenosis and in 16% of them, over 75% of renal artery stenosis were reported [20]. In this study, female gender has been proposed as a predictor affecting renal artery stenosis. This finding is emphasized in Cohen’s study as well [21].

In our study, the number of men with CAD were more than women (54.92 vs. 45.80%), but in women with renal artery stenosis, coronary artery disease was more severe (56.44% of women vs. 43.56% of men). Unlike Alhaddad [15], the results of this study confirm the results of Aqel [20], Buller [22], and Cohen [21]. This shows the potential impact of female gender on

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Mild stenosis &lt;50%</th>
<th>Moderate stenosis 50–75%</th>
<th>Sever stenosis &gt;75%</th>
<th>Total %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male No(%)</td>
<td>20(38.46)</td>
<td>22(53.66)</td>
<td>2(4.55)</td>
<td>44(43.56)</td>
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<tr>
<td>Diabetes mellitus No(%)</td>
<td>36(69.23)</td>
<td>18(43.90)</td>
<td>7(17.5)</td>
<td>61(60.40)</td>
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<tr>
<td>Hyperlipidemia No(%)</td>
<td>24(46.15)</td>
<td>1(29.27)</td>
<td>4(50.0)</td>
<td>40(39.60)</td>
</tr>
<tr>
<td>Smoking No(%)</td>
<td>13(25)</td>
<td>16(39.02)</td>
<td>3(37.5)</td>
<td>32(31.68)</td>
</tr>
<tr>
<td>Age (y) Mean±SD</td>
<td>9.00±58.10</td>
<td>3.80±51.2</td>
<td>5.80±62.2</td>
<td>56.12±12.8</td>
</tr>
<tr>
<td>BMI (Kg/m2) Mean±SD</td>
<td>3.80±29.18</td>
<td>4.22±29.01</td>
<td>1.55±28.18</td>
<td>3.42±29.0</td>
</tr>
</tbody>
</table>

*P%*, **SD ± Mean

![Diagram 1: Severity of renal stenosis in CAD patients](image-url)
renal artery stenosis independent of other risk factors in the study of Edalatifard et al., female gender is considered a factor of renal artery stenosis independent of other risk factors [17]. Other studies on the prevalence of heart disease in Iran have shown that female gender is considered a main risk factor in the occurrence and development of renal artery stenosis [23].

In earlier studies such as Harding in 1992, female gender is considered important as well as age. In Harding’s study on patients with or without hypertension who were candidate for coronary angiography, 30% of patients showed a degree of renal artery stenosis and only 11% had stenosis of more than 50%. However, in this study, instead of the number of involved coronary arteries and the severity of coronary artery stenosis, peripheral vascular disease was identified as an important factor [24].

In Liu study the prevalence of renal artery stenosis in 141 patients who underwent coronary angiography was totally 18.2%, but in the presence of coronary stenosis this ratio increased to 30.8%. [25].

In this study the frequency of coronary artery stenosis associated with renal artery disease was significantly higher than the frequency of coronary artery disease without renal artery stenosis which is consistent with the results of the present study.

Studies show that the prevalence of three-vessel involvement in coronary artery disease in Iranian society is considerably more than other communities [23]. In our study, the incidence of involvement of three vessels in patients with CAD was 54.17% and 54.17% of CAD patients had simultaneous renal artery stenosis and three-vessel involvement.

Edalatifard et al [17] believe that the close relationship between the development of hypertension and renal artery stenosis is because in many patients, especially women, high blood pressure is not appropriately controlled by medication. However, in Aqel study no relationship has been found between the control of hypertension and renal artery stenosis [20].

The results show that signs and symptoms of coronary artery disease can be a suggestion of renal artery stenosis in patients. Wierema study in 2009 suggests that renal artery stenosis in patients with coronary artery stenosis increases the risk of mortality in these patients and the growth of mortality is directly related to the severity of renal artery stenosis in these patients [26]. Zuccala et al. stated that because atherosclerosis is the primary cause of renal artery stenosis and the involvement of coronary arteries and all arteries including the coronary arteries can be involved, as a result in coronary artery atherosclerosis people, are at greater risk of atherosclerosis of the renal artery disease [9].

Results showed that in a significant number of hypertensive patients with severe coronary artery disease, renal artery is stenotic. Due to serious and irreversible complications of renal artery stenosis such as renal failure, it is recommended that during coronary angiography in patients with chronic hypertension, especially in women, renal artery angiography should be performed as well for the early detection of renal artery stenosis and taking necessary preventive management.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest
None declared.

Author contributions
All the authors read the ICMJE criteria for authorship and approved the final manuscript.

References
The relationship between severity of coronary artery disease and mean platelet volume

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Aims
Increased MPV is a risk factor for cardiovascular diseases and can be associated with coronary artery involvement. In this study, we aimed to investigate the relationship between the severity of coronary artery disease and MPV.

Materials and methods
In this study, a total of 200 patients with coronary artery disease were enrolled. All patients initially underwent coronary angiography. Plasma TG, LDL, and HDL, was measured using commercial kits Integra 800TM. MPV and platelet count was determined by the Sysmex XT-2000iTM. Population were divided into three groups based on the SYNTAX score: low, moderate and high. All angiographic grading of SYNTAX was carried out by two cardiologists with blinded clinical data. After Data collection, these data were entered to SPSS22 software and were analyzed using correlation coefficient regression analysis.

Results
A total of 200 patients entered to the study that 43% and 57% of patients were female and male, respectively. eighty-seven patients were diabetic and other 113 patients were not diabetic. There was a significant correlation between SYNTAX score and the BMI, hemoglobin, LDL, FBS, EF and particularly MPV. There was no significant correlation between SYNTAX score and systolic and diastolic blood pressure, HDL, triglycerides, WBC and glomerular filtration rate.

Conclusion
The results of this study showed that because of significant correlation between MPV and SYNTAX score, this variable can be used as an indicator of the severity of coronary artery disease.

Keywords
Mean platelet volume, SYNTAX score, Coronary artery, Risk factor

Imprint

Introduction
Cardiovascular diseases are one of the most important causes of death in developed and some developing countries [1]. Among different cardiovascular diseases, in 2013 coronary artery disease was the most common cause of death worldwide and that is why we have chosen to evaluate atherosclerosis in this study [2, 3]. Based on Framingham heart study, heart diseases are related to 9 risk factors such as gender, age, familial history of heart disease, blood cholesterol level, high density lipoprotein (HDL), blood pressure, smoking, diabetes and Left ventricular hypertrophy [4, 5]. In recent decades’ new modalities for both diagnosis and treatment of cardiovascular diseases have improved [6]. Platelets play a very important role in coagulation. Rather than this they can also cause inflammation in vessels as an inflammatory factor [7]. Both mentioned functions are strongly related with atherogenesis and atherothrombosis in pathogenesis of cardiovascular diseases[8]. Bigger platelets are more active in metabolism and enzyme activity. Mean platelet volume(MPV) is an index indicating megakaryocytes during platelet production[9]. Although there are a lot of studies performed on relationship between MPV and acute coronary events, there are only limited number of studies performed on relationship between MPV and stable angina and the results are contradictory[10, 11]. Because of this we are about to investigate relationship between severity and complexity of coronary artery disease and MPV in patients with stable angina.

Materials and methods
The patient sample was chosen among all elective referred patients to Shahid Sadoughi and Afshar

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hospitals with stable angina since 21 June 2016 till 18 Feb 2017. Stable angina is defined as exertional angina with evidences of target ischemia in Thallium scan or exercise test persistent for more than 6 months. All included patient’s age varied between 18 and 75 years. All patients involved with acute coronary syndrome, history of Myocardial infarction (MI), off pump or on pump Coronary artery bypass grafting surgery, Percutaneous coronary intervention (PCI) and syntax score 0 were excluded from our study. Other exclusion criteria were: unstable hemodynamics, neoplastic disease, Chronic kidney disease, chronic liver disease, chronic infection, autoimmune disease, severe anemia and hypothyroidism[12, 13]. Considering reliability level of 95%, power of 80% and correlation coefficient amount of 0.37 between SYNTAX score and platelet level, a number of 200 patients were finalized to involve our study with their own informed consent while having all information about research protocol. The studied patients aged 58.045±10.207 (mean±SD). Youngest patient was 32 years old and the oldest patient aged 78 years. 114 (57%) patients were male and 86 (43%) of them were female. Measuring plasma biochemical markers was done on peripheral venous blood sample one day before surgery (could vary up to 2 days before angiography) after a 12 hours fasting period. Plasma Triglycerides (TG), cholesterol, Low density lipoprotein (LDL), HDL and creatinine concentration were measured using Integra 800TM kits. MPV and platelet count was also determined using Sysmex XT-2000iTM device. Normal ranges for MPV and platelet count were defined as 6-11 mm³ and 150-450 m/mm³ respectively. Demographic and other data before angiography including past medical history, diabetes mellitus, hypertension, hyperlipidemia, smoking, Body mass index, echocardiography and laboratory data were collected based on available standards. Patients drug history was also obtained using questionnaire. In present study hypertension is defined as at least 2 measured blood pressures higher than 140/90 mmHg or consumption of antihypertensive medications. Diabetes is recorded for patients with at least 2 blood sugar level more than 126mg/dl or using antidiabetic agents. Glomerular filtration rate (GFR) is calculated based on Cockcroft-Gault equation formula. In our study we used SYNTAX score as an angiographic tool for leveling the severity of coronary artery disease. All vascular lesions with more than 50% stricture in vessels with diameter higher than 1.5mm were chosen for scoring. The score evaluation was performed by 2 expert cardiologist with other blinded clinical data. The score was measured based on SYNTAX score calculator version 2.11 downloaded from SYNTAX score website. Obtained SYNTAX scores were divided into 3 groups: (a) 22 and less, considered as low (b) 23-32, considered as moderate (c) 32 and more, considered as high [13, 14]. Collected data were analyzed using correlation coefficient regression via SPSS VER2.0 software. To determine the effect of different factors causing moderate or high SYNTAX score we entered the significant parameters in single variable analysis into linear multivariate analysis. Odds moderation ratio (OR) were calculated with 95% confidence interval (CI). To perform mentioned analyzes we used SPSS VER2.0 and Microsoft Excel softwares and P values<0.05 were considered to be significant.

**Results**

The amounts of main risk factors of coronary artery disease such as SYNTAX score, TG, fasting blood sugar (FBS), LDL, MPV and GFR are concluded in table No.1

As seen in table No.1 the average amount of FBS is higher than normal range. This shows high prevalence of diabetes in studied patients. Among 200 studied patients 87 of them were diagnosed with diabetes. Average SYNTAX score points out to a low SYNTAX score in patients. Average amount of LDL, systolic/diastolic blood pressure was in normal range. Based on SYNTAX score among 200 studied patients, 135 of them had low SYNTAX score, 34 of them had moderate score and 31 had high SYNTAX score as concluded in table No.2.

The relationship between SYNTAX score and studied variables was evaluated and the results are reported in table No.3.

As seen in table No.3 there is a significant statistical relationship between SYNTAX score and BMI, Hb, LDL, FBS, ejection fraction (EF) and specially MPV. Systolic/diastolic blood pressure, HDL, TG, white blood cell (WBC) and GFR are not significantly related with SYNTAX score. Table No. 3 also indicates that correlation coefficient between BMI, Hb, HDL, EF, WBC and SYNTAX score is negative. It means that elevation of BMI, Hb, HDL, EF and WBC decreases SYNTAX score. Correlation coefficient between LDL, systolic/diastolic blood pressure, MPV, FBS and SYNTAX score is positive meaning that higher levels of
ment and MPV. Besides, the effect of other factors on severity of coronary artery involvement such as systolic and diastolic blood pressure, TG, HDL, LDL, GFR, Hb, FBS, BMI, EF, WBC were also measured. Platelets play an important role in pathophysiology of thrombogenesis and atherogenesis. MPV is defined as mean volume of platelets circulating in systemic blood and shows the function and activity level of platelets(15). Elevated MPV is related with more activity of large platelets which have more hemostatic function compared to smaller platelets(16). Recent studies have investigated the relationship between MPV and coronary artery disease. These studies have proved that MPV rising is a poor prognostic factor in acute thrombotic events[17, 18]. At the moment platelet counter devices in clinical laboratories are accurate devices for measuring platelet volume. Platelets are small shapeless cell particles which vary in diameter from 2 to 3 microns and are derived from megakaryocytes precursors. Average platelet half-life is about 5 to 9 days. They circulate in mammal systemic blood and are involved in hemostasis process and are responsible for clot formation. Platelets are also important in development of coronary artery disease as an inflammatory

| Table No.1: Average and standard deviation amounts |
| Variable | Average | Standard deviation |
| SYNTAX score | 17.4523 | 1.29157 |
| MPV | 9.9135 | 1.16801 |
| GFR | 51.8342 | 18.61130 |
| LDL | 112.6834 | 28.91827 |
| FBS | 131.3586 | 47.47030 |
| BMI | 25.6399 | 3.32031 |
| Hb | 13.3055 | 2.01430 |
| HDL | 42.8593 | 15.9876 |
| TG | 180.3015 | 59.7406 |
| Systolic blood pressure | 13.197 | 1.8941 |
| Diastolic blood pressure | 7.9848 | 0.9998 |

| Table No.2: patient’s affluence based on average SYNTAX score |
| SYNTAX score | Number of patients | Ratio |
| 22 and less(low) | 135 | 67.5 |
| 23-32(moderate) | 34 | 17 |
| More than 32(high) | 31 | 15.5 |

| Table No.3: correlation coefficient between SYNTAX score and other related variables |
| Variable | Correlation coefficient | SYNTAX(P value) |
| BMI | -0.219 | 0.002 |
| Hb | -0.140 | 0.048 |
| LDL | +0.309 | <0.001 |
| HDL | -0.039 | 0.590 |
| TG | +0.061 | 0.394 |
| FBS | +0.152 | 0.032 |
| EF | -0.338 | <0.001 |
| WBC | -0.104 | 0.146 |
| GFR | -0.109 | 0.125 |
| MPV | +0.356 | <0.001 |
| Systolic blood pressure | +0.017 | 0.814 |
| Diastolic blood pressure | +0.130 | 0.069 |

BMI (body mass index), FBS (fasting blood sugar), GFR (glomerular filtration rate), Hb (hemoglobin), HDL (high density lipoprotein), LDL (low density lipoprotein), MPV (mean platelet volume), TG (triglycerides)

Discussion

The goal of present study was evaluating the relationship between severity of coronary artery involve-

Abbreviations: see Table 1. EF (ejection fraction), WBC (white blood cell)
They trigger inflammatory process in coronary arteries which is an etiology for coronary artery disease[20]. Elevated platelet consumption in atherosclerotic plaques site leads to release of larger platelets from bone marrow. The reality is that this increment continues even after hospital discharge. This fact confirms that platelet size is bigger in patients with infarction chronically. MPV is a useful parameter for detecting bigger platelets which are more active in hemostasis and it is a risk factor for development of coronary artery diseases leading to MI[21]. It is reported that rise of MPV is related with acute MI incidence, mortality rate due to MI, stable angina, angina pectoralis, congestive heart failure and coronary artery dilation. Rather than this platelet volume is a predicting parameter of ischemia and death, if measured after MI[22]. It is indicated that MPV level before PCI is in positive correlation with the risk of restenosis. The relationship between platelet size and hemostatic reactions shows that bigger platelets have a higher thrombotic potential but the main mechanism of this phenomenon is not yet clarified[23]. There are evidences showing that platelets are involved in thrombogenesis. Elevated systemic blood platelet activation is evaluated in different atherosclerotic diseases such as coronary artery diseases, graft vessels and carotid artery disease[24, 25]. In addition, platelet factor IV[26], and other platelet derived chemokines and growth factors are isolated from human atherosclerotic plaques[27]. In our study a statically significant relationship was recorded between MPV and coronary artery disease. Results of our study and other similar studies confirm that MPV rise is involved in prothrombotic state in coronary artery diseases and bigger platelets may play more important role in atherosclerotic plaque formation. Since bigger platelets are more active hemostatically, existence of bigger platelets is considered as a risk factor for coronary thrombosis and myocardial infarction. Patients with higher amounts of MPV can be easily diagnosed using routine blood analysis and because of this MPV can be used to determine the risk of cardiovascular diseases during routine clinical work ups[28, 29]. MPV is a practical, important, easy and cheap tool which can be wildly used to predict severity of coronary artery involvement. It is proved that MPV is higher in patients with T2DM compared to patients without T2DM. Among those diabetic patients higher MPV leads to higher cardiovascular anomalies[30], although some studies have not achieved any significant relationship between these two variables[31]. In our study a significant relationship was seen between FBS level and SYNTAX score as an index of coronary artery involvement (P value=0.0328). This finding shows that evaluated diabetic patients in our study did not have their FBS level under an appropriate control because in other studies without a significant relationship between FBS and coronary artery involvement had their diabetics under appropriate control. Different studies have investigated and proved the effect of other underlying factors on elevation of MPV and severity of coronary artery involvement. Lipid factor such as TG, LDL, HDL are among these factors[32]. Total cholesterol to HDL ratio is introduced as an important factor for evaluating cardiovascular diseases. Elevated total cholesterol and HDL depletion leads to an inappropriate condition and increases cardiovascular anomalies. Rise of TG and LDL is also important in this field and is considered to be an important prognostic factor in cardiovascular diseases, particularly coronary artery diseases. This relationship is a result of impaired endothelial function, atherosclerosis and higher number of atherosclerotic plaques. Our study showed that there is a strong relationship between LDL and SYNTAX score as a coronary artery involvement index, this is while in present study there was no significant relationship discovered between HDL levels and SYNTAX score. The same condition was also true for TG levels and no significant statistical relationship was recorded between TG level and severity of coronary artery

<table>
<thead>
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<th>Control variables</th>
<th>Correlation coefficient</th>
<th>SYNTAX(P value)</th>
<th>MPV(P value)</th>
</tr>
</thead>
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<tr>
<td>FBS</td>
<td>+0.325</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LDL</td>
<td>+0.306</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>GFR</td>
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</tr>
<tr>
<td>FBS, LDL, GFR</td>
<td>+0.307</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
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</tbody>
</table>

Abbreviations: see Table 1.
artery involvement. In some other studies there was a significant relationship recorded between TG and coronary artery involvement. Thus, results of present study are not matching with previous studies. One of the other important factors in coronary artery involvement is GFR, because chronic kidney disease is related with elevated risk for cardiovascular diseases independently. The relationship between GFR and coronary artery disease in patients underwent angiography is not yet discovered completely. There have been different studies performed around this subject but the results are controversial. Some studies found a significant relationship between GFR and severity of coronary artery involvement and some did not found this relationship to be significant[33, 34]. Our study confirms those who didn't find any significant relationship between GFR and severity of coronary artery involvement (P value=0.125). In present study the effect of blood factors on SYNTAX score such as Hb and WBC count were also evaluated. The results showed that there is a significant relationship between Hb and SYNTAX score but there is no significant relationship between WBC count and SYNTAX score. Different studies have proved the effectiveness of Hb on prevalence of cardiovascular diseases especially coronary artery diseases. Of these studies, researches by Choncho et al, Verdoia et al, Anoop et al and Yusuf et al can be pointed out(35-38). Results of our study confirmed the effectiveness of Hb level on severity of coronary artery involvement along with mentioned researches. In this study the effect of BMI, EF, systolic and diastolic blood pressure on SYNTAX score were also evaluated. The results showed significant effect of EF and BMI on SYNTAX score but they didn't show any significant correlation between systolic and diastolic blood pressure and SYNTAX Score. The primary issue of present study was to check the prevalence of coronary artery disease based on SYNTAX score. According to SYNTAX scoring system in our study 135 patients had low SYNTAX score, 34 patients had moderate SYNTAX score and 31 of them were recorded with high SYNTAX scores. Second and third issue of our research was to check the average MPV amount in patients with high and low SYNTAX score and the results showed that the average amount of MPV is in a significant positive correlation with SYNTAX score. The fourth issue was investigating the difference between mean MPV in both high and low SYNTAX score groups, the results pointed out to the significant difference of MPV in mentioned groups. This shows that this parameter can be used as an appropriate index to predict severity of coronary artery involvement. Previous studies and notions have related MPV and heart diseases in different ways but up to now no study is performed to check the effect of other variables such as Hb, EF, BMI, systolic and diastolic blood pressure and etc. on heart diseases. To sum up, our study showed that there is a significant positive correlation between MPV and severity of coronary artery involvement. This finding is matching with previous findings. Results of present study also shows that active platelet can act as an inflammatory factor in patients with stable angina. Based on this we think that a more restrict control of platelet level in patients with stable angina should be taken serious and consumption of more effective anti-platelet agents can lead to better outcomes in these patients. Resembled to all other scientific studies our study has also its own limitations which can help other researchers to perform better researches. Present study did not have a big number of patients studied, so future studies can provide with a higher number of patients to obtain better statistical results. We also suggest the researchers to use other scoring systems such as Gensini scoring system in future studies and compare the results with SYNTAX scoring technique. Future researches can also evaluate the outcomes of prescribing more anti platelet agents in patients with stable angina as a clinical trial study.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest
None declared.

Author contributions
All the authors read the ICMJE criteria for authorship and approved the final manuscript.

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Prospects for the application of mathematical modeling in clinical medicine

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Aims
The aims of the study are to follow the correlation of CAD development with various clinical and laboratory parameters and risk factors in a cohort of patients with multiple medical conditions and evaluate the effect of various parameters in the development of the disease using a new mathematical model approach.

Materials and methods
This study covers a limited patient cohort (n = 12) formed according to the rules of a local register. We have applied the methods of probabilistic mathematical modeling of cardiovascular disease with the formation of an aggregated matrix. Matrix fields were presented the instrumental methods of diagnosis and clinical and biochemical blood tests of patients.

Results
When using various methods of mathematical and statistical analysis (including cluster and factor analysis), created has been a graphic model of interaction of clinical, biochemical and instrumental parameters with the development of CAD. The mathematical and statistical completeness of the description of the patient’s condition by the parameters of pathology on the basis of the measure of reliability of the completeness of the description was R = 0.98-1.0, the coefficient of determination was equal to R² = 92.0-98.0%. The main clinical and laboratory parameters that affect the progression of the disease, as well as the main triggers for the initiation of the process have been identified in the application of this method.

Conclusions
The results of the study, obtained by applying a new mathematical analysis of the data, confirmed the theory of atherosclerosis. Total cholesterol and LDL cholesterol were the main factors in the formation of CAD in this model. Blood pressure, GGT and triglycerides become essential trigger-factors in the development of disease. The presence of atherosclerotic plaque in the carotid artery appeared as the marker of the disease. This method requires further study, creating models of other pathological conditions, and interactions of the essential trigger-factors should be investigated.

Keywords
CAD, Risk factors, Mathematical modeling, Triggers, Interaction graph, Aggregated matrix

Introduction
Cardiovascular diseases (CVD) are the main cause of death and disability of the population, and therefore society suffers large human and financial losses [1]. How to minimize costs while maintaining maximum diagnostic accuracy and thereby optimize treatment costs? Numerous studies in the field of preventive cardiology, focused on the analysis of risk factors for cardiovascular diseases, and an attempt to answer these questions have been carried out over the past decades [2-5], many investigations are still ongoing and new ones are being planned. Despite the fact that some years ago the international medical society celebrated the 100th anniversary of the publication of the first studies of the outstanding Russian scientist N.N. Anichkov on the pathogenesis of atherosclerosis and its infiltrative theory [6-7], the search for new risk factors for cardiovascular diseases is still an urgent task in preventive cardiology [8].

At the same time, it is worth noting that in medical studies, as a rule, limited data are analyzed and we do not take into account the influence of other conditions and diseases that the patient has. For example, in the prediction of cardiovascular diseases, we estimate known indicators and risk factors for cardiovascular diseases and as a rule do not take into account other biochemical markers that are not related to the development of CVD, clinical conditions and other factors.
This “linear” approach leads to certain limitations in knowledge and understanding of which factors in a particular patient ultimately lead to the development of the disease and its complications. Our work in this direction was devoted to the complex analysis of the causes of development of disease and the joint influence of various factors on it. This publication reflects the cardiological part of this study, namely the analysis of the factors that influenced the formation of coronary artery disease (CAD) in this category of patients.

Aims & Objectives

Our aims and objectives are to follow the correlation of CAD development with various clinical and laboratory parameters and risk factors in a cohort of patients with multiple medical conditions and evaluate the effect of various parameters in the development of the disease using a new mathematical model approach.

Materials and methods

The study was retrospective. A survey of patients being treated and evaluated by the Department of Cardiology and Internal Diseases of the United Hospital with outpatient department has been completed in the period from January to December 2012, when the patients were subsequently selected and included in the present study, based on the rules of the local register [9].

Our applicable exclusion criteria were as follows:
1. Persons under the age of 18 years.
2. Female representatives.
3. Lack of information to meet the inclusion criteria.

Our applicable inclusion criteria were as follows:
1. An examination for the detection of cardiovascular diseases and cancer during the hospitalization period.
2. The surveys for verification of diagnosis of CAD (as confirmed by medical records). Verified methods of the existing recommendations [10] were considered as follows: treadmill exercise stress test, multislice computed tomography with intravenous contrast and evaluation of coronary artery calcium score (MSCT CA) and / or coronary angiography (CAG).
3. Surveys for verification of the diagnosis of prostate adenoma (as confirmed by medical records). Verified methods of the existing recommendations [11] were as follows: examination by an urologist, a blood test for PSA and TRUS, and conducting a puncture prostate biopsy, when indicated, followed by histological examination of biopsy for final diagnosis verification.

As a result, 12 patients were included in the study. In accordance with the task, only cardiac pathology in these patients and the contribution of different characteristics in its development has been studied in the first part of the study. These co-morbidities, including urological, are deliberately ignored herein, since an analysis of cancer pathology is the second part of our study.

Comprehensive survey data of 12 patients were selected for the implementation of a new analytical approach in the medical research on the following parameters:

Our research method can be structured as follows:
1. During stage one the most important was a qualified selection of a set of biochemical parameters and instrumental examination results for each patient. All parameters were grouped based on reference values (N – norm, BN - below norm, AN – above norm; parameters that did not require interpretation as reference values were groups as NN – not norm) or according to the category feature of its presence (yes/no).
2. During stage two a specific possibility of the presence of each parameter was determined using mathematical procedures [12, 13] for each patient individually.
Table 1. Factor loadings according to the study parameters in 12 patients

<table>
<thead>
<tr>
<th>Factor 1</th>
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<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
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<tr>
<td>(+1,0) – (+0,72)</td>
<td>(+0,71) – (+0,4)</td>
<td>(+0,39) – (0,0)</td>
<td>(-0,01) – (-0,39)</td>
<td>(-0,40) – (-0,71)</td>
<td>(-0,72) – (-1,0)</td>
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Note: levels of parameters of factor scales are dispersed in six intervals:
1) (+1.0) – (0.72) in this interval the average value of factor scales is 74.0% - this is qualified as a strong correlation with a plus. 2) (+0.71) – (-0.40) – average value of factor scales is +31.0%. This value is qualified as a reflection of reciprocal action of average strength parameters. 3) (+0.39) – (+ 0.01) – average value of factor scales is +4.0%. This is deemed as noticeable, but has a week effect with a plus sign 4) (-0.01) – (0.39) this is a noticeable value, and has a weak effect with a negative sign in context at minus 4.0%. 5) (-40.0) – (-0.71) this value is qualified as a fact of significant reciprocal action of moderate strength, average value is negative 31.0%. 6) (-0.72) – (-1,0) is qualified as a strong negative factor minus 74.0%.

Abbreviations “N” is norm; “AN” – above norm; “BN” – below norm
Figure 1. Graph of correlations of clinical, biochemistry and instrumental parameters
3. During stage three the use of factor analysis [14, 15] allowed determination of the effect of each parameter in each specific patient and obtained information was systematized for the whole study cohort. The results of the analysis of the study group in 41 parameters presented in Table 1. The parameters of the factor analysis grouped in it – the numerical values for the factor load calculated on the basis of an aggregated matrix for 12 patients. CAD was diagnosed in eight of all 12 patients on the basis of clinical and instrumental methods of examination.

Our task was to identify the parameters with significant effect on CAD development and a correlation between them in this cohort of patients by means of the probability mathematical model approach. At the same time, amongst the subgroup of patients without CAD diagnosis based on standard examination method, it was required to determine the combination of parameters responsible for such condition of the patients.

When analyzing data in Table No.1, it is noticeable that 2/3 of parameter values are centered in the field for factors 3 and 4, which have a significant effect on a formation of a cardiac pathological condition in this cohort of patients. Thus from the total of 41 parameters, only 7 parameters form the combination of parameters, which have been found correlated and primarily responsible for the development of CAD for the population of 12 patients: 9 (cholesterol), 14 (urea), 15 (creatinine), 20 (ALT), 25 (alkaline phosphatase), 27 (bilirubin), 29 (maximal platelet aggregation), 32 (Presence of changes during Holter monitoring ECG), 37 (MSCT CA – stenosis >50.0%), 39 (Coronarography – stenosis >50.%).

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4. During stage four, the graph of correlation of parameters characterizing presence of cardiological pathological condition (i.e. development of CAD) was created according to the results of cluster analysis (see Fig No.1), based on the measurements of Euclid distances between the values of parameters [16].

An important task of the study in this case was the establishment of correlations between analyzed clinical and instrumental parameters and blood biochemistry tests. Since it was possible to propose that the presence of these systemic correlations itself characterizes the process of development of CAD.

Results

Creation of graph of correlations of clinical, biochemical and instrumental parameters revealed four correlated macrostructures (see Fig No.1).

Parameter No.34 (intima-media AN) located in the center of the first macrostructure, has demonstrated more correlations with other, primarily instrumental parameters.

The previous macrostructure through correlations with No.24 (GGT - N), No.12 (triglycerides - AN) and No.12 (triglycerides - N) is connected with the second macrostructure, which consists of four parameters: No.11 (LDL - AN), No.9 (cholesterol - AN), No.11 (LDL - N), No.9 (cholesterol - N). The second macrostructure is connected with the third one.

22 parameters in the third macrostructure are interlinked, of which 9 have above norm (AN) value. Two of them are instrumental and reflect cardiological status of the patient (CAD presence). These parameters are No.37 and No.39, and they are above norm (MSCT CA >50%, and CAG >50%).

In other words the correlated parameters of the third macrostructure reflect CAD in patients. The correlated parameters of this structure reveal the condition of CAD in the shape of internal structure of correlation of instrumental, clinical and biochemical blood parameters. Seven of these correlated parameters are blood laboratory values above norm (AN): No.5 (erythrocytes - AN), No.24 (GGT - AN), No.22 (CPK - AN), No.8 (Glucose - AN), No.28 (Fibrinogen - AN), No.23 (Amylase - AN), No.16 (Potassium - AN).

Also, 11 other parameters included in the third macrostructure below norm (BN), norm (N) and not norm (NN) are of significance. 7 of them are clinical and instrumental parameters: No.34 (intima-media - BN), No.2 (BP - BN), No.2 (BP - N), No.31 (ECG - NN), No.33 (treadmill test - NN), No.38 (MSCT CA <50%), No.40 (CAG <50%). The other 4 correlated parameters are laboratory parameters: No.5 (erythrocytes - BN), No.25 (alkaline phosphatase - BN), No.12 (triglycerides - N), No.16 (potassium - BN).

The fourth macrostructure, also correlated, like the third, with the second macrostructure (which as a whole could be characterized as “cholesterol nucleus”), consists of 21 correlated parameters. However, only three of them: No.36 (AP in the area of bifurcation of the right CCA – stenosis – AN), No.33 (treadmill test – N), No.40 (CAG <50%) were instrumental.

Parameter No.36 has the maximal amount of correlations. The rest parameters of clinical and biochemical blood tests are normal: No.29 (maximal aggregation - N), No.18 (calcium - N), No.15 (creatinine - N), No.23 (amylase - N), No.22 (CPK - N), No.13
(uric acid - N), No.10 (HDL - N), No.8 (glucose - N), No.16 (potassium - N), No.7 (ESR – N), No.6 (leucocytes - N), No.5 (erythrocytes - N), No.27 (bilirubin - N), No.4 (hemoglobin - N), No.19 (AST - N), No.3 (HR – N), No.25 (alkaline phosphatase - N), No.28 (fibrinogen - N).

Discussion

In this study by using the mathematical model approach we have confirmed N.N. Anichkov’s atherosclerosis theory [17]. Formation of CAD has a complex nature and is developed in the “force” field of heterogenic “cholesterol” nucleus. Based on the graph of correlations one can differentiate the presence of absence of CAD on this model. The third and fourth macrostructure of multiple correlations of instrumental, clinical and biochemical blood parameters reflect various clinical conditions (the presence or absence of CAD, respectively) and have a common “cholesterol” nucleus of correlations (the second macrostructure). One of the trigger elements for the transition from the nucleus to third or fourth structures is its heterogeneity, i.e. the condition of norm or above norm for parameters No.9 and No.11 (cholesterol and LDL).

It is noticed that one third of parameters in the third and fourth macrostructures (with CAD and without CAD) are the same. This can be explained by the fact that the fourth macrostructure characterizes a borderline condition, where all patients are not yet in a state of “disease”. At the same time in the third macrostructure there are factors which allow the process of development (formation) of CAD to be realized. Apart from standard lipid factors, other correlated with the disease parameters were as follows: No.14 (urea), No.15 (creatinine), No.20 (ALT), No.25 (alkaline phosphatase), No.27 (bilirubin), No.29 (maximal platelet aggregation), as well as No.5 (erythrocytes - AN), No.24 (GGT - AN), No.22 (CPK - AN), No.8 (Glucose - AN), No.28 (Fibrinogen - AN), No.23 (Amylase - AN), No.16 (Potassium - AN). These parameters were heterogenic and were outside of the limits of reference values and reflected changes of the other organs and systems, primarily in kidneys, liver and hemostasis.

But in order to initiate the process of the disease development, additional triggers must interfere (which until a certain time do not have its catalytic effect). Such triggers in our analysis were: BP, GGT and triglycerides.

The step for transition from the fourth to the third macrostructures upon combination of all of the parameters above is parameter No.36 (the presence of atherosclerotic plaque (AP) in CCA).

As a conclusion it should be noticed that the results presented in this article confirm the possibility of conduction medical scientific studies on small samples of patients. When using the described approach, we have realized a new method of preparation of databases and methods of their analysis (large samplings are not required as against the standard medical data research procedures).

Apart from that, our diagnostic method allows creation of numeric description, up to each individual patient, as a certain set. Evidence-based medicine in measurement suggested by the authors can gain the status of personified targeted diagnostics. Because evidence-based medicine is founded on analyzing large samples through a statistical computational culture using averaged parameters, it provides general knowledge. But at the same time, it explains the loss of a certain part of this knowledge due to the fact that, as a rule, parameters deviating from the mean (disper) are not studied with this approach.

Current publication is a result of scientific study presented as Patent for Scientific Invention No.2632509 “Method of diagnostics of non-infectious diseases based on the statistical methods of data processing” (Registration Number No. 2015125360 (OGRN [Primary State Registration Number] VOIS code ST-3.RU).

Conclusions

The results of the study, obtained by applying a new mathematical analysis of the data, confirmed the theory of atherosclerosis. Total cholesterol and LDL cholesterol were the main factors in the formation of CAD in this model. Blood pressure, GGT and triglycerides became essential trigger-factors in the development of disease. The presence of atherosclerotic plaque in the carotid artery appeared as the marker of the disease. This method requires further study, creating models of other pathological conditions, and to study their interactions.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.
Conflict of interest
None declared.

Source of Economic Support
None.

Author Contributions
This work was carried out in collaboration between both authors. Both authors read the ICMJE criteria for authorship, read and approved the final manuscript.

References
Challenging task of identification of cardiac cycle tones: refined development of a PCG signal processing system

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Abstract
This article presents some results of processing of phonocardiography signals (PCG signals) for cardiac cycle tone identification under ambient noise of varying intensity. For PCG signal processing, proposed is a refined approach based on active band pass filter bank, which allows improving an accuracy of cardiac cycle tone identification under ambient noise. The efficiency of the application of the proposed approach has been demonstrated by the respective qualitative, quantitative results and experimental data obtained upon processing of PCG signals according to the offered technique. A 3D model of the cardiac cycle tone identification system has been developed based on this conceptual idea.

Keywords
Processing, Phonocardiogram, Filter bank, Identification, Cardiac cycle tones, Electronic stethoscope, Visualization, Heart biomechanics

Imprint

Introduction
According to statistics from the World Health Organization (WHO), cardiovascular diseases are the primary cause of death worldwide [1,2]. To diagnose diseases of the cardiovascular system, phonocardiography, electrocardiography, electronic auscultation, and many other methods are currently used in medicine [2–4]. Phonocardiography is a method for studying the biomechanical heart activity, based on recording sound vibrations of the heart muscle and valve apparatus [2]. In the scientific literature, the identified phonocardiography signals (PCG signal) are usually called cardiac cycle tones, and their activity is conventionally referred to as biomechanics [2,3]. In practice, the cardiac cycle tones are identified by phonocardiographs or electronic stethoscopes. To simplify the recording procedure for cardiac cycle tones, on a person’s torso, a stethoscope with an electronic microphone embedded into the head is utilized [4-8]. A stethoscope is an acoustic device for listening to sound phenomena (auscultation) of internal organs (part of body). The use of electronic microphones in heads of a stethoscope for phonocardiography studies today is quite justified [4–9].

The process of identifying cardiac cycle tones consists of the following stages: recording a PCG signal at the auscultation points of the heart, an amplification of the PCG signal and its subsequent processing (filtering) with further visualization with a specialized device [3,9]. However, in practice, the identification of cardiac cycle tones is greatly complicated by the influence of ambient noise of varying intensity [3,4,9]. Under the influence of such noise, the accuracy of identification of cardiac cycle tones is significantly reduced that may lead to inaccurate visualization of phonocardiography information [9]. Thus, the development and study of filtering approaches to improve the accuracy in identifying cardiac cycle tones against the background of noises are actually a very challenging task.

At present, to solve this problem, known are some approaches [5–8], which are based on active, passive (low-frequency and high-frequency) PCG signal filtering. An analysis of the well-known works has revealed the following features of these conventional approaches: during the passage through the filtering blocks, the identified cardiac cycle tones are smoothed
and clipped that results in a crackling of the identified tones of the cardiovascular system performance and noise distortion and that demonstrates the narrowness of the transmission bandwidth low-frequency and high-frequency components of the filters. Considering the revealed drawbacks and disadvantages of the known approaches, a pioneering approach, based on active cascade band pass filtering, has been proposed in [9] to improve the accuracy of identifying tones. This fresh approach makes for extended frequency bands, namely in the mid-frequency range of cardiac cycle tones from 40 to 120 Hz, possible to reduce ambient noise. To justify the practical significance of the proposed fresh approach, experimental studies have been conducted. As a result of the study, the effectiveness has been confirmed by visualization of the PCG signal processing data on the recorded phonocardiograms with the use of Software Proteus.

As an extension of the approach presented in [9] in this work it is proposed to use a filter bank consisting of active band pass filters on operational amplifiers, where their frequency range overlaps. Our refined approach allows eliminating noise on extended frequency bands and identifying low-frequency, mid-frequency and high-frequency tones in a cardiac cycle. A similar conceptual idea is used in the processing of respiratory signals of the lungs and demonstrates the results of high accuracy [10].

This article discusses our refined approach for identifying cardiac cycle tones using the filter bank, which allows us reducing noises of varying intensity at extended frequency bands, thereby increasing accuracy in the PCG signal identification.

**Aim**

The aim of our research is to confirm the possibility of using an active band pass filter bank to improve the accuracy of identifying cardiac cycle tones when visualizing biomechanical activity of the cardiovascular system.

**Materials and methods**

To obtain quantitative and qualitative results, test patterns of a PCG signal and noise at different intensities have been employed. The PCG-signal model with the present noise is taken additively, in the form of

\[ x(t) = S(t) + n(t), \]

representing PCG signal \( S(t) \) and ambient noise \( n(t) \). When using model distorting effects, a priori information about the nature of noise is mainly applied. Models of ambient noise are based on normally distributed white noise, which is limited throughout the signal frequency band [11]. White noise models at various power values have been obtained utilizing Adobe Audition 1.5 software (developed by Adobe System) [12]. The test model of the PCG signal has been obtained from the certified International Database of the Massachusetts Institute of Technology (MIT) [13].

The phonocardiographic signals are filtered by a bank of active band pass filters on operational amplifiers, whose frequency range is overlapped. Such a PCG signal filtering scheme has been chosen on the basis of the expediency to increase the accuracy characteristics of the consequently identified cardiac cycle tones, namely, components S1 and S2 against the background noise. The frequency range of these filters is designed for an extended frequency band filter bank with the series connection of active band pass filters. For filter synthesis, a frequency analysis of components S1 and S2 is performed using the Fourier transform on the amplitude spectrum [2, 3].

A filter characteristics analysis is performed on the basis of calculation of the transfer function of the active band pass filter [14]. The frequency and phase characteristics of the analyzed filter are investigated on the basis of the Bode diagram in software MATLAB.

The effectiveness of PCG signal filtering is estimated by the respective qualitative and quantitative results. An analysis of the processing quality is performed by visual imaging [15]. An analysis of the quantitative processing results is evaluated by several criteria. These criteria are the following indicators: the signal-to-noise ratio (SNR) before and after filtering the signal (2), (3) [15], the root mean square error of signal filtering (RMSE) (4) [3] and the correlation coefficient between the filtered and the test PCG signal (r) (5) [3].

\[
\text{SNR}_{\text{before filtering}} = 10 \log_{10} \left[ \frac{\sum_{n=1}^{N} x(n)^2}{\sum_{n=1}^{N} (s(n) - x(n))^2} \right], \quad (2)
\]

\[
\text{SNR}_{\text{after filtering}} = 10 \log_{10} \left[ \frac{\sum_{n=1}^{N} x(n)^2}{\sum_{n=1}^{N} (x(n) - x(n))^2} \right], \quad (3)
\]
\[
RMSE = \sqrt{\frac{\sum_{n=1}^{N} (x(n) - x'(n))^2}{N}},
\]

(4)

\[
r = \frac{\sum_{n=1}^{N} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{n=1}^{N} (x_i - \bar{x})^2 \cdot \sum_{n=1}^{N} (y_i - \bar{y})^2}},
\]

(5)

where \(x(n)\) – test PCG signal, \(s(n)\) – noised signal, \(x'\) – de-noised signal, \(x_i\) – current value length of the filtered PCG signal, \(\bar{x}\) – mean value length of the filtered PCG signal, \(y_i\) – current value length of the test PCG signal, \(\bar{y}\) – mean value length of the test PCG signal.

To study the correlation strength of the signal values between the filtered signal and the test one, it is estimated employing a scatterplot with the use of the STATISTICA 10.0 application software (developed by Stat Soft) [16].

Our experimental studies have been performed using an electronic stethoscope with an embedded electronic microphone [9]. Recording and processing of cardiac cycle tones have been conducted in a human individual, aged twenty-seven, in the absence of any physical activity, in his upright position. Visualization of the identified tones cardiac cycle has been carried out using software product Proteus 7.10 (developed by Labcenter Electronics) [17]. 3D-modelling of the developed system has been realized also with the above mentioned software product.

### Results and discussion

For the synthesis of the parameters of the filter bank, the respective quantitative results of the analysis of frequency components of the S1 and S2 tones, based on the Fourier transform, have been obtained. As a result, component S1 has been identified to be in the range from 30 to 120Hz, and S2 from 40 to 200Hz, respectively, as shown in Figure 1 herein. Based on the identified frequency values, a filter bank has been synthesized, the results of which are presented in Figure 2 given herein.

The results of the analysis of the amplitude and phase characteristics depending on the identified frequencies have shown the following: a) the filter bank has the most flat (uniform) frequency response; b) it has moderate phase nonlinearity; c) it has rather a steep fall-off outside the signal bandwidth that is indicated by the proximity to the ideal form of band pass filters (see Figure 2 herein).

The analysis of the obtained filter bank characteristic shows that the filter bandwidths for identifying the components S1 (dashed line) and S2 (solid line) are overlapped and suppress ambient noise outside the signal bandwidth. Following the results of the analysis, we will process the PCG signal to identify cardiac cycle tones. To assess the efficiency of our proposed approach...
Based on the obtained qualitative and quantitative results, we note that the developed filter bank allows us to identify the morphology of the S1 and S2 components of the cardiac cycle tones against the background noise. A histogram of the quantitative results for signs of noise stability (noise resistance) and accuracy is presented in Figure 4 given herein.
Figure 4. Histogram of quantitative results of PCG signal processing; a) indicator SNR; b) indicator RMSE

Figure 5. The scatter plot diagram dependence filtered and test PCG signal: a) the proposed approach; b) the known approach [9]

The quantitative results and high SNR index values as exhibited by the histogram indicate the noise stability of the PCG signal (noise resistance) to noise at -5dB, 0dB, 5dB compared with the approach in [9]. Low RMSE values show the accuracy of identifying cardiac cycle tones, namely, components S1 and S2. Furthermore, the correlation coefficient between the filtered and test signal is $r = 0.968$. When using the known approach [9], the value of the correlation coefficient is $r = 0.839$. Thus, to systematize the quantitative results obtained, Figure 5 herein shows a scatter plot showing the strength of the correlation of values between the filtered and the test PCG signal.

The scatter plot results have demonstrated that the developed approach (Figure 5a) herein) reveals a very high correlation $r = 0.96880$ with a probability of 0.95, with statistical significance $p < 0.05$. A very high correlation processing result $r = 0.96880$ is available due to minimal distortions of the PCG signal processing results and accuracy of identification cardiac cycle tones against the background noise.

Thus, our analysis of the obtained qualitative and quantitative results upon processing the PCG signals makes it possible to note that the developed filter bank allows improving the accuracy of identifying cardiac cycle tones in the presence of noises of varying intensity. This refined approach maximally eliminates ambient noise with minimal distortion of low-frequency, mid-frequency and high-frequency cardiac cycle tones that is confirmed by the qualitative, quantitative and statistical results of the analysis of signal processing relative to [9].

To justify the practical significance for the developed filter bank intended for identifying tones, when processing the PCG signals, Figures 6–8 herein present...
ent visualization graphs of our experimental study. During the experiment, the PCG signal has been recorded using an electronic stethoscope and visualized using the Proteus software.

Based on the obtained experimental results (please, refer to Figures 6–8 herein), we can note that our refined approach confirms the identification of the cardiac cycle tones during the biomechanical heart activity in a human individual under study. As it is evidenced by the results of our experimental study, our developed approach allows identifying cardiac tones not only of the test signal in the presence of noise, but also of experimentally generated ambient noise PCG signal. Furthermore, the visualization of the cardiac cycle tones shows that the examined subject has no abnormalities, and the recorded tones completely coincide with the cardiac cycle of the vascular system. Figure 9 herein shows our 3D model of the developed PCG signal processing system.

Conclusion

The paper proposes our refined approach for identifying cardiac cycle tones when processing the PCG signal based on the bank of active band pass filters. This approach allows increasing the accuracy of identification of cardiac cycle tones against the background of noises of varying intensity. The efficiency of this developed approach is supported by the respective qualitative, quantitative and experimental results of the processing. The processing qualitative results reinforce the identity of the filtered waveform with the test PCG signal, and the quantitative results confirm the improved accuracy in the identification of tones when compared with other known solutions. To provide support for the practical significance and the performance of our developed approach, the required experimental studies have been conducted.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.
Conflict of interest
None declared.

Author contributions
All the authors read the ICMJE criteria for authorship and approved the final manuscript.

References
Fundamentals of Cardio-Oculography (Cardio-Oculometry)

Original publication, first release
Cardiometric detection of effects and patterns of emotional responses by a human individual to verbal, audial and visual stimuli

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Aims
The article presents the results of an experimental study of the cardiometric detection of a person’s emotional reactions to verbal, audial and visual stimuli.

Materials and methods
To test the hypothesis of our study, we carried out a series of experiments in which two groups of stimuli have been used purposefully, one of which had to cause sthenic and the other asthenic reactions in our examinees. In order to activate various types of sensory systems, only stimuli of the audial modality (the A-type stimuli), only visual modality (the V-type stimuli), and also stimuli with a combination of audiovisual modalities (the VA-type stimuli) have been included in each group. In addition, as stimuli, we prepared a list of imaginary situations (the I-type stimuli) to initiate either sthenic or asthenic emotional reactions in the examinees. For the cardiological data recording and subsequent assessment of HRV, we used the Cardiocode PC-assisted hemodynamic analyzer. Portable eyetracker GP-3 has been employed to record the examinees’ oculomotor reactions to visual stimuli.

Results
As a result of the study, it has been identified that the Baevsky stress index (SI) values, which are higher than the average values, can be considered as a fingerprint of a sthenic reaction to a stimulus, and the reduced SI value can be considered as a marker of an asthenic reaction to a stimulus. In addition, the data obtained confirm a more efficient use of the SI indicators in comparison with the heart rate parameters in assessing the nature of a human individual’s emotional reactions.

Oculographic manifestations of a moderate response to the presented visual stimuli may be the preferential fixation of respondents’ gaze at the yellow, green and blue colors from the eight-color Lüscher test. The asthenic nature of the response is most often combined with an involuntary gaze fixation at grey, black and brown colors of the Lüscher test. The pronounced sthenic reaction is most often indicated by the involuntary gaze fixation at red and yellow, red and black, red and brown, yellow and brown, observed when one visual stimulus being exposed, with marked ignorance of blue and gray.

Conclusions
Consequently, our experiments confirm our main hypothesis that the increased Baevsky stress index values, in comparison to the average values, can be considered as a fingerprint of the sthenic response to a stimulus, and the reduced SI value can be considered as a marker of the asthenic one.

Keywords
Cardiometry, Cardiocode, Sthenic reaction, Asthenic reaction, Oculometric diagnostics, Eyetracker

Introduction
The Heart Rate Variability (HRV) analysis has long been one of the most effective cardiometric methods [1, 3, 4, 8-10, 14-17], and, from the very beginning of using HRV assessments in practice, a strong influence of the individual’s emotional state produced in cardiac measurements on the obtained results has been noted as one of the HRV features [1, 3, 4]. Therefore, it is not surprising that for more than half a century many attempts to use the HRV values in studies of various types of mental processes and individual states have been made [3, 4].

Initially, HRV has been considered as a fingerprint of changes in psycho-emotional loading when solving mathematical tasks [4]. Later, as HRV parameter calculations have been improved, it has been applied to...
study different types of thinking and attention, cognitive control and motivation [3, 4]. Thus, for example, it has been found that as the individual's motivation increases, the contribution of the Mayer waves to HRV increases (as is known, this sort of waves is usually associated with vasomotor responses to a certain stimulus). A number of researchers have shown that the HRV wave changes in the range from 0.07 to 0.11 Hz can be utilized for an assessment of the subjective value of the current task to be solved by the subject tested.

Considering the HRV study results, taking into account the topic of our paper, of particular importance is the obtained evidence that the Mayer waves demonstrate a significant positive correlation with the Traube-Hering waves, observed during plethysmogram recording. Besides, similar correlations have been identified between HRV and galvanic skin reactions, occurring in individuals in response to various imaginary situations [4]. The identification of such correlations has initiated searching by some polygraph developers for ways of using HRV in concealed information detection. An example of the successfully realized engineering solution is the Baevsky stress index application in the "Epos" polygraphs for assessing the pre-test state of a suspect [2].

However, from the very beginning of using HRV in an assessment of human individual emotional responses, in particular, when applying the stress index (SI) parameter proposed by R.M. Baevsky as one of the markers thereof, researchers confused the non-linear nature in their relationship [4]. Problems with the use of HRV in the study of mental processes and states have been aggravated by the ambiguity of the examined persons' responses to, for example, test tasks of the same level of complexity. The attempts to explain such contradictions by exclusively unaccounted artifacts or differences in the examined persons' temperaments turned out to be unproductive. At the same time, many researchers, with enviable persistence, ignore the pronounced subject-genesis nature of such responses. Thus, in our opinion, the differences in HRV manifested when solving the numerical and the Stroop test tasks of the similar complexity reveal the subject-genesis nature of this kind of responses [4]. The paradoxical differences, as it may seem, between the cosmonauts' HRV in the spacecraft and that in the scheduled training on the Earth and immediately before launching show a clear subject-genesis nature [8].

As a result, even some doubts about the applicability of HRV in assessing the human psycho-emotional states have appeared [2].

In our opinion, one of the reasons for the difficulties, when using HRV in solving applied psychological problems, is that ignored are personological factors, especially the ability and desire of a human to be the subject of his/her own life, to act as the primary generator of his/her own activity. But without regard for the desire of a human to be the primary generator of his/her own activity, any analysis of emotional responses as an integral part of his/her self-regulation system loses its meaning. In our opinion, a way out of the difficulty can be found by treating the HRV variations as indicators of the character of a decision made by a human individual. In this case, for example, a significant excess in the Baevsky stress index (SI) values of average indicators can be considered as a marker of the examinee's choice in favor of intensification of his/her active actions, i.e. as a sthenic response to a stimulus. Following this logic, the SI values, which are much less than the average values, can be judged to be a sign of the examinee's choice in favor of his/her inaction, or a reduction in his/her activity, i.e. to be an asthenic response to a stimulus.

Materials and methods

To test the hypothesis of the study, we have carried out a set of experiments with the targeted use of two groups of stimuli: the first group thereof is presumed to cause sthenic responses, while the second one assumes to initiate asthenic responses in the examinees. In order to activate different types of the sensory systems, we have included in each group the stimuli of the audial modality only (the A-type stimuli), the visual modality only (the V-type stimuli) and the combined audio-visual modalities (the VA-type stimuli). Besides, for further stimulation type, we have prepared a list of imaginary situations (the I-type stimuli), which can produce either sthenic or asthenic emotional responses in the examined individuals.

The following audio recordings have been included into the scope of the A-type stimuli to induce the sthenic response:

- A-1 is the solemn patriotic song of the Great Patriotic War period “The Sacred War” (the lyrics are by V. Lebedev-Kumach, music by A. Alexandrov) performed by the A. V. Alexandrov Twice Red-Bannered and Red-Starred Academic Song and Dance Ensemble of the Russian Army;
A-2 is the March of the Soviet Tankmen “Three Tankmen” performed by Nikolai Kryuchkov (lyrics by B.Laskin, music by Pokrass brothers); A-3 is the “Peremen” song (“Changement!”) by the Soviet rock group “Kino” performed by Victor Tsoi. The following audio recordings have covered the A-type stimuli to initiate the asthenic reaction: A-4 and A-5 are referred to the audio recordings of songs “Cuckoo” and “Be wary!” performed by Victor Tsoi. A-6 is represented by song “The Isle of Bad Luck” performed by Andrei Mironov (lyrics by L. Derbenev, music by A. Zatsepin).

As the VA-type stimuli in the experiments, used have been the video clips, the visual, musical and textual components of which have been: either clear-cut sthenic in their nature: “Go, Russia!” (Mark Tishman), “Black or White” (Michael Jackson), “I Believe” (Lyapis Trubetskoy) should be referred to as the VA-1, VA-2 and VA-3 stimuli, respectively; or asthenic in their nature: “Pechal” (Viktor Tsoi, Kino), “My Love” (Aleksandr Uman, Egor Bortnik, Bi-2), “Two ships” (rock group “Agata Kristi”) should be related to the VA-4, VA-5, VA-6 stimuli, respectively.
As to the V-type stimuli, we have prepared a series of pictures that examinees have viewed on an eyetracker screen that has been accompanied by parallel measuring their cardiometric parameters. The series has included stimuli with colored square boxes, not variable from one image to the next, as well as varying animal photos and test-related value judgments, located in the center of the screen. The invariable constituent of such stimuli has been created by the square boxes of green, blue, yellow and red color placed along the upper edge area line of the screen, and the squares of brown, black, gray and lilac color (the side length of the square has been chosen of the same size (28 millimeters), as it is the case with the color squares in the Lüscher eight-color test in the printed version of the complete set of the relevant subtests [16]), arranged along the lower edge area line. The variable part of this stimulation group consists of the photos of a lion (stimulus V-1) and a newborn defenseless kitten (stimulus V-2), which change each other in the center of the screen, when moving from stimulus to stimulus, as well as words “active” (stimulus V-3), “passive” (stimulus V-4), “movement” (stimulus V-5) and “rest” (stimulus V-6), “depressive” (stimulus V-7) and “joyful” (stimulus V-8).

The I-type stimuli incorporate the test tasks for examinees to imagine the following situations upon instructing by the experimenter:

I-1 is a scandal involving someone of their relatives;
I-2 is a quiet peaceful conversation with any of their friends;
I-3 is a sleepy, relaxed state experienced in warm water, when taking bath;
I-4 is the vigorous exercise performed in the morning;
I-5 is a leisurely walk in the forest under comfortable conditions;
I-6 is a sudden attack by an aggressive dog;
I-7 is a trip in a crowded public transport in the close neighborhood of a casual fellow traveler who is loudly talking on a mobile phone;
I-8 is a comfortable trip in a half-empty public transport vehicle.

In the described experiments, 188 respondents aged from 15 to 69 years, have taken part in our studies, and 103 persons in the cohort are female. For recording of the cardiological data and the subsequent assessment of HRV, we have employed the Cardiocode PC-assisted hemodynamic analyzer (Fig.1), the general principle of operation and the functional features of which are described in detail in [9, 10, 14-17]. Portable eyetracker GP-3 has been employed to record the eye movement responses to visual stimuli; the various capabilities of the eyetracking equipment in oculometric diagnostics and its successful application in combination with the Cardiocode PC-assisted hemodynamic analyzer have been detailed in [5-7, 11, 12]. The time covering the exposure of each stimulus and recording of the related cardiological data is 20 seconds (Fig.2).

When working with each examinee, we have determined the respective stimulus-conditioned stress index (SI) values in the regulatory systems and the heart rate (HR) parameters. When employing the V-type stimulation, in addition thereto, the time of the examinee’s gaze fixation at certain fragments of the visual stimulus has been recorded with the eyetracker and its percentage (%) of the total stimulus exposure time have been calculated.

The statistical analysis of the obtained data has been performed using universal statistical software package STADIA 8.0 (“Big version” with a data volume of 64000 digits).

A normality test has been applied to determine that the obtained data sets are well-modeled by a Gaussian distribution with the use of the Kolmogorov criteria as well as the omega-squared test and the chi-squared test. It has been found that the HR values only are well-modeled by the Gaussian distribution. Therefore, to assess the degree of similarity and difference between the SI values and the fixation durations analyzed by the eyetracker, the non-parametric criteria such as the Chi-square, the Spearman’s rank correlation coefficient and the Kendall correlation coefficient have been applied, and for an analysis of the HR values applied have been the parametric criteria such as the Pearson correlation coefficient, the Fisher and Student statistics, as well as all the above non-parametric criteria.

**Results and discussion**

Main statistical parameters of the obtained experimental data distributions are presented in Tables 1–4 herein.

When processing the average statistical indicators obtained with the eyetracker, objective experimental evidence to support our idea of the sthenic and assthenic nature of the V-type stimuli has been found.
Table 1. Main statistical data upon analysis of measured parameters upon exposure to stimulus Type A

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Measured parameter</th>
<th>Sample mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>SI</td>
<td>657</td>
<td>538</td>
</tr>
<tr>
<td>A-2</td>
<td>HR (beats per minute)</td>
<td>89</td>
<td>10</td>
</tr>
<tr>
<td>A-3</td>
<td>SI</td>
<td>391</td>
<td>269</td>
</tr>
<tr>
<td>A-4</td>
<td>HR (beats per minute)</td>
<td>84</td>
<td>9</td>
</tr>
<tr>
<td>A-5</td>
<td>SI</td>
<td>521</td>
<td>340</td>
</tr>
<tr>
<td>A-6</td>
<td>HR (beats per minute)</td>
<td>87</td>
<td>9</td>
</tr>
</tbody>
</table>

Thus, when using pictures with an unchanged set of the colored square boxes, it has turned out that when a lion picture (the V-1 stimulus) has appeared in the center of the screen, the respondents' gaze has been concentrated on the yellow and red squares for a longer time (14% and 12% of the total stimulus exposure time, respectively). As is known, the respondents' choice of such color combinations from the Lüscher test is among the markers of the inspiration and excitement experienced by the test subjects [14]. In the case under consideration, the respondents' fixation at the gray and brown squares has taken their shortest time (2% of the total stimulus exposure time).

Table 2. Main statistical data upon analysis of measured parameters upon exposure to stimulus Type VA

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Measured parameter</th>
<th>Sample mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA-1</td>
<td>SI</td>
<td>797</td>
<td>735</td>
</tr>
<tr>
<td>VA-2</td>
<td>HR (beats per minute)</td>
<td>87</td>
<td>11</td>
</tr>
<tr>
<td>VA-3</td>
<td>SI</td>
<td>500</td>
<td>488</td>
</tr>
<tr>
<td>VA-4</td>
<td>HR (beats per minute)</td>
<td>83</td>
<td>10</td>
</tr>
<tr>
<td>VA-5</td>
<td>SI</td>
<td>636</td>
<td>570</td>
</tr>
<tr>
<td>VA-6</td>
<td>HR (beats per minute)</td>
<td>83</td>
<td>10</td>
</tr>
</tbody>
</table>

Analyzing the picture with the same unchanged set of the colored squares, but showing a photo of a defenseless kitten in the center of the screen (stimulus V-2), the respondents' gaze has been concentrated on the grey square for the longest period of time (15% of the total stimulus exposure time). It is known that the choice of this color usually indicates the respondent's latency [14]. In this case, examining the yellow, green and red squares has taken the respondents the shortest time (3-4% of the total stimulus exposure time).

As a result of this part of the study, it has been also found that when displaying the word “active” (stimulus V-3) in the center of the screen, for the longest time respondents have focused their attention on such colors as...
red (21% of the total duration of the corresponding stimulus), yellow (19% of the total duration) and green (14% of the total duration). The least attention in this case has been paid to such colors as brown (2% of the total duration), black (3% of the total duration) and grey (4% of the total duration). When the word “passive” (stimulus V-4) has appeared in the center of the screen, the respondents have paid their greatest attention to such colors as grey (24% of the total duration), brown (11% of the total duration) and blue (11% of the total duration).

Table 3. Main statistical data upon analysis of measured parameters upon exposure to stimulus Type V

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Measured parameter</th>
<th>Sample mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-1</td>
<td>SI</td>
<td>829</td>
<td>651</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>79</td>
<td>10</td>
</tr>
<tr>
<td>V-2</td>
<td>SI</td>
<td>425</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>77</td>
<td>10</td>
</tr>
<tr>
<td>V-3</td>
<td>SI</td>
<td>704</td>
<td>614</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>79</td>
<td>10</td>
</tr>
<tr>
<td>V-4</td>
<td>SI</td>
<td>277</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>78</td>
<td>9</td>
</tr>
<tr>
<td>V-5</td>
<td>SI</td>
<td>519</td>
<td>484</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>77</td>
<td>10</td>
</tr>
<tr>
<td>V-6</td>
<td>SI</td>
<td>220</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>74</td>
<td>8</td>
</tr>
<tr>
<td>V-7</td>
<td>SI</td>
<td>257</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>74</td>
<td>8</td>
</tr>
<tr>
<td>V-8</td>
<td>SI</td>
<td>425</td>
<td>322</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>78</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 4. Main statistical data upon analysis of measured parameters upon exposure to stimulus Type I

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Measured parameter</th>
<th>Sample mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-1</td>
<td>SI</td>
<td>384</td>
<td>293</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>86</td>
<td>11</td>
</tr>
<tr>
<td>I-2</td>
<td>SI</td>
<td>220</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>I-3</td>
<td>SI</td>
<td>205</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>77</td>
<td>10</td>
</tr>
<tr>
<td>I-4</td>
<td>SI</td>
<td>346</td>
<td>262</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>83</td>
<td>11</td>
</tr>
<tr>
<td>I-5</td>
<td>SI</td>
<td>220</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>78</td>
<td>10</td>
</tr>
<tr>
<td>I-6</td>
<td>SI</td>
<td>317</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>81</td>
<td>10</td>
</tr>
<tr>
<td>I-7</td>
<td>SI</td>
<td>292</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>82</td>
<td>11</td>
</tr>
<tr>
<td>I-8</td>
<td>SI</td>
<td>228</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>HR (beats per minute)</td>
<td>79</td>
<td>11</td>
</tr>
</tbody>
</table>
During an alternate demonstration of the pair “movement” (stimulus V-5) and “rest” (stimulus V-6), which are logically connected with the previous conceptions, it has been revealed that in the first case (when the word “movement” is in the center), the respondents have paid their greatest attention to red (17% of the total duration), yellow (15% of the total duration) and lilac (14% of the total duration) colors, and the least attention has been given to grey (6% of the total duration) and black (7% of the total duration). When demonstrating the word “rest”, the respondents have paid their greatest attention to grey (19% of total duration), blue (17% of the total duration) and black (12% of the total duration).

The word “depressive” (stimulus V-7) in the center of the screen has stimulated the respondents to attentively focus on the squares of grey (38% of the total duration) and black (11% of the total duration) colors and pay their least attention to the squares of blue (4% of the total duration) and lilac colors (2% of the total duration). The word “joyful” (stimulus V-8) has encouraged the respondents to fix their attention at the squares of yellow (21% of the total duration), blue (15% of the total duration) and red (11% of the total duration) and ignore the squares of grey (2% of the total duration) and black color (1% of the total duration).

The data given in Tables 1-4 herein demonstrate that the sample mean values of SI and HR for the sthenic stimuli exceed those recorded for the asthenic stimuli, which have been presented immediately after the sthenic stimuli or before them. However, upon the mathematical processing of the obtained data using universal software package STADIA 8.0, the statistical significance of these differences at an error level of no more than 5% has been confirmed for the obtained SI values only.

Conclusions

To summarize the overall data of the study, we can state that the higher SI and HR values correspond to the stimuli of the sthenic nature. The obtained evidence bears also witness to the fact that the lower SI and HR values are referred to the stimuli of the asthenic nature. However, as a rule, only the SI values have statistically significant differences for the sthenic and asthenic stimuli. So, it follows that the conducted experiments confirm our main hypothesis that an increased, in comparison with the average values, Baevsky stress index (SI) value can be considered as a fingerprint of the sthenic response to a stimulus, and its decreased value can be deemed to be a marker of the asthenic response to a stimulus, respectively. Besides, the obtained evidence is treated to be in favor of a more efficient use of the SI values, as against the heart rate values, to assess the nature of a human subject’s emotional responses.

The preferred fixation of the respondents’ gaze at yellow, green and blue colors from the eight-color Lüscher test may serve as oculographic manifestations of a moderate response to the exposed visual stimuli. The asthenic nature of the response is most often combined with an involuntary fixation of the gaze at grey, black and brown colors of the Lüscher test. The pronounced sthenic response is most often indicated by an involuntary fixation of the gaze, observed under the same visual stimulus, at red and yellow, red and black, red and brown, yellow and brown, under a distinct ignorance of blue and grey. Gaze fixation at red and purple color, which in the Lüscher test appears under the name ”magenta”, can also be treated as a marker of the sthenic response.

The obtained evidence has also confirmed the applicability and effectiveness of using short-term recordings (from 10 to 30 seconds) to assess a subject’s psychoemotional response to presented stimuli.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest

None declared.

Author contributions

V.A.Z., E.V.L., L.P.N. and M.Y.R. conceived and planned the experiments, interpreted the results. D.D.D., D.S.Y. P.A.M. and N.V.M. carried out the experiments. A.S.O. took the lead in writing the manuscript. All the authors read the ICMJE criteria for authorship and approved the final manuscript.

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Use of cardiometry and oculography in concealed information detection

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Aims
The article presents the results of an experimental study on the use of cardiometry and oculography to detect concealed information. It has been shown that a complex assessment of the person's emotional-cognitive state based on cardiometric and oculographic recording of reactions to specially selected stimulus material of visual and audial modality can be successfully used in concealed information detection.

Materials and methods
We used the Cardiocode single-lead cardiograph and the GP-3 eyetracker as the instrumental basis for testing the hypothesis of the study. We have selected the above devices taking into account the previous analysis of their functional features and the basic possibility to use both devices together, the availability of the devices for a wide range of researchers and practitioners. To prove the hypothesis of the study, a complete set of the relevant subtests has been developed that implied both verbal (tests No. 1-3) and visual graphic presentation of stimulus material (tests No. 4-6).

Results
It has been established that a combination of the average Baevsky stress index (SI) values, with mostly involuntary fixation of the examinee's attention at the main colors of the Lüscher test (primarily at green and yellow) and the calm response of the respondent to the presented stimuli in the absence of forced or suppressed respiration, can be considered as evidence for the trustworthiness of the information reported. In order to increase the effectiveness of detecting concealed information, it is advisable to separate the asthenic and sthenic variants of the involuntary manifestation of the respondent's fears of a disclosure of that concealed information. The respondent's blocking fear of disclosing information, i.e. the asthenic response variant, manifests itself in a sharp decrease in the SI values compared to the performance indicators upon presentation of neutral stimuli. The fear initiating the hectic internal activation of cognitive and affective processes, i.e. the sthenic variant of response, manifests itself in a sharp increase in the SI values compared to the performance indicators upon presentation of neutral stimuli.

Conclusions
Consequently, significant signs of a desire to conceal information are any considerable deviations in the Baevsky stress index values from its averages. When using eyetrackers as means of presenting visual stimuli with elements of the eight-color Lüscher test, such SI variations are usually combined with a sharp increase in the duration of fixation of the respondent's gaze at the verbal stimulus components (usually more than 40% of the total stimulus exposure time) and at grey and brown colors for more than 10% of the total stimulus exposure time. The effective means of overcoming the respondent's resistance to revealing his true attitude to the objects being evaluated is the alternation of verbal and visual components of stimulus presentation.

Keywords
Cardiometry, Cardiocode, Eyetracker, Lie detection, Psychoemotional reaction

Imprint

Introduction
The use of such hemodynamic parameters as features of the pulse, changes in blood pressure, heart rate variability in assessing the truthfulness of human responses has a centuries-old history [1, 8, 11]. There have already been both many disappointments and encouraging achievements in this history. Nevertheless, researchers and practitioners continue seeking for opportunities to use the response of the human individual's cardiovascular system to certain stimuli.

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in studying his/her personality, in making personnel decisions, in various types of investigations. A successful combination of this type of diagnostics with an analysis of other manifestations in a person’s desire to conceal information, supported by an intensive development of equipment and instrumentation for recording various types of human psychoemotional reactions, can vigorously contribute thereto [1-8, 11].

Significant difficulties in identifying the true attitude of a person to certain types of information by the nature of his/her psycho-physiological reactions are associated with a multi-factorial influence of various functional systems on recorded parameters. Attempts to record only one type of such responses or reactions have been found to be ineffective, so that it initiates further search for productive combinations in recording reactions and responses of different types of the human body systems. In our opinion, a serious contributor to an adequate solution of this problem can be an approach to consider the manifestations of the affect and intelligence in various psychophysiological reaction types as integral, but not identical in their nature. We assume that a bounded set of possible combinations of affective responses and permissible cognitive processes under these conditions will minimize ambiguity in interpretation of the observed reactions and, therefore, will also increase the accuracy in lie detection. As a hypothesis in our research, we have suggested that a complex assessment of a person’s emotional-cognitive state, based on the cardiometric and oculographic recording of his/her responses to some specified sample materials of visual and audial modality, can be successfully used for concealed information detection. Based on our own original research [1–8, 11], we have also anticipated that for such cardiometric and oculographic recording, the estimates of the Bayevsky stress index and the respondent’s gaze parameters can be effectively used.

Materials and methods

We have decided to employ single-lead cardiograph Cardiocode and portable eyetracker GP-3 as the instrumental basis for verification of our research hypothesis. This decision has been made taking into account the previous analysis of the functional features of the instrumentation and the basic potential of effectively combining the above devices [3-6, 9, 10, 13-15, 17-19], considering the availability of the equipment and easiness in use of these instrumental techniques for a wide range of researchers and practitioners.

To verify the research hypothesis, a complete set of the relevant subtests targeted both for verbal-communication (tests Nos.1-3) and visual graphics (tests Nos.4-6) presentation of stimuli has been developed.

A classical test involving the name of the respondent (stimulus test) has been offered as the No.1 test. The symptomatic question addressing the respondent’s intentions has been put in the first place. The third, fourth and fifth items have been conventional stimulus test questions such as “Are you called ... <then the examiner is usually using the name of the respondent in the form, which has been preferred by the latter before> ...?”. Taking into account the results of research by S.V. Popovich [7, 8], the control questions, involving doubt, have been used in the second and the last place in test No.1. As a result, the following questions have been included in test No.1:

1. Are you going to honestly answer the subsequent tests questions?
2. Do you doubt that when you tell a lie, it will not manifest itself in any way?
3. Are you called ... <then called has been the name, consonant with the respondent’s real name, which does not cause him any significant associations, strong emotional experiences> ...?
4. Are you called ... <then the examiner is using the name of the respondent in the form, which has been preferred by the latter before> ...?
5. Are you called ... <then called has been the name, consonant with the respondent’s real name, which does not cause him any significant associations, strong emotional experiences, but which differs from the No.3 question name> ...?
6. Do you doubt that when you tell a lie, it has not manifested itself in any way?

During the testing procedure, the given test has been presented four times, but with different tasks for the examinee. During the first presentation, the respondent has been asked to give truthful answers to all questions; during the second presentation the same individual has been requested to give false answers; during the third presentation the examined subject has been instructed to give answer “no” to all test questions, and during the fourth presentation the same tested subject has been asked to say “yes” to all test questions. The cardiometric recording of every exam-
nee's reaction or response has been started immediately upon administering of each question.

Test No.2 has been compiled by analogy with tests of control comparison questions, which are widely used in various types of polygraphic tests [1, 7, 8, 10, 11]. The following questions have been included in test No.2 after preliminary pilot studies:
1. Are you in a sitting position now?
2. Are you going to honestly answer the questions about alcohol use?
3. Are you a man?
4. Are you a woman?
5. Have you ever used alcohol?
6. Have you ever smoked?
7. Are you a student?
8. Are you an associate professor?
9. Did you ever take anything of value without authorization?
10. Have you ever been late for studies?

It has been assumed that for the majority of respondents in test No.2, the “no” answers to questions 1, 5, 9, 10 and the “yes” answers to questions 2, 4, 6, 9 shall be their deliberate lie.

Test No.3 has been developed using questions that are usually incorporated in a manual scoring system of the conventional psychological survey techniques. In addition, the control questions involving doubt as mentioned above have been included in the given test. As a result, the following questions have been utilized in our test No.3:
1. Do you doubt that when you tell a lie, it will not manifest itself in any way?
2. Do you never gossip?
3. Do you sometimes gossip?
4. Do you always tell the truth?
5. Do you sometimes tell untruth?
6. Are you never late?
7. Are you sometimes late?
8. Do you sometimes brag?
9. Do you never brag?
10. Do you doubt that when you were telling your lie, it has not manifested itself in any way?

It has been assumed that for the majority of respondents in test No.3, the “no” answers to questions 1, 3, 5, 7, 8, 10 and the “yes” answers to questions 2, 4, 6, 9 shall be their deliberate lie.

Tests No.2 and 3 have been presented to each respondent four times. According to the experimental conditions, at the first time, the respondent is instructed to intentionally give an incorrect answer to each question using the “yes” or “no” variants. At the second time, he or she should give a truthful answer, using “yes” or “no” again. The opposite order of such test tasks as compared to test No.1 has been purposefully chosen by us to reduce the respondent’s resistance influence on the quality of the results obtained. At the third time, as it is the case with passing test No.1, the respondent has been instructed to give the “no” answers to all the questions. At the fourth time, he/she is requested to answer “yes” to all the questions.

Test No.4, involving the use of the eyetracker, has contained a set of visual stimuli, when each of them has incorporated a color figure component common to all stimuli and a verbal part to be varied from one stimulus to the next.

In test No.4, an image with its center in the form of a white field has been employed as the first stimulus. Along the edges of stimulus 1 and all subsequent stimuli from test No.4, colored square boxes have been arranged in correspondence to the eight-color table of M. Lüscher in the printed version of the test set [16]. In test No.4 applied has been the following arrangement of the colored squares:
- along the upper edge of the screen located are squares of green, blue, yellow and red colors;
- along the lower edge placed are the squares of brown, black, grey and purple colors.

The variable part of the visual stimuli in test No.4 has contained the following words exhibited in the center of the screen:
stimulus 2: “truth”;
stimulus 3: “lie”;
stimulus 4: “I am sitting now.”;
stimulus 5: “I am standing now.”;
stimulus 6: “Have you ever used alcohol?”;
stimulus 7: “Have you ever smoked?”;
stimulus 8: “I am in Moscow now.”;
stimulus 9: “I am in Kostroma now.”;
stimulus 10: “I am a student.”;
stimulus 11: “I am an associate professor.”;
stimulus 12: “I am a man.”;
stimulus 13: “I am a woman.”;
stimulus 14: “I study at MGU.”;
stimulus 15: “I study at RosNOU.”

We have anticipated that for the majority of respondents (undergraduate and postgraduate students from RosNOU), stimuli 4-8, 10 and 15 automatically reflect reality.
To reduce the influence of every preceding stimulus on the gazer parameters, when looking at the stimulus, which is being displayed at a given time, a masking stimulus of sky-blue color has been shown to the respondent for 5 seconds.

During the experiment, all respondents have been asked to simply view the images, automatically displayed on the screen after calibration of the eyetracker. The exposure time of each stimulus should be 20 seconds. Within this specified period of time, an ECG and a rheogram of each examinee have been recorded.

Test No. 5, also involving the use of the eyetracker, has offered a set of visual stimuli; in this case, each stimulus has a color figure component common to all stimuli and a verbal part to be varied from stimulus to stimulus. Four stimuli have been included in test No. 5, the invariable part of which (colored squares from the eight-color Lüscher test) has been the same as it is the case with test No. 4. Their variable part has incorporated the following verbal components:
- stimulus 1: “I am in the past”;
- stimulus 2: “I am in the future”;
- stimulus 3: “I am in the present”;
- stimulus 9: “I like it”.

In test No. 5, a combination of image-related and verbal components has also been employed by stimulus 8. A sentence “similar to me” typed in Font size 72 has been placed in the center of the mentioned stimulus, and four pairs of fighting animals, namely, tigers, foals, kittens and dogs, have been arranged along the edges. There has been a clear-cut distinction between an offending animal (“pursuer”) and a defending animal (“victim”) found in each pair demonstrated.

In addition, in test No. 5, the following stimuli have been used as visual image-type stimuli (free of any verbal component):
- stimulus 4: the image of a man at the edge of a sea cliff;
- stimulus 7: the two-row photos showing animals, looking at the viewer, who include a lion, a gorilla, a wolverine, a huski dog, a mare, a piglet, a cow and a cow elephant.

The following stimuli incorporating the verbal component only have been involved in test No. 5:
- stimulus 5: the phrase “I do preferably” placed in the center of the screen and typed in Font size 88, combined with the words “strong”, “weak”, “successful” and “unsuccessful” typed in the screen corners in Font size 72.

Similar to test No. 4, in test No. 5, between the working stimuli, a sky-blue masking stimulus has been demonstrated to the respondent for 5 seconds.

Test No. 5 has been presented twice to each respondent. During the first presentation, the respondent has been asked to decide where he would “truly” desire to gaze at, and then deliberately focus his/her attention on something diametrically opposite (a fictitious variant of gaze fixation). During the second presentation, the respondent has been requested to gaze exactly where he would “truly” desire (an authentic variant of gaze fixation). The exposure time of each stimulus is 20 seconds for both variants of the testing procedure. Within this entire time span, an ECG and a rheogram of the respondent have been recorded.

257 respondents in total, aged from 18 to 38 years, who are RosNOU under- and post-graduate students in the humanities and engineering, have taken part in our experimental studies as mentioned above. Within the experimental framework, only tests Nos.1-4 have been presented to a subgroup of 102 individual; tests Nos. 4-6 have been offered to a subgroup covering 86 test subjects, and the complete set of the tests has been demonstrated to the rest of the respondents. Since the processing of the obtained data (for this purpose the “Extended version” of the STADIA 8.0 statistical software package has been applied) has not revealed statistically significant differences for the same type of tests in different groups, there is no need to treat hereinafter the above mentioned groups separately. Upon completion of a series of pilot test studies, in which the reaction recording time has been fixed for 10, 20 and 30 seconds, in order to obtain the best combination of the completeness and the adequate performance in the respondents in the main part of the study, as already noted above, their cardiometric and oculographic parameters have been recorded for 20 seconds calculated from the time of the stimulus presentation.

Results and discussion

Our analysis of the obtained data has revealed statistically significant differences in the Baevsky stress index (SI) values calculated for each stimulus between
all the paired answers, with one of which true and another false. The most noticeable differences between the truthful and false answers have been observed in case, when the answer “no” has been given as a false one. It has also been found that, in certain groups of questions, false answers caused a reaction in the respondents, which is characterized by a sharp increase in the SI value as compared to the SI value recorded for the truthful answers, and in some cases reported has been a sudden decrease in the SI parameter against that reported for the truthful answer. The use of post-test conversations, recommended as additional techniques aimed at detecting concealed information and the behavioral indicators of veracity/deception of testimony used in forensic science [1, 7, 8, 10-12], have made it possible to refine the following results.

Without exception, all cases of reporting false information have been perceived by the examinees as something unpleasant, producing their internal discomfort. At the same time, in cases when the Cardiocode device has recorded a significant increase in the SI values against those found under the truthful answers, the respondents have experienced unpleasant excitement. At such moments, involuntary hard swallowing and throat clearing, forced respiration, intensified fidgeting and involuntary movements with the hands, fingers, legs and feet and facial mimic expressions are frequently observed. Some test subjects have reported that at such moments they have experienced a state similar to a panic attack. Some of them have described this sort of states using definitions and attributes like “a desperate search for a suitable behavior pattern (response)”, “vigorouse emotional turbulence”, “intense internal activity”. As a whole, all the above observed fingerprints are evidence for a pronounced sthenic affective reaction exactly to the process of reporting false information.

At the moments, when Cardiocode recorded a sharp decrease in SI, it was possible to observe some rigidity in the respondents, their pronounced decrease in movements. At such moments, our respondents often have demonstrated respiration apraxia. In these cases, as a rule, they have given their voice answers with a clear delay in time (as compared to the truthful answers to the similar questions), and very often their voice tones have been found to produce more dull and hollow sounds. Our respondents have defined their experienced states using expressions like “stupor”, “an inside self-concentration” and “longer tensful response latency”. As opposed to the situations described above, a sharp decrease in the SI values, as a whole, has been found to be closely associated with pronounced manifestations of an asthenic affective reaction to the process of reporting false information.

Mathematical processing of the portable eyetracker data has allowed us identifying the following, essential for solving the research problem, sample averaged indicators of our test gazers, when they have surveyed various visual stimuli from test No. 4.

When respondents viewed stimulus 2 with the word “truth” framed in colored squares from the Lüscher test, they spent most of their time by examining the squares of green (26% of the total stimulus exposure time), blue (15% of the time) and yellow (11% of the total exposure time) colors. At the same time, the shortest time their gaze has been fixed at the squares of grey (4% of the total stimulus exposure time) and brown (3% of the total stimulus exposure time) colors. The transition to stimulus 3 with the word “false” in the same frame of the squares from the Lüscher test has produced a significant redistribution in the gaze fixation duration. In this case, the time of gaze fixation at the squares of green, blue and yellow colors has decreased to 5-6%, and the time of fixation at the squares of brown and grey colors has been recorded to be 13 and 7% of the total stimulus exposure time, respectively. The similar twofold redistribution of attention between the squares of green, yellow, brown and black has been also observed, when changing the stimuli with the words “I am in sitting position” to “I am in a standing position”. It is noteworthy that the gaze fixation preferably at the squares of blue and green colors, as a rule, has been reported to be accompanied by the average SI index values recorded with Cardiocode.

The appearance of sensitive uncomfortable statements on the screen such as “Have you ever smoked?” (stimulus 7) has involved a significant decrease in SI and a simultaneous increase in gaze fixation at the squares of black and grey, up to the values that have been observed when the phrase “the worst” has been displayed in the center of the stimulus.

The true phrase “I am in Moscow now” (stimulus 8) has been accompanied by the preferable gaze fixation at the squares of green (20% of the total stimulus exposure time), yellow and red colors (12% each, respectively). At the same time, the respondents (on the average) have paid no more than 3% of the time to the brown and grey squares.
The presentation of the false statement “I am in Kostroma now” (stimulus 9) in the center of the screen has resulted in a reduction in the attention to the green square to 3% of the total stimulus exposure time, and to the yellow one - to 4%. At the same time, the gaze fixation at the squares of brown and grey has increased to 9% and 11% of the time, respectively.

The same pattern has been observed when changing the statement “I am a student” (stimulus 10), that is true for the participated respondents, to statement “I am an associate professor” (stimulus 11) that is false for them. In that case, the percentage of gaze fixation at the squares of grey and brown has demonstrated an increase from 2% and 1% to 8% and 9%, respectively.

A transition from one stimulus, showing the true gender of the respondent, to another, indicating the opposite gender (stimulus 12 and 13 with phrases “I am a man” and “I am a woman”, respectively) has been characterized by a considerable redistribution of the attention between the normatively accepted colors (green, blue, yellow and red) and those normatively rejected (brown, black and gray) characterized. That has been also accompanied by a multiple change in the SI values.

Similar changes have been reported when replacing the phrase “I study at MGU” (stimulus 14) with another “I study at RosNOU” (stimulus 15). Thus, the response to stimulus 14, which contains the false statement, has been detected as the preferred fixation of the respondents’ gaze at the squares of brown (29% of the total stimulus exposure time), black (19% of the time) and purple (16% of the total stimulus exposure time) colors. When the true statement has been presented (stimulus 15), 27% of the time of the respondents’ gaze has been devoted to the green square and 12% of the total stimulus exposure time to the yellow one, respectively. At the same time, the respondents have paid greatest 2% of the time to the brown and purple square and no more than 1% of the total stimulus exposure time to the black square (on the average).

The gaze parameters, traced by the eyetracker at the first presentation of the stimuli from test No. 5 (the fictitious variant of gaze fixation), have statistically significant differences from those recorded at the second presentation of the stimuli of the same test (the authentic variant of gaze fixation). A descriptive exemplary case of such differences may be the data on the averaged indicators of gaze fixation at various regions of the stimulus, when each of which has a color figure component, as mentioned above, common to all of them, and a verbal component, varying from stimulus to stimulus (stimulus 1, 2, 3 and 9, when the variable components of which are phrases “I am in the past”, “I am in the future”, “I am in the present” and “I like it”, respectively) are offered. The distribution of the gaze parameters for these stimuli is presented in Table 1 herein.

In Table 1, the squares of the following colors correspond to the numerical designations of the stimulus fragments as listed below: No. 1 is referred to green, No. 2 is referred to blue, No. 3 is referred to yellow, No. 4 is referred to red, No. 5 is referred to yellow, No. 6 is referred to purple, No. 7 is referred to black and No. 8 is referred to brown. Variant 1 (Var.1) in the Table corresponds to the gaze parameters at the first presentation of Test No. 5, when, according to the instructions received from the examiner, the choice by the respondent shall be deliberately fictitious. Variant 2 (Var.2) in the Table corresponds to the gaze parameters at the second presentation of Test No. 5, when, according to the instructions received from the examiner, the choice by the respondent shall be authentic.

The subsequent correlation and factor analysis of the obtained data has revealed a slight, but statistically significant, inverse relationship between the SI values and the duration of the respondents’ gaze fixation at the green and blue square boxes in the Test No. 5 visual stimuli. Using the Spearman correlation coefficient, a slight, but statistically significant, direct relationship has been also found between the heart rate (HR) and the gaze fixation duration at dangerous areas of stimulus 4, incorporated a picture showing a person on a cliff top. Using the Kendall coefficient of concordance, a statistically significant relationship has been detected between the HR values and the gaze fixation duration at the “dispute” fragment in stimulus 5, as well as between the gaze fixation duration at the “successful” fragment in stimulus 6 and the SI and HR values recorded during the demonstration of this stimulus. It has been also established that the above noted statistically significant differences in cardiometric parameters for all pairs of the same stimuli, without exception, at the first (fictitious gaze fixation) and second (authentic gaze fixation) variants of their presentation have been identified for the Baevsky stress index (SI) only. Similar statistically significant differences have not been revealed for the heart rate, when using the
Table 1. Distribution of the gaze fixation duration between various fragments of visual-verbal stimuli in Test No. 5

<table>
<thead>
<tr>
<th>Stimulus No. and Test Variant</th>
<th>Specific fixation duration as % referred to the total exposure time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. 1</td>
</tr>
<tr>
<td>No. 1, Var. 1</td>
<td>9</td>
</tr>
<tr>
<td>No. 1, Var. 2</td>
<td>10</td>
</tr>
<tr>
<td>No. 2, Var. 1</td>
<td>5</td>
</tr>
<tr>
<td>No. 2, Var. 2</td>
<td>12</td>
</tr>
<tr>
<td>No. 3, Var. 1</td>
<td>4</td>
</tr>
<tr>
<td>No. 3, Var. 2</td>
<td>20</td>
</tr>
<tr>
<td>No. 4, Var. 1</td>
<td>6</td>
</tr>
<tr>
<td>No. 4, Var. 2</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 2. The main statistical parameters of the SI values delivered in Test No.5

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Arithmetic mean for the SI values</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First presentation</td>
<td>Second presentation</td>
</tr>
<tr>
<td>Stimulus 1</td>
<td>316</td>
<td>280</td>
</tr>
<tr>
<td>Stimulus 2</td>
<td>338</td>
<td>289</td>
</tr>
<tr>
<td>Stimulus 3</td>
<td>368</td>
<td>285</td>
</tr>
<tr>
<td>Stimulus 4</td>
<td>374</td>
<td>275</td>
</tr>
<tr>
<td>Stimulus 5</td>
<td>341</td>
<td>296</td>
</tr>
<tr>
<td>Stimulus 6</td>
<td>324</td>
<td>304</td>
</tr>
<tr>
<td>Stimulus 7</td>
<td>361</td>
<td>356</td>
</tr>
<tr>
<td>Stimulus 8</td>
<td>314</td>
<td>303</td>
</tr>
<tr>
<td>Stimulus 9</td>
<td>329</td>
<td>258</td>
</tr>
</tbody>
</table>

Table 2 shows the main statistical parameters of the SI values, obtained by the Cardiocode device, when the respondents have completed Test No.5.

same estimation methods (in our case, using the Chi-square test with the Bonferroni correction).

Conclusions

1. A combination of the average Baevsky stress index values (SI), the primarily involuntary fixation of the examinee’s attention at the Lüscher test main colors (first and foremost to green and yellow), the examinee’s peaceful posture & tonus and facial expression reactions to the presented stimuli in the absence of forced respiration or respiration suppression can be judged to be the evidence for the truthfulness of the reported information.

2. To increase the efficiency of the concealed information detection, it is reasonable to separate the asthenic and sthenic variants of the involuntary manifestation of the respondent’s fears of the detection of information concealed by him. The fear of revealing the information, which disables the respondent’s activity, is an asthenic variant of his/her response, and it manifests itself in a sharp decrease in the SI values against those recorded in case of neutral stimuli. Such decrease is usually combined with an involuntary fixation of the examinee’s attention at the normatively rejected colors of the Lüscher test (primarily brown, black and grey), accompanied by a stiff posture, gestures inconsistent with the situation, and disorders in the respiration rhythm (involuntary sighing, appearance of delayed exhale of breath and so on). The fear, which results in a hectic internal activation of the cognitive and affective processes, being the sthenic variant of the response, appears as a sharp increase in the SI values against those recorded in case of presentation of the neutral stimuli. This sort of activations is usually combined with an involuntary preferable fixation by the examinee’s attention either at black and red, or red and brown, or yellow and black, or yellow and brown col-
ors of the Lüscher test. Complementary fingerprints of such response are involuntary abrupt (cramping) movements of the respondent, eloquent and quickly changing facial expressions, an increased rate of respiration, interrupted breathing and respiration arrhythmia in the respondent.

3. The informative markers of the subject’s desire to conceal information are any significant deviations in the Bayevsky stress index (SI) values from the SI averages. When using eyetrackers to present the visual stimuli with elements of the eight-color Lüscher test, the above SI fluctuations are usually combined with a sharp increase in the duration of the respondent's gaze fixation at the stimulus verbal components (usually more than 40% of the total stimulus exposure time) and an increase in the percentage of the gaze fixation at the grey and brown colors by more than 10% of the total stimulus exposure time.

4. An effective way to overcome the respondent's resistance to revealing his/her true attitude to the objects being evaluated is an alternation of verbal and visual components within the stimulus presentation session. As to the verbal part of the tests, the best calibration comparison questions are the questions, the "no" answers to which should be intentionally given false. With regard to the visual part of the tests, along with the use of hemodynamic recorders of the Cardiocode type and the eyetrackers, the effectiveness of concealed information detection can be improved by alternating stimuli with various combinations of image- and text-related fragments. A particularly noticeable increase in the accuracy of determining the associative relation between the image fragments of a stimulus and its verbal components is achieved by a repeated, shortened in time, presentation of the same image elements without any test.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest
None declared.

Author contributions
V.A.Z., E.V.L., L.P.N. and M.Y.R. conceived and planned the experiments, interpreted the results. A.A.T., D.S.Y. P.A.M. and N.V.M. carried out the experiments and prepared the manuscript. A.S.O. took the lead in writing the manuscript. All the authors read the ICMJE criteria for authorship and approved the final manuscript.

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Validity of cardiometric performance data: an integral part of complex assessment of training session effectiveness

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Aims
The paper offers some results from our experimental studies to determine validity of a complex performance fingerprint: the Baevsky stress index used to assess effectiveness of training programs: training sessions targeted at formation of psycho-somatic self-regulation skills and visual & verbal practical training course aimed at development of emotional intelligence.

Materials and methods
In order to determine the criterion-related validity of cardiometric assessments of training results, we have organized training sessions addressing scheduled staged formation of the self-regulation skills.

Before the training sessions and after them, our training participants have been instructed to perform a set of three tasks, covering the following:
- to imagine a calming video clip;
- to imagine some TV news reporting various dramatic incidents, emergencies, calamities etc.
- to generate self-relaxation, to perform the task to get relaxed and initiated or induced an emotional balance.

During the execution of the above mentioned test tasks, we have recorded synchronously an electrocardiogram (ECG) and a rheogram (Rheo) of every tested individual with the use of PC-assisted hemodynamic analyzers CARDIOCODE.

In order to estimate the construct validity, test simulation & training equipment sessions for operators, who have shown differing levels in their training and actual experience in the operation of complex machinery and equipment systems, have been conducted. Each operator has been offered some variants of images of a control panel related to one of the equipment item serviced by them: the images have appeared on the screen of portable eyetracker GP-3.

In order to assess the content validity of the measured cardiometric parameters as fingerprints of the available training effect, if any, we have investigated the affective-cognitive processes, which have appeared during the visual and verbal practical training of the examined individuals to develop their emotional intelligence.

Results and conclusions
Upon completion of our scientific investigations we have obtained the experimental confirmation of the validity of the applicability of a complex cardiometric fingerprint, like the Baevsky stress index, in order to assess the applicability and effectiveness of the training courses. Thus we have shown by the example of the psychosomatic self-regulation that it is just the Baevsky stress index that may be properly exploited in assessing the fact that the desired skills to control its own emotional state by a trainee have been effectively formed as the designed outcome of this training type. Discussing an example illustrating the execution by the complex machinery operators of the specific training test tasks, we have pioneered in demonstrating that the Baevsky stress index can be best applied in estimating the degree of interiorization of the formed skill and the robustness of the integration of the latter into the human individual life experience. Upon treating one more exemplary case of the visual-verbal practical testing to develop emotional intelligence, we have shown that there is a possibility to trace the availability of the training effect according to the variations in the Baevsky stress index values, while performing the above test tasks in the training course.

Keywords
Cardiometry, Cardiocode, Validity, Training, Training effectiveness

Imprint
Introduction

Successful applications of instrumental cardiometry in assessments of functional states in a human organism encourage researchers and practitioners to utilize it on a regular basis as an advanced monitoring and control tool capable of tracing processes of any interventions in the performance of the human body and mind [2]. As cardiometric equipment base is improved, a variety of techniques for an analysis of heart rhythm variability is finding ever increasing use, and that relates specifically to the Baevsky stress index methodology [17].

Therefore, using the above cardiometric index as a means for monitoring and control of data and processes a well as for an assessment of effectiveness of various types of training sessions seems to be absolutely reasonable. However, in doing so, it is required to conduct some additional investigations, which should address an estimation of validity of the applications of this sort of performance indicators in parallel with other types of assessments of effectiveness of trainings. So, it has been just our research work seeking how to solve this validation problem.

Materials and methods

It is common knowledge that the most important criteria for suitability and applicability of measuring instrumentation are the following types of validity: the criterion-related validity, the construct validity and the content validity [1, 13]. It is a generally accepted practice that a mandatory procedure for an evaluation of soundness of any diagnostics method or technique must involve the requirement to test the said types of validity.

In order to determine the criterion-related validity of cardiometric assessments of training results, we have organized training sessions addressing scheduled staged formation of the self-regulation skills, which have met stage one in autogenic training and which have been conducted according to an original technique described extensively in papers [3, 5-11, 15, 16]. Before the training sessions and after them, our training participants (the total cohort of this group has included 101 individuals) have been offered to perform a set of three tasks, which have covered the following:

- to imagine a calming video clip;
- to imagine some TV news reporting various dramatic incidents, emergencies, calamities etc.
- to generate self-relaxation, to perform the task to get relaxed and initiated or induced an emotional balance.

During the execution of the above mentioned tasks and tests, we have recorded synchronously an electrocardiogram (ECG) and a rheogram (Rheo) of every tested individual with the use of PC-assisted hemodynamic analyzers CARDIOCODE, the theoretical concept of which and the principle of its operation are described in detail in [14, 19-21]. Upon recording the curves with the Cardiocode instrumentation, the original Cardiocode software has been applied to process the recordings according to a special algorithm and compute the respective values of the Baevsky stress index for every examinee.

In order to estimate the construct validity, test simulation & training equipment sessions for operators, who have shown differing levels in their training and actual experience in the operation of complex machinery and equipment systems, have been conducted. Each operator has been offered some variants of images of a control panel related to one of the equipment item serviced by them: the images have appeared on the screen of portable eyetracker GP-3. The variants of the images have contained different combinations of indicating signals, by tracing of which the tested operator should to visually fix the procedure of the proper actions related to the control components of the equipment item. In parallel to the visual testing procedure, we have recorded cardiometric parameters of each examined individual with the use of hemodynamic analyzer Cardiocode. Upon completion of recording, for every episode/situation presented on the screen, the respective values of the Baevsky stress index (SI) have been computed.

In order to assess the content validity of the measured cardiometric parameters as fingerprints of the available training effect, if any, we have investigated the affective-cognitive processes, which have appeared during the visual and verbal practical training of the examined individuals to develop their emotional intelligence. During the practical training sessions, each trainee has been presented multi-component images, exhibiting facial expressions of various emotions, at a time interval of 20 seconds. To provide current control of the behavior of the tested individual, we have applied the effect of a deficit-burden stimulation, which has been detailed in our recent papers [1-8, 11]. In our experimental studies, we have used either the words to nominate certain emotions (joy, sadness etc.) or pictorial representations of this sort of emotions by emoji as deficit-burden stimuli: the words have been
located in the center of the screen. Around such a deficit-burden stimulus, responsible for initiation of a certain direction for a searching activity in a test subject, there have been placed photos of children and adults represented both genders.

At stage one of the training courses, each stimulus has comprised paired photo pictures of the same human individuals, who have experienced diametrically opposed emotions, and one of the emotions in this case has been referred to as a deficit-burden stimulus. All stimuli utilized at the above stage have been collected into single-type groups, and each of these groups has included four unchanged sets of photos depicted human faces and two sets to express one of the respective diametrically opposite emotions. It can be illustrated by the example as follows: the pair of emotions joy – sadness has been referred to a set of the words “sadness” and “joy”, alternatively displayed in the center of the screen, furnished with the respective emoji to express the emotions. The groups of the stimuli have differed from each other in the number of the photos located around a deficit-laden stimulus: the number of the photos depicted human individuals has varied from 4 to 24.

At stage two of the training courses, we have employed verbal expressions of the emotions only as deficit-laden stimulation. At this stage, in addition to the paired emotions, the deficit-laden stimuli have reflected some separated emotions. The list of the selected emotions has included surprise, fear, anger, disgust, rage and enjoyment. Moreover, the surrounding of the center-placed deficit-burden stimulus has incorporated not only the photos, but also the respective emoji, which have expressed different variants of emotional responses by a human. To achieve the required simulation effect, the number of such images has been gradually increased from 8 to 24.

From the beginning till the end of the presentation of each stimulus, we have employed our PC-assisted hemodynamic analyzer Cardiocode to record an ECG and a Rheo of every examinee. Upon completion of the recordings, based thereon, the corresponding values of the Baevsky stress index (SI) have been calculated with the use of the proprietary software of the Cardiocode device.

A total of 147 tested subjects, aged from 18 to 46, have been enrolled in our experimental studies. All measured cardiometric parameters have been obtained with the above hemodynamic analyzer Cardiocode, and all oculometric measurements and the demonstration of visual stimuli have been performed with portable monitoring-type eyetracker GP-3. The delivered parameters and the obtained data have been processed with statistics software package STADIA 8.0.

### Results and discussion

The main data, obtained in the course of determining criteria validity of cardiometric assessments of results upon psychosomatic self-regulation training, conducted in accordance with the above described procedures, are given in Table 1 herein.

Table 1 offers tabulated statistics parameters upon processing the values of the Baevsky stress index (SI) in individuals, measured under the pre- and post-test conditions utilizing PC-assisted device Cardiocode, in the course of the psychosomatic self-regulation training, when performing the same test tasks. The test tasks in Table 1 are numbered as given below: 1 – imagination by the examined subjects of a calming video clip; 2 – imagination by examinees of TV news reporting dramatic incidents, emergencies and calamities; 3 – self-relaxation, the task to get relaxed and initiated an emotional balance.

The statistical significance of the differences shown in Table 1 has been estimated with the chi-squared criterion, considering the obtained empirical distributions. Since it has been found that all values of the chi-squared criterion, computed by applying statistics software STADIA 8.0, reach at least 1000, all differences and deviations computed and indicated in Table 1 can be treated to be statistically significant at a level of no less than 0.01. Besides, as indicated by

<table>
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<th>Test task No.</th>
<th>Mean Pre-test</th>
<th>Mean Post-test</th>
<th>Standard deviation Pre-test</th>
<th>Standard deviation Post-test</th>
<th>Median Pre-test</th>
<th>Median Post-test</th>
<th>Asymmetry Pre-test</th>
<th>Asymmetry Post-test</th>
<th>Excess Pre-test</th>
<th>Excess Post-test</th>
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<td>2.4</td>
<td>1.5</td>
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</table>

Table 1. Main statistics SI parameters before vs. after psychosomatic self-regulation training
Table 1 herein, upon the completion of the training, the SI parameters are characterized by a narrower dispersion of the observed values. This sort of more compact distributions of the SI data can be explained by an adjustment of the level of preparedness of the examinees to solve the test task targeted at formation of calm, well-balanced emotional state by them. All this can be considered as a clear demonstration of the criterion validity of the cardiometric assessments of the effectiveness results of the completed training.

During the evaluation of the construct validity of the measured cardiometric values, we have detected that for the well-trained operators, who have a large experience in the proper operation of complex machinery, typical is a gradual decrease in the Baevsky stress index values as they complete the different tasks of the above described visual test simulation & training session. As to those, who have been found to be less skilled and experienced, we can observe a diametrically opposite tendency: their stimulation advance has been accompanied by an increase in the SI values. It should be noted that in this case, according to the indicators of the eyetracker equipment, in general, both tested groups have selected the proper sequence of the procedural actions.

All this bears witness to the fact that the Baevsky stress index can be successfully used to judge the degree of effectiveness in mastering a skill. As to group one, the skill has been acquired to such a degree that it has become automated, when the experienced operators have perceived the simulation tasks to be performed as their routine job. Therefore, when going from one task to another, they have demonstrated their capability performance of keeping customary pace with their usual work that has been well represented by the decrease in the Baevsky index level. The tested subjects in group two have viewed the test tasks as serios examinations, which have induced stress in them, even though these less experienced operators have properly decided on how to act. So, following this way, we can say that these results lend credence to our idea that the cardiometric parameters enable us to assess the degree of effectiveness in mastering a skill formed upon the respective training sessions.

As a result of our investigations, addressed assessing of the content validity of cardiometric measurements as fingerprints of the availability of the desired training effect, it has been detected that as the number of photos surrounding a deficit-laden stimulus increases, the Baevsky index values show their statistically significant growth rates. Typically, such growth for most tested subjects reaches a two- or three-fold increase as compared with the data recorded upon presentation of the first stimulus. Later we observe a considerable decrease in this parameter: it averages between 30 and 40% of the achieved maximum value. As a rule, this effect has been identified after the photos appearing around the deficit-laden stimulus are over 14-16 in number. Since in this case, according to the eyetracking data, the accuracy in correspondence between the deficit-laden stimulus and the respective photos remains at the same level, we can state with assurance that the tested individuals have reached their qualitatively higher level of mastering the skill to identify facial expressions of emotions.

In our post-test communication, the majority of the tested persons have noticed that at the instant their Baevsky stress index value substantially drops, they “suddenly” experience “ease” of finding the required images. This has also supported the fact that the cardiometric parameters are capable of properly indicating the key points of qualitative transformations associated with the level of mastering of the desired skill immediately at the training-in-progress stage.

**Conclusions**

Upon completion of our scientific investigations we have obtained the experimental confirmation of the validity of the applicability of a complex cardiometric fingerprint, like the Baevsky stress index, in order to assess the applicability and effectiveness of the training courses. Thus we have shown by the example of the psychosomatic self-regulation that it is just the Baevsky stress index that may be properly exploited in assessing the fact that the desired skills to control its own emotional state by a trainee have been effectively formed as the designed outcome of this training type. Discussing an example illustrating the execution by the complex machinery operators of the specific training test tasks, we have pioneered in demonstrating that the Baevsky stress index can be best applied in estimating the degree of interiorization of the formed skill and the robustness of the integration of the latter into the human individual life experience. Upon treating one more exemplary case of the visual-verbal practical testing, focused on the development of emotional intelligence, we have shown that there is a possibility to identify and trace the availability of
the training effect according to the variations in the Baevsky stress index values, when performing the test tasks in the training as described above.

**Statement on ethical issues**
Research involving people and/or animals is in full compliance with current national and international ethical standards.

**Conflict of interest**
None declared.

**Author contributions**
V.A.Z., E.V.L., L.P.N. and M.Y.R. conceived and planned the experiments, interpreted the results. R.S.K., P.A.K., P.A.M. and N.V.M. carried out the experiments and prepared the manuscript. A.S.O. took the lead in writing the manuscript and supervised the findings of this work. All the authors read the ICMJE criteria for authorship and approved the final manuscript.

**References**
**Cardiometric taxonomy of stress-inducing potential in diverse domestic situations**

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**Aims**
The aim of our study is to empirically verify the conceptual possibility of constructing a taxonomy of diverse domestic situations, which may become the basis for choosing the best ways to increase an individual stress resistance in a human subject.

**Materials and methods**
To achieve the aim, after ranking of the subjective evaluations of the occurrence rate of this sort of situations and the degree of intensity of stress induced by the situational cases, we have prepared a set of their laconic descriptions. As a result, a catalogue of 10 paired tasks has been prepared by us. One of these tasks offers that an examinee should imagine and hold in his/her memory for a certain time an image of a stress-inducing situation case as designated by the examiner. The other examinee in this pair has been instructed to imagine an alternative situation, when anticipated are a high level of the calm, trouble-free state, physical comfort and good emotional balance. During the execution of each task, an ECG and a rheogram of every examinee have been recorded. For this purpose, the Cardiocode PC-assisted devices have been used, and the respective mathematical models of the performance of the human cardiovascular system have been applied. Upon processing of the completed cardiometric records, values of the Baevsky stress index (SI) have been automatically computed.

**Results**
The post-test conversations with the tested subjects have demonstrated that the adult men most often consider the disputes with their wives to be the strongest memory impressions, and the women’s disputes with their daughters are recognized by the female test subjects as most impressive. Attempts made by a human individual to find an emotional balance after such memorized events by imagining a peaceful conversation result greatest in a decrease in the SI values up to the SI level typical for the memories stored after encountering aggressive animals.

**Conclusion**
In the course of solving the above formulated research problem, we have succeeded in building a taxonomy of diverse domestic situations that can be used to refine and adjust the best ways of improving the stress resistance of a human individual. The presented taxonomy allows us to significantly narrow the range of possible targets for the targeted therapeutic treatment and select effective images used for the correction of a psycho-emotional state in a human.

**Keywords**
Cardiometric taxonomy, Cardiocode, Eyetracker, Stress resistance, Eustress, Distress, Domestic situations

**Imprint**

**Introduction**
Stress as a defensive reaction, expressed as an increased tension of the human body in response to various adverse factors, has been one of the most actively studied phenomena during a whole century. For more than half a century, various cardiometric indicators of heart rate variability (HRV) have been used in scientific research of stress [1-4, 6-10]. The Baevsky stress index developed by R.M. Baevsky, employed to assess the HRV fluctuations in the regulatory systems in a human organism, is often referred to as a stress index, the values of which can be referred to a gradation to represent a sort of taxonomies, namely, the human subject’s conditions and states ranging from eustress (corresponding to the optimal mobilization) to a destructive distress.

In one form or another, some researchers sporadically try to use the variability indices to assess the stress-inducing potential in diverse situations. Thus,
for example, based on the analysis of heart rate variability, A.P. Kulaichev has derived implications that the HRV values are markers of the prevalence of explicit or implicit stress in students within their examination session time and their intersessional period [3]. One more exemplary case is when researchers, in fact, provide an indirect assessment of a stress-triggering potential in various types of activity in athletes and complex machinery operators, when the investigators identify a relationship between the Baevsky stress index values and certain types of operational activities, or classify the associated groups of situations as normal-, subextreme- and extreme-type situations [2]. But, in our opinion, the capabilities of the heart rate variability analysis for assessing the stress-inducing potential of the different situations are far beyond the conventionally used cases in science and practice. In this connection, the task has been formulated to empirically verify the conceptual possibility of constructing a taxonomy of diverse domestic situations, which may become the basis for choosing the best ways to increase an individual stress resistance in a human subject.

Materials and methods

To solve the above research problem, upon completion of a polling survey of 154 respondents, a group of the most frequently encountered stress-inducing situations in the everyday life of a modern human subject has been identified. After ranking of the subjective evaluations of the occurrence rate of this sort of situations and the degree of intensity of stress induced by the situational cases, we have prepared a set of their laconic descriptions. This set has included the following situational cases: domestic disputes with various employees and relatives, conflict situations during daily trips on public or private transport and at workplace, unexpected encounters with dangerous animals and cases of inadequate behavior of some human individuals, sudden changes in plans combined with an increase in the degree of uncertainty or the need for additional costs, etc.

For each description of a stress-inducing situation, we have also produced another description to fix an alternative situational case, implying the state of being calm, peaceful, and untroubled, the state of well-balanced emotions and a greater sense of physical comfort. As a result, a catalogue of 10 paired tasks has been prepared by us. One of these tasks offers that an examinee should imagine and hold in his/her memo-

ry for a certain time an image of a stress-inducing situation case as designated by the examiner. The other examinee in this pair has been instructed to imagine an alternative situation, when anticipated are a high level of the calm, trouble-free state, physical comfort and good emotional balance.

During the execution of each task, an ECG and a rheogram of every examinee have been recorded. For this purpose, the Cardiocode PC-assisted devices have been used, and the respective mathematical models of the performance of the human cardiovascular system have been applied, including those cases described in detail in [5, 7, 9-11]. Upon processing of the obtained cardiometric records, values of the Baevsky stress index (SI) have been automatically computed. The group of the tested subjects covers 206 persons recruited from students and academics from Moscow universities, pilots from staff of some Russian airline companies, as well as participants of various groups practicing yoga and psycho-somatic self-regulation techniques. Statistical data processing has been performed using STADIA 8.0 mathematical software.

Results and discussion

Table 1 shows the respective statistical parameters of the obtained values of the Baevsky stress index (SI) in its descending order for diverse stress-inducing situations (in each pair this sort of situations comes first: 1.1, 2.1, 3.1, etc.). The SI values indicated in the Table have been obtained, as mentioned above, with the use of the Cardiocode PC-assisted hemodynamic analyzer, under the conditions, when the examinees have been performing the test tasks to imagine the following situational cases:

1.1 – a domestic dispute;
1.2 – a peaceful conversation;
2.1 – a conflict situation at workplace;
2.2 – a discussion of the routine job tasks;
3.1 – a conflict situation related to a public transport trip;
3.2 – a usual trip on public transport;
4.1 – receiving an expected instruction to urgently solve an irritating task that may deprive the examinee of something important and interesting;
4.2 – a peaceful evening at home;
5.1 – receiving an unanticipated message about considerable unforeseen expenses;
5.2 – a feeling of self-confidence in the test subject’s sustainability and social recognition, belief to be capable of coping with various difficulties.
6.1 – an undesirable neighborhood to a very unpleasant person;
6.2 – a comfortable loneliness;
7.1 – a flashback to some troubles in the past;
7.2 – to imagine something causing a calm, well-balanced emotional state;
8.1 – to be accused by somebody of incompetence;
8.2 – obtaining evidence in favor of the examinee’s competence;
9.1 – detecting of the examinee’s wrong-doing act;
9.2 – to have a day off without any worries;
10.1 – to experience a sudden encounter with an aggressive pet;
10.2 – to have a quiet walk.

As may be seen from Table 1, the SI values can serve as a fingerprint for assessing the stress-triggering potential of various situations associated with the usual way of life of the average working adult. Among the above listed stressors, which are often found in our everyday life, these are precisely the domestic disputes which leave the strongest emotional memories, considering their psycho-physiological consequences.

The post-test conversations with the tested subjects have demonstrated that the adult men most often consider the disputes with their wives to be the strongest memory impressions, and the women’s disputes with their daughters are recognized by the female test subjects as most impressive. Attempts made by a human individual to find an emotional balance after such memorized events by imagining a peaceful conversation result greatest in a decrease in the SI values up to the SI level typical for the memories stored after encountering aggressive animals.

It is particularly remarkable that the SI values can also assess the regulatory potential of various types of soothing memories. In this regard, simple memories of a quiet, enjoyable walks have been found to be the most successful in producing the desired result.

Conclusions

In the course of solving the above formulated research problem, we have succeeded in building a taxonomy of diverse domestic situations that can be used to refine and adjust the best ways of improving the
stress resistance of a human individual. The presented taxonomy allows us to significantly narrow the range of possible targets for the targeted therapeutic treatment and select effective images used for the correction of a psycho-emotional state in a human.

Statement on ethical issues
Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest
None declared.

Author contributions
V.A.Z., E.V.L., L.P.N. and M.Y.R. conceived and planned the experiments, interpreted the results. D.D.D., D.S.Y., P.A.M. and N.V.M. carried out the experiments and contributed to the interpretation of the results. A.S.O. took the lead in writing the manuscript and drafted the final version. All the authors read the ICMJE criteria for authorship and approved the final manuscript.

References
ANALYTICAL NOTE

Cardio-oculometric (cardio-oculographic) detection of functional states in a human individual

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The cardio-oculometric detection (COD) is an integrated method aimed at studying personal preferences, individual traits and current functional states of a human individual. The method is based on the use of some cardiac markers and parameters of oculomotor activity in response to specially selected visual and auditory stimuli. To date, there is experimental evidence obtained that the COD method is capable of properly assessing the following:
- the nature of involuntary emotional reactions to the event, object or phenomenon under study;
- the degree of the psycho-physiological conditioning (readiness) to take various types of stress loading;
- the effectiveness of knowledge and experience acquisition.

The above method offers the following:
- to identify personally significant information even with the active willingness of the respondent to conceal it;
- to assess actual stress-inducing loading for a human individual in various problem situational cases;
- to determine the human individual's conditioning (readiness) to successfully overcome difficulties in his/her own life.

This fresh method has been effectively employed for the following purposes:
- an assessment of actual effectiveness of various training programs;
- identification and clarification of the problem components in the respondents' internal life scenarios;
- identification of the true respondents' attitude to various types of objects to be evaluated by him (to advertising products, to another human individual, to himself).

At present, the COD is implemented by the CARDIOCODE PC-assisted hemodynamic analyzers and various types of eyetrackers. Due to the existing hardware complex, designed to be extensible, easy in operation and user-friendly, provided is an accurate express technique offering to complete the testing procedure within a very short time (a session, depending on the tasks to be solved, lasts from 5-10 to 15-25 minutes), so that the method can be considered to be easily reproducible.