Mathematical Modelling of the Multifactorial Influence of Striking Fragments on the Dynamics of the Rehabilitation Processes of the Wounded

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Abstract. The article analyses the possibility of solving an important scientific and technical problem that is relevant for the security and defence of any country where natural and man-made disasters, military conflicts and other emergencies occur, in which penetrating injuries of people occur. The article reports on the possibility of improving the efficiency of the rehabilitation technology for patients with penetrating gunshot wounds by reducing the rehabilitation period using modern methods of medical diagnostics, mathematical modelling and statistical methods for processing biomedical information. The scientific idea underlying the conducted research is that dynamic changes of a set of biomedical indicators depend not only on the time of their observation, but also on the levels of those physical factors that characterize physical parameters: temperature and dynamics of fragments. As a working hypothesis, in this case, it is possible to consider the inverse task, in which it is possible to solve the problem of assessing the levels of physical factors characterizing fragments using measurements of biomedical indicators during the initial examination of the wounded. In the paper, the authors substantiated the possibility of using primary biomedical measurements to assess the physical characteristics of fragments. This, in turn, makes it possible to take into account the characteristics of the physical impact of fragments on the dynamics of changes over time in biomedical indicators characterizing the treatment, and will lead to a reduction in rehabilitation time.

Keywords: Medical diagnostic, Disaster medicine, Penetrating gunshot wounds, Biomedical indicators, Mathematical modelling.

1 Introduction

Emergency situations are constantly occurring in the world: industrial accidents, natural and man-made disasters, military conflicts and other incidents that lead to inevitable human casualties with penetrating wounds. Mortality, especially if the injuries were caused by high-velocity particles of solid material, is high despite appropriate treatment.

This is especially clear during military conflicts, when penetrating injuries are inflicted not only on professional soldiers, but also on the civilian population. Thus, the need for proper quality and timeliness of medical care is very acute.

The authors considered this problem from the point of view of the possibility of using primary biomedical measurements to obtain additional biomedical information, which will increase the efficiency of patient rehabilitation technology due to the prediction and control of the patient's condition throughout the rehabilitation process.

Preliminary multivariate statistical analysis conducted by the authors based on experimental studies made it possible to obtain important information that indicated the possibility of planning medical technologies for the rehabilitation of the wounded taking into account the physical parameters of fragments: such as temperature, dynamic characteristics, weight of fragments.

2 Features of Biophysical Processes in Fire Injuries

According to the type of projectile that causes damage, gunshot wounds are classified into: bullet, shrapnel (standard shrapnel elements and fragments of irregular shape), secondary (stone, glass, brick), non-table (ball, arrow-shaped), mine-explosive. According to the penetration into the body cavities, they are distinguished as penetrating and impenetrable wounds, according to the nature of the injuries - injuries only to soft tissues, internal organs, blood vessels, nerves, bones, etc.

In connection with the constant improvement of weapons, an increase in the severity of damage to soft tissues and bones, a high frequency of infectious complications and a high percentage of delayed consolidation of fractures are observed [1-3].

Tissue damage during the passage of a wounding projectile occurs with the participation of several factors: the direct impact of the projectile, the main shock wave (action of a direct impact and compressed air), a side shock wave (in a temporary pulsating cavity), a vortex wake (flow of air and tissue particles behind the projectile) [4].

Gunshot wounds have their own characteristics related to the high kinetic energy of the bullet [5]. In the case of a gunshot wound, the high kinetic energy of the projectile creates a cavity, the size of which significantly exceeds the size of the projectile. This phenomenon is called "pulsating cavity phenomenon" Fig. 1.

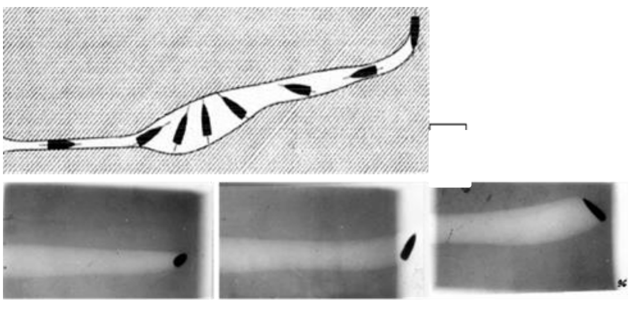

Fig. 1. Pulsating cavity phenomenon

Also, the formation of local disorders around the wound channel is observed. First of all, we are talking about disorders of a microcirculatory nature, accompanied by edema and, as a result, a local increase in pressure. Secondly, the accumulation and selection of pathogenic microflora is observed around the wound canal.

A basic understanding of the ballistic behaviour of projectiles or fragments after entering the human body is important for military surgery of any part of the victim's body, especially the head and neck, due to the number of blood vessels and nerve endings located in these areas. Mainly, in practice, this knowledge is used by doctors to predict the diagnostic and therapeutic consequences of this type of injury.

Although a large number of factors affect the projectile in flight and after penetrating the body, the most important factor is still the amount of kinetic energy transferred to the tissues.

$$Ek = \frac{m(v_1^2 - v_2^2)}{2g}, \quad (1)$$

where: Ek - kinetic energy of the projectile transmitted to the body;

m - mass of the projectile;

υ_1 - speed of the projectile at the time of its impact on the body;

υ_2 - speed of the projectile at the time of its exit from the body;

g - gravitational acceleration.

The following elements play a leading role in the mechanism of a gunshot wound:
- The main shock wave (ballistic), a wave of highly compressed air that forms in front of the bullet.
- The projectile itself that injures.
- Temporary pulsating cavity (side impact energy).
- Secondary wounding projectiles (bone fragments flying at a speed of up to 70 m/s).
- Vortex wake inflow.

The current state of the problem of rehabilitation of the wounded is based mainly on the use of classical methods of obtaining information about the condition of a patient with shrapnel injuries: clinical, radiological and ultrasound diagnostics.

Monitoring the patient's condition requires periodic repetition of these diagnostic procedures, which has a significant impact on the effectiveness of patient treatment. At the same time, the existing methods do not use information that connects multivariate statistical analysis with the possibility of planning medical rehabilitation technologies taking into account the physical parameters of fragments.

Therefore, as a working hypothesis, the authors propose the use of the possibility of assessing the levels of physical factors characterizing shrapnel using measurements of biomedical indicators during the initial examination of the wounded.

This hypothesis is based on a multivariate statistical analysis of time sequences of multivariate measurement results of systems of biomedical indicators, so it can be considered reliable. The relevance of this reseache is determined by the complete absence of similar studies in world practice, even when considering similar studies of traditional disaster medicine.

3 Analysis of the Solution of the Problem of Rehabilitation of Patients with Fire Injuries

To assess the state of solving the problem of rehabilitation of patients with gunshot wounds, we will make an analytical review of the existing methods of diagnosis and control of the condition of these patients.

Given the importance and urgency of the problem under consideration, there are currently many methods and ways of determining the condition of patients with penetrating gunshot wounds.

For the completeness of providing information, we will consider the main methods used both in clinical medicine and in forensic medical examination related to gunshot injuries. In order to obtain maximum information about the object being studied, in each specific case, a complex of laboratory and instrumental research methods is used.

At this time, the following classical research methods are known and widely used [6-8].

1. Visual examination, including inspection gunshot wounds with the naked eye, using a magnifying glass, in infrared and ultraviolet rays. Examination with the naked eye provides detection of localization, shape, size and nature of the gunshot wound and its elements (defect, edges, walls, bottom), traces of chemical and thermal action of powder gases, presence and topography of the location of soot and small particles. To clarify the area, dust and metal particles, especially on dark, soiled or blood-soaked fabrics, an examination in reflected infrared rays or filtered ultraviolet rays is carried out.

2. Photographic methods include macro and micro photography. Currently, the methods of color and digital photo and video recording using computer technology are widely implemented, which significantly speeds up image acquisition and makes this method of research less time-consuming.

3. X-ray examination for differential diagnosis of the entrance and exit holes, establishing the presence of a ball and defects of bone tissue, metal particles in the area of the entrance wound. X-ray examination helps to determine the location of multiple gunshots and their fragments for the construction of spatial models, etc.

4 The methods of spectral analysis, chromatography, and methods of chemical analysis make it possible to distinguish the entrance hole from the exit hole and determine the state of contamination of the patient's body with chemically active components.

5. Histological examination of skin with a subcutaneous base (edges of gunshot wounds or areas near them, soft tissues along the course of the wound channel) can provide information on establishing the direction of the wound channel, and decide the age of the gunshot injury.

6. The method of situational three-dimensional modelling allows you to accurately reproduce the metric parameters of the body: length, proportions, etc., to take into account the mobility in the joints of the limbs, characteristic of a person. With the help of 3D modelling, you can record all the damage, wound channels and perform a visual situational reconstruction of the mechanism of gunshot injuries, which is quite important for surgical intervention and prognosis in the treatment of the patient.

7. Mathematical and graphic modelling of the process of projectile interaction with an obstacle and mathematical and statistical analysis of a gunshot wound are modern methods of analysis that allow you to reproduce the processes that occur when a fragment collides with an obstacle (the patient's body).

The mathematical model is generally based on the laws of conservation of mass, momentum and energy, the equation of state of matter, the model of stress-strain states of materials. The numerical model is based on the approximation of the basic conservation laws by Euler's explicit equations. Interacting bodies are considered as a collection of particles that have certain physical and mechanical properties.

This model was named the method of smoothed particles - SPH (Smoothed Particle Hydrodynamics). It is widely used for intensive dynamic loading of bodies, when there is a significant change in the topology of the modelled objects. But for now, this question has been worked out enough for rigid bodies, and the use of this method for predicting the condition of a patient with a gunshot wound is quite limited [9].

Mathematical and statistical analysis of gunshot injury is generally based on the results of previously conducted diagnostic, identification and classification studies, that is, it has an integrative nature.

There are studies that determine the possibility of causing injuries in a particular situation, optimal mathematical methods of qualitative and quantitative assessment of the signs of gunshot injuries to objectify the conclusions of the condition and state of the injury in relation to external factors [9]. But these studies are quite limited in terms of the possibility of predicting the recovery process when using certain methods of treatment.

The authors propose further development of the method of statistical analysis and mathematical modelling of medical and biological processes by establishing the dependence of dynamic changes of biomedical indicators in conditions of randomness of the levels of influencing factors obtained during the primary investigation of patients with gunshot wounds [10-12].

4 The Use of Multivariate Statistical Analysis of Biomedical Indicators for Improving Technology of Accelerated Rehabilitation of Patients

For further development of the method using mathematical and statistical analysis and computer modelling, the authors propose a new approach based on a multivariate analysis of dynamic changes in biomedical indicators under conditions of randomness of the levels of influencing factors [13-14]. This approach presupposes the use of random models for the study of the factor effects of striking fragments on the dynamics of changes in biomedical indicators.

As one of these models, it is possible to use the statistical model of variance components, which allows you to adjust the sensitivity of the statistical analysis method, simultaneously setting the risks of the first and second kind and additionally taking into account the minimum number of experimental subgroups. Moreover, the basic feature of the studied objects is that from the point of view of mathematical statistics, they are considered as diffuse objects.

This means that it is impossible to completely solve the task, but a significant reduction in rehabilitation time is permissible. In addition, the research objects are considered as multi-level, and the functional relationship between the levels is selected based on multiple regression models, in which the number of regressors is random.

Previous studies conducted to model the effect of shrapnel injuries on rehabilitation processes in animals have provided evidence that the rehabilitation time depends not only on the size of the wound, but also on the temperature of the shrapnel and other biophysical factors [15-17]. Moreover, random changes in the results of biomedical measurements were also dependent on the temperatures of the fragments. The preliminary multivariate statistical analysis made it possible to obtain important information that indicated the possibility of planning medical technologies for the rehabilitation of animals taking into account the physical parameters of fragments: temperature, dynamic characteristics, weight of fragments.

The results of preliminary tests on animals, which were conducted to assess the possibility of modelling the impact of shrapnel wounds on the rehabilitation processes of animals during their treatment, showed a significant (up to 20%) increase in rehabilitation efficiency. This makes it possible to predict the possibility of increasing the use of these methods to improve the treatment and rehabilitation of patients with shrapnel injuries. In addition, previous studies have proven that biomedical indicators can be divided into three groups according to the degree of influence on them - separately temperature, time and the interaction between temperature and time. This means that it is desirable to use appropriate groups of indicators to control the levels of factors *A* and *B*. In addition, the possibility of dividing biomedical indicators into informative and uninformative ones regarding the dynamics of wound healing over time was quantitatively substantiated. This allows you to create tables of decreasing informativeness (by linear correlation coefficient over time) for all selected indicators ranked by informativeness.

Conducting a multiple correlation analysis of the obtained experimental information proved that the informativeness of the system of indicators reaches a maximum at specific values of the number of these indicators. It is for the latter that the informativeness of the system is maximum.

The result of research shows that each level of factor A (fragment temperature) corresponds to its own system of informative indicators, the informational properties of which are determined not only by temperature, but also by observation time. Although these systems (for the studied temperatures) partially overlap, it should be noted that when choosing biomedical indicators, it is desirable to know the degree of severity of the influencing factor (in this case, the temperature of the fragment). The task of assessing the potential level of such a factor requires additional research [18-20].

An example of assessing the independence of the amount of information from the dimensions of the space of biomedical indicators shown in fig. 2. It is clearly visible from the example that when the level of the determined value of the p indicators is reached, the informativeness decreases. Also, this dependence changes with changes in other significant indicators - for example, temperature.

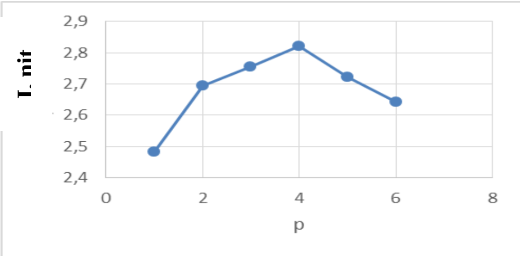

Fig. 2. An example of estimating the amount of dependence of the amount of information on the dimension of the space of biomedical indicators

In order to create a multiple regression model, the following analytical approach was used for the information analysis of the indicator system for the models. Any system of biomedical indicators that is used in an experiment with limitations on the amount of such information can be considered as a system with increased information uncertainty. Since the information components of such a system are based on one-dimensional regressions, the latter can be considered as regressions with random variables. Let us first classify the models of such basic one-dimensional regressions, which are ranked by the degree of information uncertainty increase. Let the evaluation of the controlled parameter Y (the studied biomedical indicator) be based on the results of measuring $x_1,\ldots x_p$ values of the controlled values $X_1,\ldots X_p$ with the subsequent functional transformation of these values into the Y^* estimate. This procedure corresponds to the indirect measurement model, where $X_1,\ldots X_p$ are arguments or variables, and the transformation model is selected based on the measurement method (indirect, cumulative, etc.). We will use the method of indirect measurement to select a measurement transformation model, for which such a model has the form:

$$Y = F\left(X_1,\ldots X_m\right), \tag{2}$$

where: m – the number of input physical quantities that can be directly measured.

In the absence of information about the type of physical model for choosing a functional relationship, such a relationship is assumed to be stochastic, for which model (3) can be formally written in the form of a multiple linear regression with random regressors [19, 20]:

$$Y = \beta_0 + \beta_1 u_1 + \ldots + \beta_{p-1} u_{p-1} + \varepsilon, \tag{3}$$

where: $\beta_0,\ldots\beta_{p-1}$ – coefficients of the model;
$u_0,\ldots u_{p-1}$ – random repressors;
ε – random residue,
p – the number of model parameters.

Several variants of the models were considered, and their adequacy was assessed. The obtained results showed the effectiveness of the chosen direction of research. To continue research with the aim of developing new technologies for accelerated rehabilitation of injured people, the following algorithm was proposed:

1. To conduct a multivariate regression analysis of biomedical indicators that can be measured during the initial examination of the wounded, taking into account their changes during treatment;
2. To carry out a statistical ranking of these biomedical indicators according to their informativeness in relation to the rehabilitation time and the level of influencing physical factors of striking fragments;
3. To improve the mathematical models of statistical evaluation of the amount of information regarding the dynamic properties of each biomedical indicator, depending on the level of the studied factor influence characterizing the selected physical characteristic of the fragment;
4. Develop and research a statistical optimization method taking into account the volume of the number of measurements and the number of biomedical indicators;
5. To develop a method of discriminant analysis to recognize (estimate) the levels of the studied factor influence, which characterizes the physical characteristics and dynamics of fragments;
6. Develop statistically based assessments of the reliability and risks of decision-making, which are made in the course of discriminant analysis as a result of multivariate measurements;
7. Develop a strategy for optimizing the indicators of the computerized system of information support for the technology of accelerated rehabilitation of the wounded.

As a result of this work, it is supposed to develop a qualitatively new technology for the rehabilitation of patients with gunshot penetrating wounds.

5 Conclusions

Thus, the preliminary analysis showed that the application of the technology of mathematical modelling of the multifactorial impact of impact fragments on the dynamics of rehabilitation processes, followed by their adaptation to the process of treatment and rehabilitation of the wounded, will allow one to significantly increase the effectiveness of the relevant medical technologies.

Taking into account the fact that currently there are no analogues of such technology in world science, theoretical research can be the basis for further improvement of the means of obtaining additional information on the condition of patients with shrapnel wounds, increasing the effectiveness of their treatment and rehabilitation methods.

The proposed technology is faster, economically feasible, does not depend on the type of injury, and allows one to significantly increase the efficiency of the rehabilitation process by increasing the accuracy and reliability of obtaining biomedical information.

Conflict of Interest. The authors declare that they have no conflict of interest.

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