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DOI: <https://doi.org/10.22141/2224-0586.21.2.2025.1852>Ye.I. Sokol<sup>1</sup> , P.F. Shchapov<sup>1</sup> , V.V. Nehoduiko<sup>2,3</sup> , R.M. Suprun<sup>1</sup> , K.R. Mygushchenko<sup>4</sup> <sup>1</sup>National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine<sup>2</sup>Military Medical Clinical Center of the Northern Region, Kharkiv, Ukraine<sup>3</sup>Kharkiv National Medical University, Kharkiv, Ukraine<sup>4</sup>California Institute of Technology, Pasadena, California, USA

## Evaluation of thermal and kinetic parameters of fragment in gunshot injuries

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**Abstract. Background.** The purpose was to demonstrate the potential of statistical assessment for determining shrapnel fragment temperature and velocity based on biomedical indicators of injury severity. **Materials and methods.** Chinchilla breed rabbits were selected as experimental material and subjects for modeling ballistic and shrapnel wound injuries. The scientific experiment was conducted as an active study having the controlled temperature and velocity of impacting shrapnel and bullets as the main influencing factors. Primary measurement data was collected using biophysical and biochemical examinations of the wounded animals. This data was then processed using methods of multivariate parametric statistics, validating the scientific findings with a specified level of confidence. **Results.** A statistically significant influence of the levels for the factors "Fragment temperature" and "Fragment linear velocity" on the selection of optimal subsets of biomedical indicators maximally correlated with observation time has been proven. The fundamental possibility of independent evaluation of the temperature values (according to the indicators "Alanine transaminase", "Alkaline phosphatase") and speed (according to the indicators "Total protein", "Segmented neutrophils") of damaging fragments during the initial examination of the wounded has been proven. Mathematical models (1) and (2) are presented for evaluating, respectively, the temperature and linear velocity of the fragment. It has been shown that the given errors in distinguishing between temperature and velocity levels are within the range of 25–30 % for a confidence probability of  $P = 0.8$ , and the error for the speed evaluation of a fragment is less than its temperature evaluation. The increased accuracy of fragment velocity evaluation provides additional information about the depth of the wound, which is another positive result of the study. **Conclusions.** A statistically significant influence of the levels for the factors "Fragment temperature" and "Fragment linear velocity" on the selection of optimal subsets of biomedical indicators maximally correlated with observation time has been proven. The fundamental possibility of independent evaluation of the temperature values (according to the indicators "Alanine transaminase", "Alkaline phosphatase") and speed (according to the indicators "Total protein", "Segmented neutrophils") of damaging fragments during the initial examination of the wounded has been proven. Mathematical models are presented for evaluating, respectively, the temperature and linear velocity of the fragment. It has been shown that the given errors in distinguishing between temperature and velocity levels are within the range of 25–30 % for a confidence probability of  $P = 0.8$ , and the error for the speed evaluation of a fragment is less than its temperature evaluation. The increased accuracy of fragment velocity evaluation provides additional information about the depth of the wound, which is another positive result of the study. The statistical reliability of regression models for estimating shrapnel temperature and velocity has been confirmed through biophysical experimental results. This approach expands the informational foundation for developing treatment technologies in shrapnel wounds.

**Keywords:** shrapnel wound; temperature and velocity of the fragment; biomedical indicators; regression identification

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## Introduction

A search for scientific publications focused on assessing the effects of thermal and kinetic parameters of impacting shrapnel on biochemical indicators revealed a lack of such studies. However, evidence strongly supports a direct relationship between the severity of thermal burns and changes in certain biochemical markers [1–4].

The kinetic energy of a fragment can be evaluated, for example, by the appearance of the primary wound channel and secondary necrosis of its walls [5–8]. When it comes to the complication of mathematical models for the formation of new informative indicators characterizing the current state of the patient, then such models are typical for informationally redundant biomedical signals [9, 10]. However, such methods are possible for active monitoring procedures, and not for initial rapid examination.

If the biomedical indicators are considered only for the initial examination of the wounded, then most often it is about evaluating their information content or forming an optimally informative subset [11]. There are no real examples of indirect evaluation by biochemical indicators of the levels of influencing factors (temperature and fragment velocity).

The problem is that the number of biomedical indicators that carry additional information about the severity of the shrapnel wound expands during the initial examination of the wounded. The number of such indicators is limited: the area and extent of the wound (they, unfortunately, are much correlated), the temperature of the wound surface, also weakly informative ones — age, body mass index. And, in fact, that is all. Unfortunately, it is technically impossible to estimate the temperature and speed of the fragment (in flight) by direct measurements. The problem of such evaluation, at least indirectly, can be solved only in physical experiments on animals.

In this case, it is possible to use correlation models of multiple regression analysis linking temperatures and fragment velocities with biophysical and biochemical parameters available in medical practice.

**The purpose** is to show the influence of the temperature of damaging fragments on the selection of the most informative subsets of biomedical indicators.

## Materials and methods

Male chinchilla rabbits, aged 7 months, weighing 2600–3600 (on average  $3100 \pm 126$ ) grams, six of which were not injured (control group), were used as experimental material and objects for the study of gunshot wounds. Two weeks before the beginning and three months after the study, the rabbits lived in a vivarium. In the period before the start of the study, the rabbits were in vivarium enclosures, in a quarantine room with a standard temperature of  $19 \pm 1$  °C. They received the same moderate caloric diet. Animals were provided with access to food and water. A week before the study began, the animals were fixed twice in the machine for adaptation.

The content, care and methods of experimental work with animals corresponded to generally accepted norms and the rules stipulated by the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (Strasbourg, 1986), Council Directive 86/609/EEC of November 24, 1986, the Declara-

tion of Helsinki, the International Guiding Principles for Biomedical Research Involving Animals (1990), the Order of the Ministry of Health of Ukraine No. 32 dated February 22, 1988 and the Law of Ukraine on the Protection of Animals from Cruelty Treatment No. 1759 dated December 15, 2009.

Animals were wounded by pneumatic and firearms at a specialized shooting range (Safari, Latek LLC) and at a training ground (the training ground of the Ministry of Internal Affairs in the village Ruska Lozova, Kharkiv region) with the observance of safety measures. Wounds were inflicted with a fragment of low-quality steel measuring  $5 \div 6 \times 4$  mm, weighing 0.36–0.52 grams from the distance at which blind wounds were received. When inflicting a wound from a pneumatic weapon (PSRM air rifle; initial speed 140 m/s, caliber 4.5 mm), fragments of different ambient temperatures (50 and 100 °C) were used. The animals were fixed in the machine and anesthetized before and after the study with nalbuphine at a dose of 0.3 mg/kg. The areas of the suspected thigh injury and the opposite symmetrical area were shaved an hour before the examination. Wounds were inflicted through two variants of military uniforms of old and new models.

Gunshot shrapnel single wounds were caused by firing from a FORT (Ukraine) revolver (caliber 4 mm, initial velocity 380 m/s).

List of biochemical indicators used: pulse; partial pressure of oxygen in venous blood ( $PO_2$ ); frequency of breathing movements; pH, an indicator of blood acidity; hemoglobin (Hg); red blood cells (RBC); white blood cells; band neutrophils (BN), %; segmented neutrophils (SN), %; monocytes (Mn), %; platelet count; aspartate transaminase (AST); alanine transaminase (ALT); bilirubin; alkaline phosphatase (ALP); glucose (GL); blood creatine kinase (CK); lactate dehydrogenase (LD); urea; creatinine; total protein (TP); prothrombin index; lymph (LM), %; wound area (WA).

The main features of the active biophysical experiment were:

- modeling of shrapnel wounds under multifactorial influences;
- generation of the fragment impact was carried out using mechanical devices simulating military weapons. At the same time, constant levels of temperature (17.5, 50 and 100 °C) and speed (140 and 380 m/s) of damaging metal fragments were strictly recorded.

Unfortunately, the number of rabbits with the temperature and splinter speed factors was limited (9 rabbits were used with the temperature factor, and 12 rabbits with the speed factor). The area of the wound in animals corresponded to  $0.35 \pm 0.15$  cm<sup>2</sup>.

An additional feature of the experiment is the repetition of all biochemical measurements (for the main group) not only on the first, but also on the third and fifth days of observation.

## Results

### Evaluating the influence of fragment temperature on regression models of biomedical indicators

The study of regression models was carried out in two stages and was aimed at identifying subsets of indicators that maximally correlated with the observation time.

At the first stage, the paired linear correlation of each indicator with time was evaluated for each level of the “Fragment temperature” factor. Then the indicators were ranked by decreasing modulus of the normalized correlation coefficient. At the second stage, systems were sequentially formed from a subset of indicators that maximally correlated with time ( $m = 1, m_0$ ).

The optimal number  $m_0$  of indicators corresponded to the maximum of the determination adjusted coefficient [9, 12] for the studied linear multiple regression of time on  $m$  biochemical indicators.

Regression models of the indicators were examined separately for each of the three fragment temperatures (17.5, 50 and 100 °C).

From the ranked indicators at the first stage, indicators were identified that had a statistically significant correlation with  $m = 1, m_0$  time for the first type risk  $\alpha = 0.05$  (the sample size ( $n = 9$ ) corresponded to three rabbits and three time points of 1, 3 and 5 days).

Table 1 presents the corresponding subgroups of biochemical parameters for three fragment temperatures (the normalized pairwise linear correlation coefficients  $R$  of each parameter with time are indicated in parentheses).

Table 2 presents the values of the Fisher statistic ( $F_{m; n-m-1}$ ) and the critical statistic ( $F_{m; n-m-1; \alpha}$ ). Also, the maximum values of the adjusted coefficient of determination ( $\max R_{adj}^2$ ) for the optimal subsets of biochemical parameters are presented, with the corresponding shading in Table 1.

Analysis of the results presented in Table 1 and 2 shows the following:

1. Changing the levels of the factor “Fragment temperature” has a statistically significant effect on the selection of subsets of biomedical indicators that are maximally correlated with the time of their observation during the rehabilitation period of the wounded.

2. From conclusion 1 it follows that the same influence can be expected, for example, in relation to the factor “Fragment linear velocity”.

3. Since for all levels of fragment temperatures the Fisher statistics exceeds the critical value by 3–12 times, the reliability of conclusions 1 and 2 exceeds 0.95 and indicates the need to continue such experiments.

### Study on the procedures for evaluating temperature and fragment velocity values using biomedical indicators

Such studies were carried out in two stages. First, the indicators that maximally and statistically significantly correlated were determined, separately with temperature, and separately with fragment velocity. For this purpose, 18 rabbits were used for temperature and speed factorial experiments. Only two indicators had the maximum and statistically significant correlation with temperature: ALT ( $R = 7.8022$ ) and ALP ( $R = 7.1863$ ). Their Fisher statistics  $F_{1; 16}$  exceeded the critical values  $F_{1; 16; 0.05} = 4.49$ . The evaluation of cross-correlation between ALT и ALP was equal to  $R = 0.081$  and was found to be statistically insignificant ( $n = 18$ ).

Seven indicators had the maximum correlation, statistically significant ones, in the tests on the influence of fragment speed: TP ( $R = 0.886$ ), SN ( $R = 0.885$ ), GL ( $R = -0.786$ ), urea ( $R = 0.766$ ), LM ( $R = 0.728$ ), Mn ( $R = -0.709$ ), AST ( $R = 0.685$ ).

Analysis of cross-correlation between indicators (ALT, ALP) responsive to temperature and seven indicators responsive to speed allowed identifying two indicators (TP, SN) from the latter. They turned out to be the least correlated with ALT and ALP (cross-correlation coefficients ranged from  $-0.014$  to  $-0.385$ ).

To model the procedures for estimating the temperature and velocity of fragments, two-factor linear multiple regression was used:

$$y = b_0 + b_1x_1 + b_2x_2,$$

where  $y$  is level of influencing factor;  $b_0$  is free coefficient;  $b_1, b_2$  are angular coefficients;  $x_1, x_2$  are regressors corresponding to the selected two indicators.

A group of 9 rabbits was taken for temperature tests, and a group of 12 rabbits for tests on the speed effect.

**Table 1. Subgroups of indicators that are statistically significantly correlated with time ( $i$  is indicator rank)**

$i$	Biochemical parameters (correlation coefficient $R$ )					
	17.5 °C		50 °C		100 °C	
1	RBC	(-0.779)	RBC	(-0.782)	WA	(0.832)
2	AST	(0.737)	BN	(0.756)	CK	(-0.740)
3	CK	(-0.655)	Pulse	(0.726)	LM	(0.707)
4	LD	(0.645)	Urea	(0.696)	SN	(-0.696)
5	TP	(0.589)	LM	(-0.656)	Hg	(-0.686)
6		–	SN	(0.598)	RBC	(-0.644)

**Table 2. Values of Fisher statistics and critical statistics ( $m = m_0; n = 9$ )**

$t, ^\circ\text{C}$	$m_0$	$F_{m; n-m-1}$	$F_{m; n-m-1; \alpha}$	$\max R_{adj}^2$
17.5	4	31.118	6.39	0.772
50	2	15.367	5.14	0.626
100	3	50.464	6.39	0.853

For the first group, the fragment velocity was constant ( $V = 140$  m/s), and for the second, the fragment temperature was constant ( $t = 100$  °C). The wound area for rabbits from both groups was approximately the same ( $0.35 \pm 0.15$  cm<sup>2</sup>).

Table 3 presents the initial data in the form of measurement results for the variables  $y$ ,  $x_1$ ,  $x_2$  (temperature tests,  $n = 9$ , ALT and ALP indicators).

Table 4 shows the results of regression analysis of data from Table 3 based on Excel using standard data analysis settings.

Main results of regression analysis:

1. Mathematical model for estimating fragment temperature values:

$$y = -23.656 + 0.940x_1 + 0.3x_2. \quad (1)$$

2. Standard error  $\sigma = 20.83$  °C.

3. Reduced estimation error, with confidence probability  $P = 0.68$ ,  $\gamma = \pm 25.25$  %, relative to temperature range  $\Delta t = 82.5$  °C.

4. Fisher's variance ratio statistics and its critical value  $F_{2;6} = 8.941$  and  $F_{2;6;0.05} = 5.14$ .

Regression is statistically significant because  $8.941 > 5.14$ .

From the results obtained it follows that with probability  $P = 0.68$ , it is possible to distinguish between adjacent temperature levels, the difference between which is  $\varepsilon \leq 2\sigma$  (or  $\varepsilon \leq 41.66$  °C). For confidence probability  $P = 0.8$ , the value is  $\varepsilon \leq 1.28 \cdot 2\sigma$  (or  $\varepsilon \leq 53.32$  °C;  $\gamma \leq 32.32$  %).

Table 5 presents the initial data of the experiment for the factorial influence of the linear velocity ( $y$ ) of the fragment ( $n = 12$ , TP, SN indicators).

The results of the regression analysis are presented in Table 6.

Main results of regression analysis:

$$1. y = -270.229 + 5.013x_1 + 4.875x_2. \quad (2)$$

$$2. \sigma = 47.902 \text{ °C.}$$

3.  $\gamma = 19.96$  % (relative to speed range  $\Delta V = 240$  m/s,  $P = 0.68$ ).

$$4. F_{2;9} = 33.153 \text{ and } F_{2;9;0.05} = 4.26.$$

Regression is significant because  $33.153 > 4.26$ .

From the results obtained it follows that the width  $\varepsilon$  of the interval for distinguishing speed levels  $\varepsilon \leq 61.315$  m/s for  $P = 0.8$ ; where in  $\gamma \leq 25.55$  %.

## Discussion

The initial examination of victims with shrapnel wounds is always accompanied by an analysis of the primary measurement of certain biomedical indicators. Qualitative information is always added to quantitative measurement in the form of certain expert evaluation. Regardless of its type, such information allows evaluating the severity of the traumatic injury and choosing a technology for medical treatment and subsequent rehabilitation of the wounded. However, the results of physical modeling of shrapnel wounds on animals (chinchilla rabbits) showed that different temperatures of damaging fragments correspond to different subsets of bio-

**Table 3. Measurement results (factor "Fragment temperature")**

$y$ (t, °C)	17.5			50			100		
$x_1$ (ALT)	40	36	37	48	92	52	76	66	78
$x_2$ (ALP)	23	36	82	34	23	114	136	90	202

**Table 4. Results of regression analysis (factor "Fragment temperature")**

Regression statistics						
Multiple R	0.865312					
R square	0.748764					
Adjusted R square	0.665019					
Standard error	20.8304					
Observations	9					
ANOVA						
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>	
Regression	2	7759.068	3879.534	8.940967	0.015858	
Residual	6	2603.432	433.9054			
Total	8	10362.5				
	<i>Coefficients</i>	<i>Standard error</i>	<i>t stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	-23.6554	22.27336	-1.06205	0.32908	-78.1563	30.84559
x variable 1	0.939688	0.390504	2.406349	0.052836	-0.01584	1.895216
x variable 2	0.300084	0.130531	2.298945	0.061189	-0.01931	0.619482

Table 5. Experiment data (factor “Fragment linear velocity”)

y (V, m/s)	140						380					
x <sub>1</sub> (TP)	66.8	59.2	62.1	57.5	54.1	62.6	95.8	79.9	78.8	81.5	74.9	78.1
x <sub>2</sub> (SN)	26	18	24	24	34	24	49.8	42.1	41.8	42.2	44.1	59.8

Table 6. Results of regression analysis (factor “Fragment linear velocity”)

Regression statistics						
Multiple R	0.938343					
R square	0.880487					
Adjusted R square	0.853929					
Standard error	47.90248					
Observations	12					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	2	152148.2	76074.09	33.15284	7.05E-05	
Residual	9	20651.83	2294.647			
Total	11	172800				
	Coefficients	Standard error	t stat	P-value	Lower 95%	Upper 95%
Intercept	-270.229	91.68846	-2.94726	0.016293	-477.643	-62.8156
x variable 1	5.01295	1.857367	2.698955	0.024435	0.811293	9.214607
x variable 2	4.874889	1.812263	2.689946	0.024799	0.775266	8.974513

medical indicators characterizing the dynamics of the rehabilitation process.

Taking into account the level of the factor “Fragment temperature” allows planning the selection of biomedical indicators that carry maximum information about the dynamics of such rehabilitation. In a broader perspective, it could potentially lead to planning elements of medical technology for treating wounds and further treatment.

The article presents the results of mathematical modeling of procedures for evaluating the levels of the factors “Fragment temperature” and “Fragment linear velocity” using uncorrelated biomedical indicators. The results of biochemical measurements in physical simulations of shrapnel wounds in rabbits were used to verify the accuracy and adequacy of such procedures. The temperature and velocity levels of the fragments were fixed and known. The errors in indirect estimation of such levels were on average 25–30 % in relation to the ranges of temperature and speed changes.

## Conclusions

1. It has been proven that the temperature levels of injurious fragments influence the selection of biomedical indicators subsets that undergo the most significant changes as the rehabilitation period of injured individuals increases.

2. The feasibility of simultaneously assessing the temperature and velocity of injurious fragments has been proven.

This assessment is based on independent subsets of biomedical indicators at the stage of the initial examination of the wounded.

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**Authors' contribution.** Ye.I. Sokol — the author of the idea; P.F. Shchapov — writing the article; V.V. Nehoduiko — conducting the experiment; R.M. Suprun — mathematical modeling; K.R. Mygushchenko — literature review.

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### Оцінка термічних та кінетичних параметрів осколка при вогнепальних ушкодженнях

**Резюме. Актуальність.** Метою було продемонструвати можливість статистичної оцінки для визначення температури та швидкості уламків шрапнелі на основі біомедичних показників тяжкості ушкодження. **Матеріали та методи.** Як експериментальний матеріал та об'єкти для моделювання балістичних і осколкових поранень були обрані кролики породи шиншила. Науковий експеримент проводився як активне дослідження, основними факторами впливу були контрольована температура та швидкість влучання осколків і куль. Первинні дані вимірювань збирали за допомогою біофізичних і біохімічних досліджень поранених тварин. Потім ці дані були оброблені за допомогою методів багатовимірної параметричної статистики, що дозволило підтвердити наукові висновки із заданим рівнем вірогідності. **Результати.** Доведено статистично значущий вплив рівнів факторів «Температура фрагмента» та «Лінійна швидкість фрагмента» на вибір оптимальних підмножин медико-біологічних показників, що максимально корелюють із часом спостереження. Також доведено принципову можливість незалежної оцінки значень температури (за показниками «Аланінтрансаміназа», «Лужна фосфатаза») та швидкості (за показниками «Загальний білок», «Сегментоядерні лейкоцити») ушкоджуючих осколків при первинному огляді поранених. Наведено математичні моделі (1) та (2) для оцінки відповідно температури та лінійної швидкості осколка. Показано, що надані похибки розрізнення рівнів температури та швидкості знаходяться в межах 25–30 % для довірчої ймовірності  $P = 0,8$ , а похибка оцінки

швидкості фрагмента є меншою, ніж оцінка температури. Підвищена точність оцінки швидкості осколків дає додаткову інформацію про глибину рани, що є ще одним позитивним результатом дослідження. **Висновки.** Доведено статистично значущий вплив рівнів факторів «Температура фрагмента» та «Лінійна швидкість фрагмента» на вибір оптимальних підмножин медико-біологічних показників, що максимально корелюють із часом спостереження. Також доведено принципову можливість незалежної оцінки значень температури (за показниками «Аланінтрансаміназа», «Лужна фосфатаза») та швидкості (за показниками «Загальний білок», «Сегментоядерні лейкоцити») ушкоджуючих осколків при первинному огляді поранених. Наведено математичні моделі для оцінки відповідно температури та лінійної швидкості осколка. Показано, що надані похибки розрізнення рівнів температури та швидкості знаходяться в межах 25–30 % для довірчої ймовірності  $P = 0,8$ , а похибка оцінки швидкості фрагмента є меншою за оцінку його температури. Підвищена точність оцінки швидкості осколків дає додаткову інформацію про глибину рани, що є ще одним позитивним результатом дослідження. Статистична вірогідність регресійних моделей для оцінки температури та швидкості осколків була підтверджена результатами біофізичних експериментів. Такий підхід розширює інформаційну базу для розробки технологій лікування осколкових поранень.

**Ключові слова:** осколкове поранення; температура і швидкість осколка; біомедичні показники; ідентифікація регресії