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PROBLEMS ASSOCIATED WITH CREATING SPECIAL SOFTWARE FOR SIMULATING OF HUMAN PHYSIOLOGICAL RESPONSES TO DYNAMIC $\pm G_z$ ACCELERATIONS

Under extreme accelerations, human physiological mechanisms cannot provide adequate circulation. Special methods and devices protecting pilot's brain and eye functionality have been proposed but their efficiency is individual and depends on pilot's skills. Currently, the lonely technology to safely acquire and test the necessary skills is based on use of special centrifuges. However, lack of adequate data about physiological and biomechanical events are two main causes worsening the training results. Special computer simulators, capable to model and visualize the main mechanical and physiological effects occurring under dynamic accelerations, could increase the effectiveness of future pilot's training process. This publication aims to define fundamental problems concerned with creating the required software. There exist two main groups of problems. The first group is concerned with the necessity to create basic mathematical models quantitatively describing both the physiological events and effects induced by protective maneuvers. Here special logical procedures, individualizing the basic physiological models, have to be proposed. The second group of problems is predominantly technical and associated with the necessity of special user interface (SUI) development. SUI must be subdivided into two functional sections – one for preparing a single computer experiment (simulation), and another – for analyzing the results of simulation. An experiment preparation includes the following events: i) a preliminary tuning of models according to biometrical data; ii) a setting of acceleration profile; iii) a choosing of protective algorithms and tools (or without protections); iv) a choosing of forms for results storage. Graphs presenting the dynamics of input and output variables are the main forms while the table forms are also included. The user (trainer or trainee) will be able to retrieve from the memory graphs of previous simulations to compare the effectiveness of additional protective elements. The software must be autonomic for the Windows platform.

Keywords: human extreme physiology, quantitative models, simulator, training, information technology.

Introduction

Maneuvers on modern fighter aircraft are associated with rapid altering and often highly sustained extreme accelerations [1-3]. Both physiological [4-9] and biotechnical [10-12] problems that arose in parallel with an increase in military aircraft's maneuverability have been properly investigated [4-18]. Human physiology evolutionarily adapted to the one g Earth environment, cannot provide adequate functioning of the brain and eyes of a sitting person. Two of these organs, very sensitive to oxygen and glucose supply, suffer in parallel with the decreasing of their input blood pressure. Under accelerations, the hydrostatic pressure proportional to the acceleration value expands the vascular wall, accumulating greater blood volume. The altered pressure gradients do not provide the necessary circulation at the cardiovascular scale. Accelerations also alter the ventilation-perfusion ratio in lungs [13,14].

Most critical are positive (+Gz) accelerations acting in the direction of head-legs, or negative (-Gz) accelerations acting in the opposite direction [4-6]. In terminal zones (brain, eyes), the lowered circulation causes oxygen lack and worsens the pilot's vision and consciousness [9,12]. Under -Gz, the elevated local blood pressure in the eyes and brain causes rupture of microscopic vessels and hemorrhages. Both the value of Gz and the gradient of acceleration change play an essential role in these events.

Under relatively slow (0.1-0.4 g/sec) linearly increasing +Gz accelerations, a mean healthy person not using artificial protections is operable for approximately +4Gz accelerations [11]. Further elevation of the G-load causes the G-lock phenomenon usually disappearing after a break [2,6,8].

Modern fighter aircrafts (like F16, F35, and others) can provide acceleration gra-

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dients exceeding 2 g/sec. This requires special protection algorithms and devices. Currently, typical protection algorithms include the use of special pneumatic or water-augmented anti-G suits, muscle stress, as well as breathing with a positive pressure air [1,11,17]. The adaptive protection algorithms combining multiple methods depending on the dynamics of accelerations are the most effective. So, a technology helping to optimally combine protective methods and tools is encouraged.

Traditionally, empiric research on centrifuges is the main way for inventing more effective protections [1,5,6-8]. As was demonstrated in [18-20], mathematical models realized as special software provided by additional ways to maximize the individual resistance of a pilot to the negative effects of accelerations. The experience in this special area is a basis for creating an advanced version of such software.

This article defines the main requirements for future software and ways for its creation.

Main functional blocks of the future software

1. The main blocks of models

The main mathematical models conventionally divided into two groups are shown in Fig.1.

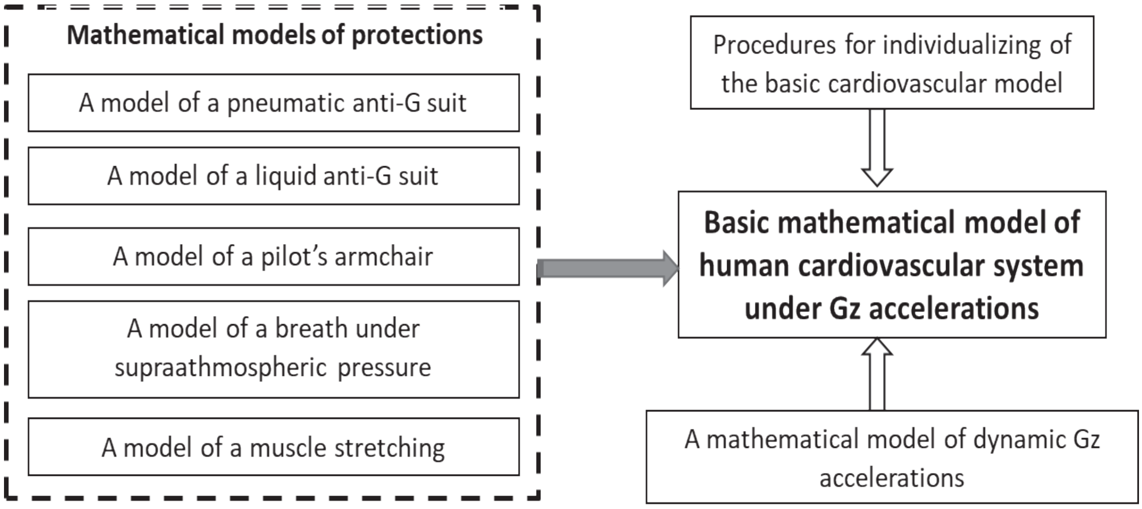

Figure1. Mathematical models and procedures to be used in the future software.

Fig.1 indicates that there should be created two blocks of quantitative models: models of physiological mechanisms; and models representing environmental physical factors modulating local, regional, or total hemodynamics.

Models of physiological mechanisms should quantitatively describe the dynamics of blood pressures, volumes, and flows of a sitting person under altering blood hydrostatic pressure. Important is that the model must describe the main neural-hormonal influences (modulations) of characteristics, involved in descriptions of both the cardiac pump function and vascular tonus.

A correct understanding of the student (future pilot) of the essence of physiological processes during flight overloads can play an essential role in the acquisition of professional skills. Usually, empirical technologies for training pilots to counteract the undesirable effects of g-forces focus on two main circumstances caused by extreme accelerations: 1) narrowing of the field of peripheral vision or loss of vision; 2) loss of consciousness as an extreme manifestation (G-lock). These phenomena, caused by a deterioration of the eyes and brain oxygen supply, are only manifestations of more extensive changes in human hemodynamics. However, empirics provide very scant information about these hemodynamic processes. The matter is that standard measurements are limited to monitoring the dynamics of heart rate (HR) and blood pressure. The shift in HR can be provided by multiple mechanisms. Several of them are known as physiological regulators reacting to a drop in pressure in the reflexogenic zones of the arterial tree. Other regulators can be largely activated by the mechanical stretching of body structures. Therefore, the proper model must describe the effects of both mechanisms. Finally, the specific dynamics of blood pressure are associated with movements and redistribution of significant volumes of blood under the influence of increased hydrostatic pressure.

The quantitative mathematical model of human hemodynamics is the single method that can illustrate the cause-and-effect relationships of developing dynamic events. It should be emphasized that the maximum additive effect of protective agents can only occur when each additional protective agent is activated at the right time. It can be detected using the mathematical model we create.

To increase the visibility of the protective effect, a special simulation mode will be provided when the physiological regulators are turned off. This simulation will reveal what could happen to hemodynamics if the body is late to respond to the mechanical movements of blood in the human body.

In Fig. 1, the second group of models collects models quantitatively describing the influences of external mechanical dynamic forces on local, regional, or total hemodynamics. Namely, these models describe hemodynamic modulations of each protective tool and algorithm.

In the right part of the Fig. 1, two additional options are indicated. The bottom-located rectangle accentuates the fact that a special model will be proposed for the simulation of acceleration profiles. At last, the upper rectangle indicates that special logic and mathematic approximations must be proposed to individualize the physiology model using anthropometrics and the sex of the person to be tested (simulated).

At last, the software must provide a computer experiment (simulation) and recording of its results as a special experiment protocol (SEP). Personalized records of SEPs can be accumulated in special files for their reproducing and deep analysis. The latter must provide an option for comparing of chosen variables for at least two experiments. These basic requirements mainly determine the software architecture.

The future software is intended to be autonomous Windows oriented. Exe module called “Accel.exe”. The success of software depends on two main factors: 1) how much it is needed; and 2) how practical is its user interface (UI). In our particular case, UI must be oriented both to student pilots and their trainers-instructors. Therefore, icons intuitively appointing procedures needed to be activated for the program’s preparation before executing is desirable. In addition, special icons intuitively appointing procedures for visualizing and analysis of simulation results are encouraged. Fig.2 below indicates the main procedures necessary for preparing and executing a single computer experiment (simulation), and that have to be provided by a UI.

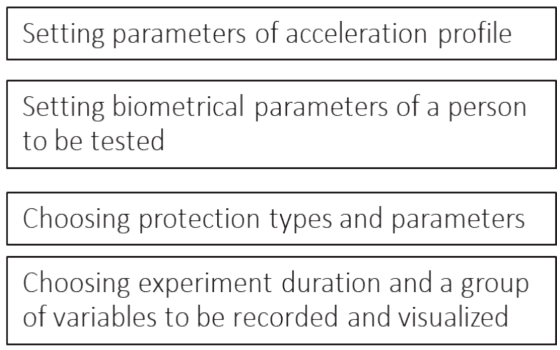

Fig.2. Procedures that are necessary for preparing and executing a single computer experiment (simulation), and that have to be provided by a special user interface (UI).

2. Main functional blocks of UI

By downloading the future autonomous “Accel.exe”, the user will have a core (basic version) of the quantitative model that has to be specially tuned for providing a single computer experiment (simulation). The tuning operations, provided by the UI, are intended to transform the basic version of complex models to a person-oriented model possessing a set of constants characterizing both physiological and environmental parameters.

Personal sensitivity of nervous regulators can vary in a wide range. There is no strain recommendation for associating the sensitivity coefficients with anthropometric data. At the same time, it is known that some tests (in particular, the postural test) can help us to approximately individualize the heart rate's neurogenic sensitivity. During the project execution, several ideas have to be algorithmically realized and tested.

Mathematical models

The principle is to differentiate two blocks of mathematical models. The first block describes human hemodynamics under varying hydrostatic pressures and extravascular pressures. The model does take into account the main effects of physiological control mechanisms that normally provide acute cardiovascular responses to dynamic accelerations.

1. *The background of the physiological models*

The human cardiovascular system (CVS) must be presented in the model as a structure combined with two subunits. The first subunit represents the vascular bed as a net of arterial and venous compartments each localized at different distances from the foot level. Every vascular compartment will have its fixed initial parameters (rigidity $D_i(0)$, unstressed volume $U_i(0)$, and resistance $r_i(0)$). Current (dynamic) values of these variables will be calculated taking into account increments provided by nervous-endocrine regulators:

$$U_i(t) = U_i(0) \pm \sum_j \Delta U_j, \qquad (1)$$

$$D_i(t) = D_i(0) \pm \sum_j \Delta D_j, \qquad (2)$$

$$r_i(t) = r_i(0) \cdot \mathrm{Z}(D_i(t), U_i(t)). \qquad (3)$$

The principal is to model the influences of gravitational and extravascular mechanical forces on local output blood flows $q_i(t)$:

$$q_i(t) = [(P_i(t) + P_i^G(t) + P_i^E(t)) - (P_{i+1}(t) + P_{i+1}^G(t) + P_{i+1}^E(t))] / r_i(t), \qquad (4)$$

where the gravitational component $P_i^G(t)$ is calculated using the distance of the vascular compartment from the foot h_i, the current value of acceleration $G_z(t)$, and the angle $\alpha_i(t)$ between acceleration vector and body vascular compartment.

$$P_i^G(t) = \gamma \cdot h_i \cdot G_z(t) \cdot \sin \alpha_i(t). \qquad (4.1)$$

As observation intervals under simulating of acceleration events are limited by minutes, the total blood volume $V = const.$ Shifts of compartmental ($V_i(t)$) and regional blood volumes appear due to alterations of compartmental input-output flows:

$$\frac{dV_i}{dt} = q_{i-1}(t) - q_i(t). \qquad (5)$$

Arterial baroreceptor reflexes are considered to be the main physiological mechanisms counteracting to lowering of perfusion pressure in the brain [67]. In a rigid cranium, the normal extravascular pressure is slightly subatmospheric. +Gz accelerations, especially in non-collapsible venous sinuses, aggravate the negative pressure. These biomechanical factors, lowering the venous return from a cranial basin to the heart, play a specific counteracting role against the gravitational decrease of brain circulation. Besides, within 50 mm Hg alterations of brain perfusion pressure, autonomic nervous mechanisms provide a practical constancy of the summary brain flow. Additional protective effects are provided by a reflector mechanism activated due to the lowering of intravascular pressure in the circle of Willis. This effect was first shown in [78].

Practically always real military fighter missions are accompanied by mental stress and delivery of catecholamines that additionally mobilize CVS. Empiric observations have also shown a phenomenon of heart rate extreme increase despite essentially elevated blood pressure in the aortic arch. This phenomenon can be explained and modeled in the assumption that under high levels of acceleration, the mechanical stress of muscles originates high proprioception capable of compensating the depressor influence of the aortic arch baroreflex.

2. *The background of models describing the physical environment*

Fighter pilots, functioning in a highly dynamic environment, are provided by artificial specifically acting biomechanical protective tools and methods. Standardly, they include: i) a pilot's chair with a declined to horizon under angle A supine; ii) anti-G suit; iii) a helmet provided by a device for breathing under positive pressure. To this list can be added special technics for tensing the muscles of the legs and abdominals.

So, to simulate the protective effects of the artificial tools, additional equations describing the transformation of external biomechanical forces into the body's regional vasculature are required. Simulation algorithms must provide applications of a chosen acceleration profile for every combination of protections. To demonstrate protection effects, as well as to compare the effects of every single method, it desirable is to have two special model versions. The first one illustrates hemodynamics under accelerations with switched-of physiological regulators. The second version does simulate hemodynamic responses of a person with the normal functioning of the physiological controllers of CVS. There are three specific ways to counteract extreme increases in vascular volume: 1) increasing the vascular rigidity; 2) decreasing the non-stressed volume; 3) elevating the extravascular pressure.

The first two ways are incorporated into physiological reflector regulators. The third opportunity can be used without or with the application of artificial devices. In the first case, the person being under acceleration forces can consciously increase the tension in the muscles of the legs and abdominals. When additional efforts to exhale with a closed airway have been provided, the protective effect is higher.

Constructively, anti-G suits can be with pneumatic or water-filled chambers. The standard anti-G suit is sectional (for body sections of the abdomen, thighs, and shins). Versions of suits containing special sections for creating certain supra-atmospheric pressure at the chest are also proposed [6]. In general, these suits do resist the accumulation of local blood volumes. So, in the background of +Gz, a pumping of pressured air into the anti-G suit lowers the sectional blood volume. The matter is how to model these protective effects.

In equation (4) above, there is a variable $P_i^E(t)$ which presents local extravascular pressure. Certainly, leg muscles, abdomen, or thoracic cavities will have their transfer coefficients for transmitting the applied external pressure ($P_E(t)$) to the depth of blood vessels. In (4), summary extravascular pressure should be calculated as:

$$P_i^E(t) = k_i \cdot P_E(t) \ . \qquad (4.2)$$

3. *Models describing input loads*

The model to be used in the future software will calculate human hemodynamic responses to two different types of input dynamic loads. During simulations of the pilot who is not using protections, the dynamics of accelerations are the lonely input loads initiating alterations of the normal physiology of circulation and causing reflector responses. Protection activation should be considered as the second type of input load. Real flight maneuvers, especially combat maneuvers, occur under combined input loads. To estimate the separate effects of each input load, it is necessary to design algorithms providing arbitrary combinations of both types of input loads. Below, supposing the value of A to be constant, the first and the second types of input loads are consequentially considered.

The initial hemodynamic alterations depend on both acceleration gradients and amplitude. So, to correctly simulate these biomechanical events, our software must include a model, describing accelerations dynamics. It is planned to provide the following acceleration profiles: a) a linear with a given gradient a and of τ duration; b) a linear with a further transforming to a constant (plateau) of τ duration; c) a trapezoidal with given parameters; d) a special profile for imitating the known "push-pull" effect; e) arbitrary constructing by a user profile. Formalisms for modeling these profiles are described below.

The first profile is presented as:

$$a(t) = \begin{cases} 0, & t \le t_s \\ A_g(t - t_s), & t > t_s \end{cases}, \qquad (6)$$

where t_s - is start time of the increasing of acceleration with a gradient of A_g .

The second profile is presented as:

$$a(t)=\begin{cases}0, & t\le t_s\\ A_g(t-t_s), & t<t_s\le t_p\\ a_m, & t_p<t\le t_p+T\end{cases}, \qquad (7)$$

where t_p - is the time of reaching a plateau level with acceleration value of a_m.

The trapezoidal profile formalism looks as:

$$a(t)=\begin{cases}0, & t\le t_s; a_m\le 0\\ a_g(t-t_s), & t<t_s\le t_p\\ a_m, & t_p<t\le t_p+T\\ a_m-d_g(t-t_p-T), & t>t_p+T\end{cases}, \qquad (8)$$

where d_g - is the deceleration gradient, T - is the plateau's duration.

Formalisms describing the second type of the input loads look as:

$$p(t)=\begin{cases}0, & a(t)\le 0\\ \Delta_j\cdot a(t), & a_1<a(t)\le a_m\\ \Delta_j\cdot a_m-d_g(t), & 0<a(t)<a_m\end{cases}, \qquad (9)$$

where Δ_j can be altered step-like.

Equations (1)-(9) were involved in this publication to help readers to understand our approach to the modeling. Much detailed information one can find in [18-21]. The final version of the mathematical model describing the formal basis of the future software and simulation results will be published separately.

Requirements to input and output data organization

As already mentioned above, the "Accel.exe" is planned to be autonomic software that provides an option for personalization. To satisfy these requirements, special algorithms are needed. They should provide initial data for characteristics of every vascular compartment, as well as for physiological regulators. In fact, this is the basic version of physiological models (BVPM). All additional procedures for BVPM's personalizing using the input data must be algorithmically organized.

1. The input data

BVPM should be tuned for the hemodynamics of a healthy man with mean anthropometric parameters of mas (M) and, height (H). Special formulas used M to calculate the total blood volume (V) must be provided. Then, utilizing incorporated special massive of coefficients must be distributed in four cardiac chambers and 33 vascular (arterial and venous) compartments. Coefficients will characterize human horizontal position sectional or regional blood volumes. The next procedure does provide automatic recalculating of these initial blood volumes to new ones characteristic for the relaxed human in a standard sitting position on a pilot armchair. Equations for these recalculations must take into account the initial parameter V. Individual anatomical peculiarities (if they are) concerning lengths of neck, tights, and shins have to be taken into account.

2. The output data

There are planned two types of output data: one by default, and another – in special cases. The default data concerning acceleration profile, arterial pressures in three body zones (brain, eyes, aortic arch), and HR should have been presented in graph forms. This form is recommended to both student-pilots and instructors. Additional data including inside information about parameters of models is best to collect in table forms. Experts developing advanced protections can be the users of these data. Namely, this class of users can prepare and simulate novel combat maneuvers avoiding risks for testers.

Conclusion

Combat maneuvers of modern fighter aircraft originate extreme accelerations negatively influencing on pilot's physiology and operability. Empirical investigations were the only way to develop and test protective methods and tools providing fighter pilots functionality under combat maneuvers. The main tools used for acquiring student pilot initial skills necessary to resist the negative effects of dynamic extreme accelerations were centrifuges. The skilling process of student pilots of modern fighter aircraft is not duly formalized yet. Potentially, special computer simulators providing additional data concerning characteristics of both human physiology and protective methods under dynamic accelerations could improve the skilling process and its efficiency. Certain scientific-practical problems associated with creating the needed simulator have been considered in the paper. To create special software, quantitative mathematical models must be previously created. They represent both the human cardiovascular physiology and protective technologies under exposure to sustained and extreme $\pm G_z$ accelerations.

References

1. Burton, R.R.; Whinnery, J.E. Biodynamics: Sustained acceleration. In Fundamentals of Aerospace Medicine, 3rd ed.; DeHart, R.L., Davis, J.R., Eds.; Lippincott Williams & Wilkins: Philadelphia, PA, USA, 2002; pp. 122–153.
2. Slungaard E., McLeod J., Green, N.D.C., Kiran A., Newham D.J., Harridge S.D.R. Incidence of g-induced loss of consciousness and almost loss of consciousness in the Royal Air Force. Aerosp. Med. Hum. Perform. 2017, 88, 550–555.
3. Newman, D.G. The cardiovascular system at high Gz. In High G Flight: Physiological Effects and Countermeasures, 1st ed.; Newman, D.G., Ed.; Ashgate: Farnham, UK, 2015; pp. 57–72.
4. Park, M.; Yoo, S.; Seol, H.; Kim, C.; Hong, Y. Unpredictability of fighter pilots' G duration by anthropometric and physiological characteristics. Aerosp. Med. Hum. Perform. 2015, 86, 307–401.
5. Yun, C.; Oh, S.; Shin, Y.H. AGSM proficiency and depression are associated with success of high-G training in trainee pilots. Aerosp. Med. Hum. Perform. 2019, 90, 613–617.
6. Polock,R.D.,Hodkinson,P.D.,&Smith,T.G.Oh G:Thex,yandzofhumanphysiologicalresponses toacceleration. Experimental Physiology, 2021,106,2367–2384. https://doi.org/10.1113/EP089712
7. Albery, W. B. Acceleration in other axes affects +Gz tolerance: Dynamic centrifuge simulation of agile flight. Aviation, Space, and Environmental Medicine, 2004,75(1), 1–6.
8. Burton, R., & Whinnery, J. Operational G-induced loss of consciousness: Something old; something new. Aviation, Space, and Environmental Medicine, 1985,56(8), 812–817.
9. Cao, X.-S., Wang, Y.-C., Xu, L., Yang, C.-B., Wang, B., Geng, J., Gao, Y., Wu, Y. H., Wang, X. Y., Zhang, S., & Sun, X.-Q. Visual symptoms and G-induced loss of consciousness in 594 Chinese Air Force aircrew— A questionnaire survey. Military Medicine, 2012, 177(2), 163–168. https://doi.org/10.7205/milmed-d-11-00003.
10. Chung, K. Y. Cardiac arrhythmias in F-16 pilots during aerial combat maneuvers (ACMS): A descriptive study focused on G-level acceleration. Aviation, Space, and Environmental Medicine, 2001,72(6), 534– 538.
11. Eiken, O., Bergsten, E., & Grönkvist, M. G-Protection mechanisms afforded by the anti-G suit abdominal bladder with and without pressure breathing. Aviation, Space, and Environmental Medicine, 2011. 82(10), 972–977. https://doi.org/10.3357/ASEM.3058.2011
12. Eiken, O., Keramidas, M. E., Taylor, N. A. S., Grönkvist, M., & Gronkvist, M. Intraocular pressure and cerebral oxygenation during prolonged headward acceleration. European Journal of Applied Physiology, 2017,117(1), 61–72. https://doi.org/10.1007/s00421-016-3499-3
13. Grönkvist, M., Bergsten, E., & Eiken, O. Lung mechanics and transpulmonary pressures during unassisted pressure breathing at high Gz loads. Aviation, Space, and Environmental Medicine, 2008,79(11), 1041–1046. https://doi.org/10.3357/ASEM.2371.2008.
14. Henderson, A. C., Sá, R. C., Theilmann, R. J., Buxton, R. B., Prisk, G. K., & Hopkins, S. R. The gravitational distribution of ventilationperfusion ratio is more uniform in prone than supine posture in the normal human lung. Journal of Applied Physiology, 2013, 115(3), 313–324. https: //doi.org/10.1152/JAPPLPHYSIOL.01531.2012
15. MacDougall, J. D., McKelvie, R. S., Moroz, D. E., & Buick, F. The effects of variations in the anti-G straining maneuver on blood pressure at +Gz acceleration. Aviation, Space, and Environmental Medicine, 1993,64(2), 126–131.
16. Sundblad, P., Kölegård, R., Migeotte, P. F., Delière, Q., & Eiken, O. The arterial baroreflex and inherent G tolerance.EuropeanJournal of Applied Physiology, 2016,116(6), 1149–1157. https://doi.org/10.1007/s00421-016-3375-1

17. Whiny,J.E.,&Forster,E.The+Gz-induced loss of consciousness curve. Extreme Physiology and Medicine, 2013,2(1),19. https://doi.org/10.1186/2046-7648-2-19
18. Grygoryan, R.D., Kochetenko, E.M., Informational technology for modeling of fighters medical testing procedures by centrifuge accelerations. Selection &Training Advances in Aviation: AGARD Conference Proceedings 588; Prague, 1996. May 25-31, PP3,1-12.
19. Grygoryan, R.D., 2002. High sustained G-tolerance model development.STCU#P-078 EOARD# 01-8001 Agreement: Final Report. 66p.
20. Grygoryan R.D. Problem-oriented computer simulators for solving of theoretical and applied tasks of human physiology. Problems of programming. 2017, №3, 102-111.
21. Grygoryan R.D. Modeling of mechanisms providing the overall control of human circulation. Advances in Human Physiology Research, 2022,4, 5 – 21, https://doi.org/10.30564/ahpr.v4i1.4763.

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