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MODELING OF WOUND BALLISTICS IN BIOLOGICAL TISSUES USING ENGINEERING SIMULATION SOFTWARE

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Key words: *gunshot wound, gushot injury, modelling of bullet injury, numerical modeling*
Ключові слова: *вогнепальна рана, вогнепальне поранення, моделювання кульового поранення, чисельне моделювання*

Abstract. Modeling of wound ballistics in biological tissues simulators. Tsymbaliuk V., Lurin I., Gumeniuk K., Herasymenko O., Furkalo S., Oklei D., Negoduyko V., Gorobeiko M., Dinets A. *Modern weapons cause severe damage, accompanied by high rates of complications and mortality. The investigation of such kinds of weapons is in high demand considering the ongoing active phase war against Ukraine since February 2022. In order to understand the pathological processes that occur in and outside the gunshot wound, we conducted an experimental study using mathematical simulation. The results presented in the article will help to choose the appropriate surgical management and improve the results of treatment. The aim of this study was to investigate and evaluate the damaging effect of a 5.45 mm 7N6M bullet and a 5.45 mm V-max expansive bullet using numerical modeling of wound canals in ballistic plasticine. The Ansys Explicit Dynamics engineering complex was used to simulate the dynamics of the bullet's motion. The basic equations, solved by the explicit dynamic analysis, express the conservation of mass, momentum, and energy in Lagrange coordinates. Together with the material model and the set of initial and boundary conditions, they determine the complete solution to the problem. Taking into account that the initial velocity of the bullet is 1185 m/s at a mass of 3.9 g, we obtain energy 2740 J. All this energy acts at the area of the wound canal with a depth of 150 mm. Injury with a conventional 7N6M bullet is characterized by the fact that it passes through the block and loses only part of the kinetic energy. The simulation results showed that the velocity of the bullet at the outlet is 220 m/s. Taking into account the initial velocity of the bullet 918 m/s with a mass of 3.4 g, we obtain the kinetic energy acting on the walls of the wound canal with a depth of 200 mm of about 830 J. Mathematic analyses showed that the expansive bullet has a soft core that deforms and transfers all the kinetic energy to the tissues immediately after penetration into the tissues. The loss of kinetic energy of the bullet (ΔE, J) is defined as the difference between the kinetic energy at the time of injury (Ec, J) and the residual energy of the bullet when leaving the material (Er, J). Numerical modeling of wound ballistics in biological tissue simulators allows us to determine with high accuracy the features of wound canal formation and tissue response to damage of bullets having different kinetic energy, which contributes to the choice of adequate surgical management during surgery for gunshot wounds.*

Реферат. Моделювання ранової балістики в біологічних тканинах за допомогою програмного забезпечення з інженерної симуляції. Цимбалюк В., Лурін І., Гуменюк К., Герасименко О., Фуркало С., Оклей Д., Негодуйко В., Горобейко М., Дінець А. *Моделювання балістики вогнепальної рани в сучасній системі інженерного аналізу ANSYS. Сучасна зброя завдає серйозних ушкоджень, що супроводжується високим рівнем ускладнень і смертності. Дослідження такого виду зброї є вкрай важливим, ураховуючи триваючу активну фазу війни проти України з лютого 2022 року. Щоб зрозуміти патологічні процеси, які відбуваються при вогнепальному пораненні, ми провели експериментальне дослідження за допомогою чисельного моделювання. Наведені в статті результати допоможуть підібрати адекватне хірургічне лікування та покращити результати лікування. Метою цього дослідження було дослідити та оцінити уражаючу дію кулі калібру 5,45 мм 7Н6М та експансивної кулі калібру 5,45 мм V-max за допомогою чисельного моделювання ранових каналів у балістичному пластиліні. Для моделювання динаміки руху кулі використовувався інженерний комплекс Ansys Explicit Dynamics/Ls-Dyna. Програмний комплекс Ansys Explicit Dynamics проводить числові розрахунки за допомогою обчислювача Ls-Dyna. ANSYS Ls-Dyna – це інструмент явного аналізу для моделювання нелінійної динаміки твердих тіл, рідин, газу та їх взаємодії. Основні рівняння, розв'язані шляхом явного динамічного аналізу, виражають збереження маси, імпульсу та енергії в координатах Лагранжа. Разом з матеріальною моделлю та набором початкових і граничних умов вони визначають повне розв'язування поставленої задачі. Ураховуючи, що початкова швидкість кулі 1185 м/с при масі 3,9 г, отримуємо енергію 2740 Дж. Вся ця енергія діє на ділянку ранового каналу глибиною 150 мм. Поранення звичайною кулею 7Н6М характеризується тим, що вона проходить через блок і втрачає лише частину кінетичної енергії. Результати моделювання показали, що швидкість кулі на виході становить 220 м/с. Враховуючи початкову швидкість кулі 918 м/с при масі 3,4 г, отримуємо кінетичну енергію дії на стінки ранового каналу глибиною 200 мм близько 830 Дж. Аналіз отриманих результатів показав, що експансивна куля має м'який сердечник, який деформується і передає всю кінетичну енергію тканинам відразу після проникнення в тканини. Втрата кінетичної енергії кулі (ΔE, Дж) визначається як різниця між кінетичною енергією в момент поранення (Ec, Дж) і залишковою енергією кулі при вильоті з матеріалу (Er, Дж). Числове моделювання ранової балістики в сучасній системі інженерного аналізу ANSYS дозволяє з високою точністю визначити особливості формування ранового каналу та реакцію тканин на пошкодження кулями з різною кінетичною енергією, що сприяє вибору та адекватному хірургічному веденню під час хірургічного втручання при вогнепальних пораненнях.*

Dedicated to the heroic deeds of Ukrainian doctors in the name of life

The severity of gunshot wounds is increasing due to frequent traumatic shock, multiple organ failures, and high mortality [1]. The active phase of russia's war against Ukraine is demonstrated new challenges to military surgeons because of the high incidence of severe gunshot wounds due to the frequent application of high-energy weapons as well as modified bullets [2, 3]. Our experience from the patient's management during russia's invasion showed some specific features of such gunshot wounds such as severe functional disorders, an increased frequency of complications, and a high mortality rate [3, 4, 5, 6, 7, 8, 9].

A specific feature of such gunshot wounds is related to the kind of bullets to be made with a changed center of gravity type 5.45x39 PS (7N6M) and expansive characteristics of the bullets (hollow-point bullets) type 5.45x39 V-max as also shown in other studies of gunshot trauma [2, 10, 11, 12, 13, 14]. The consequences of the application of the above-mentioned types of bullets showed in the clinical photographs (Fig. 1)

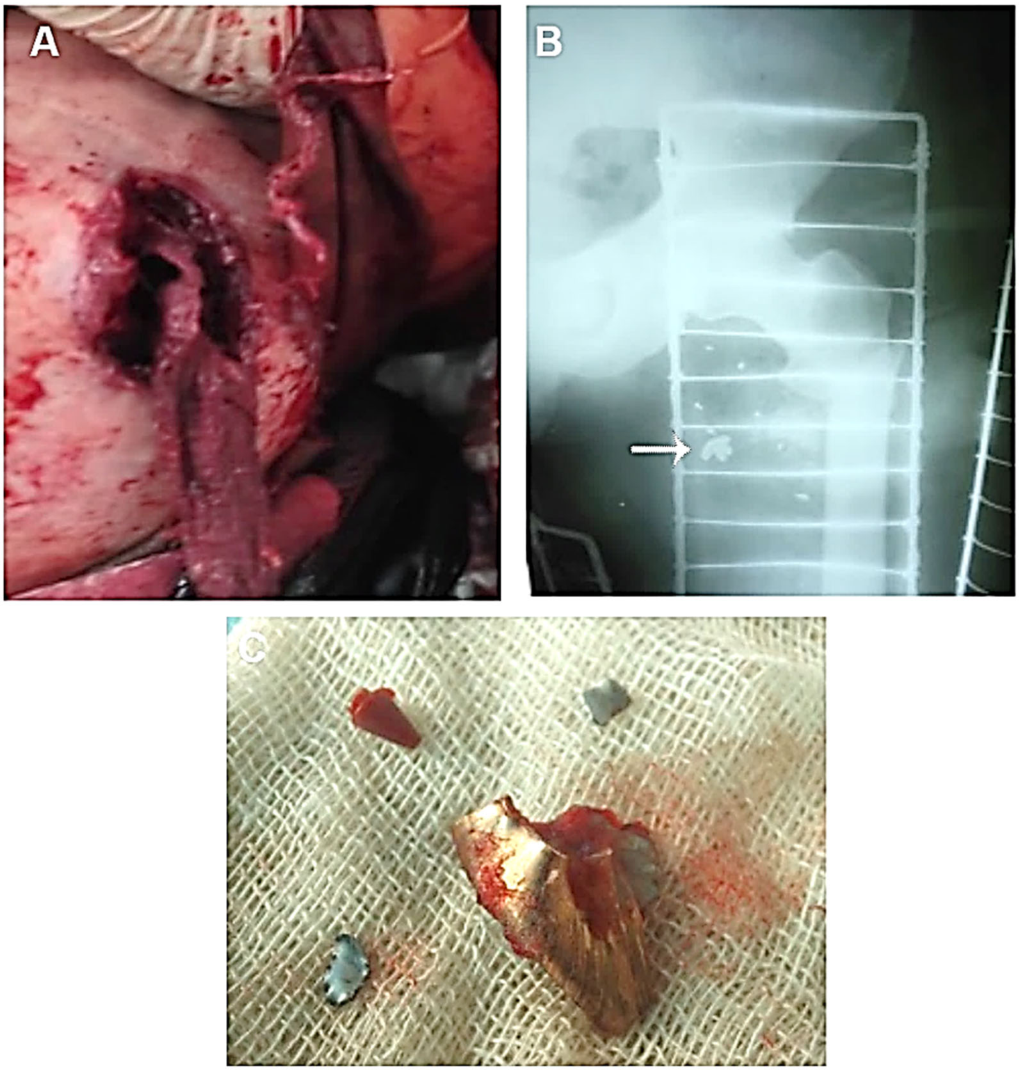

Fig. 1. Gunshot bullet blind wound of the left hip joint with an expansive bullet: a – view of the inlet of the gunshot wound, b – X-ray of the left hip joint in direct projection (epy arrow indicates a deformed bullet), c – removed fragments of the expansive bullet

According to our experience, injuries with such kinds of bullets have some differences in the nature of tissue damage along the wound canal. However, the mechanism of these particular damages that are seen in clinical settings, is not fully understood, requiring further investigations and comparative characterization of the damaging effect between bullets with a changed center of gravity and expansive bullets by using mathematic simulation and numerical modeling [15]. Numerical modeling a gunshot wound becomes of the main methods of studying wound ballistics and predicting the course of the wound process [16, 17]. Some authors used the gelatin model to study the mechanism of spherical projectiles and bullet penetration into biological tissues [18, 19]. Gelatin is presented as a quasistatic model of expansion of a cylindrical cavity for radial stress on the walls of the cavity. By using the gelatin model, it is possible to evaluate the pressure on the cavity surface as the energy required for the quasistatic opening of a single volume in the medium. Based on this interpretation, it is possible to propose an approximate expression for the dynamic pressure acting on the cavity surface by analyzing the conversion and conservation of energy. A resistance model for spherical projectiles was obtained, and the model's ability to describe motion was tested by comparing the results of various measurements for projectiles of different shapes, weights, and densities. The numerical model of motion is based on the theory of cavity expansion, which may be the basis for understanding the interaction of small arms ammunition within biological soft tissues [20].

It is also worth mentioning, that other researchers have also shown a high utility of the gelatin models, demonstrating the behavior of 20% gelatin under high-speed loading using numerical simulation and Finite Element (FE) simulation [15, 21]. The normal penetrating effects of the hard sphere in gelatins were studied before, and the FE model was developed and compared with the experimental data and the analytical model according to published literature. The numerical model uses bullets of three calibers (2.38, 4.76, 6.3 mm) with impact speeds from 230 to 2229 m/s. The results from the published series also confirmed our idea to use the gelatin model, which is associated with important experimental tests and calculations for ballistics experiments [15].

Wen Y. et al. conducted experiments with the penetration of the rifle bullet into the blocks of the ballistic gelatin, and software for finite elements LS-DYNA was used to build mathematical models [20]. In that study, a model of ballistic gelatin was investigated in terms of an elastic-plastic linear-deformation reinforcing material with a polynomial equation of the state. It was found that the calculated penetration depth and cavity profiles were close to those observed experimentally. Hydrostatic pressure at points close to the area where the bullet passes has "two peaks", the first due to the initial impact of the bullet, and the second was the movement of the bullet in gelatin. Plastic deformations occurred in a narrow, approximately 8 mm area around the surface of the cavity, and most of the gelatin underwent only elastic deformations. It was found that the angle of attack significantly affects the depth of penetration when the bullet is thrown over 90°. The kinetic energy of the bullet was transferred to the gelatin due to overturning and increased with increasing the angle of the shock by the bullet. The closeness of the test results to the calculated results was associated with conclusions that may predict significant features of changes in living tissues [20].

Susu L. et al. described the motion of bullets in ballistic gelatin by obtaining an appropriate mathematical model. In this paper, the change in the effective area of the bullet with increasing the angle of rotation in the penetration process is investigated by [22]. Due to the introduction of the coefficient of separation of the area and the influence of slenderness, a new structure for the coefficients of resistance and lift is proposed. The proposed models of movement, based on new structures of coefficients of resistance and lift, accurately describe the behavior of the rifle bullet when penetrating the simulators of biological tissues, which can be applied in practice [22].

Gilson L. et al. simulated the damaging effects of two types of ammunition: 9 mm and 44 calibers "Magnum" [23]. A high-speed camera and a pressure sensor were used to measure the fragmentation rate of projectiles and the pressure at a given location of gelatin during shell penetration. The observed instability of 9 mm bullets was also investigated. Four numerical models were developed and solved with the help of LS-DYNA and compared with experimental data. High consistency was obtained between mathematic simulation and experiments, which confirms the effectiveness of the proposed method [20].

There was also found a significant data in the published series advocating the following methods of mathematic simulation of wound ballistics in biological tissue simulators: Polygon program (2016) by a group project of Simon Fraser University (SFU, Canada), "polygon-procedure" of polygon modeling by approximating the surface using polygons grids [24]; non-uniform rational basis spline (NURBS) by a mathematical model that uses basis splines to represent curves and surfaces (3D objects) [25]; models HUByx, ANSYS AUTODYN, FEM – Finite element method [15, 20, 21, 22, 26, 27].

The analyses of the published series allow us to plan and perform a mathematic simulation of the formation of wound canals in ballistic plasticine with a 5.45 mm 7N6M bullet and a 5.45 mm V-max expansive bullet as shown in previous studies, including forensic investigations and applications of numerical modeling simulation engineering systems namely Ansys Explicit Dynamics/Ls-Dyna [7, 11, 28].

The aim of this study was to investigate and evaluate the damaging effect of a 5.45 mm 7N6M bullet and a 5.45 mm V-max expansive bullet using numerical modelling of wound canals in ballistic plasticine using engineering software.

MATERIALS AND METHODS OF RESEARCH

The Ansys Explicit Dynamics engineering complex was used to simulate the dynamics of the bullet's motion. The basic equations, solved by the explicit dynamic analysis, express the conservation of mass, momentum, and energy in Lagrange coordinates. Together with the material model and the set of initial and boundary conditions, they determine the complete solution to the problem. To formulate Lagrange, the grid moves and deforms together with the material it simulates, so the preservation of mass is satisfied automatically.

At each time step, these equations are solved explicitly for each element of the model based on the inlet data obtained at the previous step. Only mass and momentum conservation were used.

The simulated block of ballistic plasticine measuring 100x100x200 mm is divided into elementary volumes whose size does not exceed 1 mm. The size of the calculation model is about 1 000 000 elements (Fig. 2).

A special method of constructing a calculated grid was used to simulate the deformation of the bullet (Fig. 3).

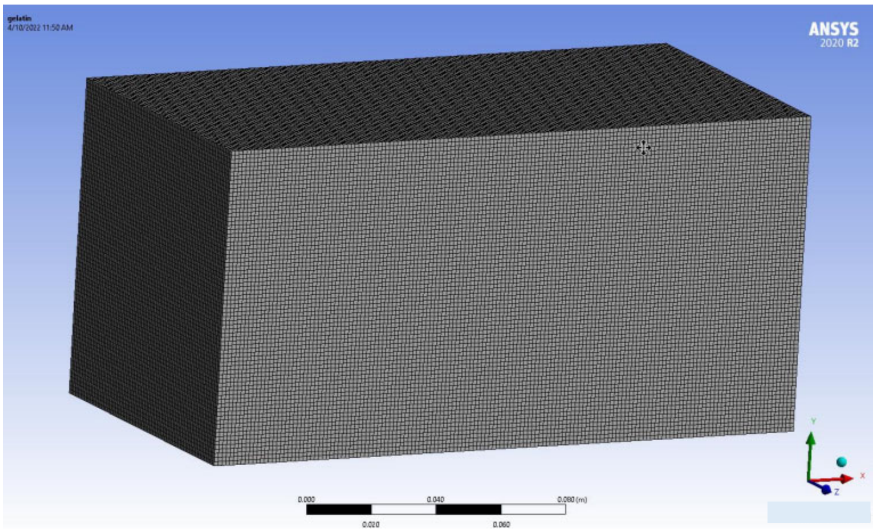

Fig. 2. Illustration of numerical modeling of a ballistic plasticine block using ANSYS software

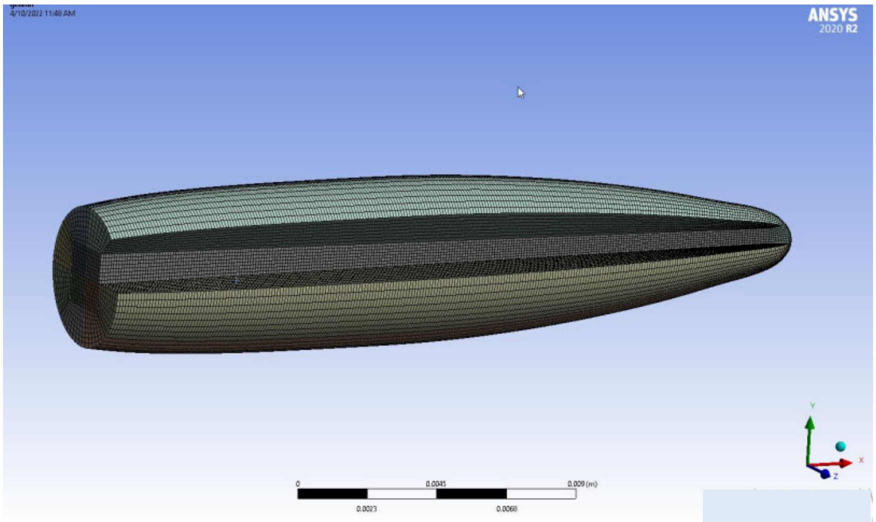

Fig. 3. Simulation of a bullet 5.45x39 PS (7N6M) by using ANSYS software

Table 1 presents the main characteristics of the ballistic simulators used.

The Power Law plasticity material model was used to model the behavior of ballistic plasticine. This model depends on strain and strain rate, which coma only underwent analyses of superplastic materials. [ANSYS, Inc. ANSYS LS-DYNA User's Guide: ANSYS release 12.0, 2009]

Table 1

Physical-mechanical characteristics of ballistic plasticine

ρ, kg/m3	E, MPa	Et, kPa	k, mPa	m	n
1,500	4.94	10	0.2	0.1	0.01

In this model of the material, the axial stress σ_{yy} shows a nonlinear relationship between the strain ε and the strain rate $\dot{\varepsilon}$. It can be recorded:

$$\sigma_{yy} = k\varepsilon^{m}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{n}$$

Equation legend: k – the material constant, m – the strain hardening, n – the strain rate sensitivity coefficient, ε – the initial strain rate, usually equal to 1. Additionally, the modulus of elasticity E was specified in the material model.

The main characteristics of the bullets are shown in Table 2.

Calculations were performed for bullets of caliber 5.45 type 7N6M and expansive bullet type V-max. The main criteria for comparing the severity of the injury:

– deformation of the ballistic plasticine block depending on time;

– the value of the equivalent strain at a certain moment in time;

– features of the trajectory of the bullet

Table 2

Types of ammunition used, weight, and initial velocity at the outlet of the barrel

Cartridge caliber and a bullet type	Weight (g)	Bullet speed, m/s
5.45x39 PS (7N6M)	3.4	918
5.45x39 V-max	3.9	1185

The use of a surface that shows the part of the plasticine on which the kinetic energy of the bullet acts, allows you to visualize the extent of damage to biological tissues by the bullet. The study was approved by the local ethical committee.

RESULTS AND DISCUSSION

Numerical modeling of gunshot injury by using a simulator of the damaging action of a 5.45 mm 7N6M bullet at 0.0001 s after a shot is shown in Figure 4.

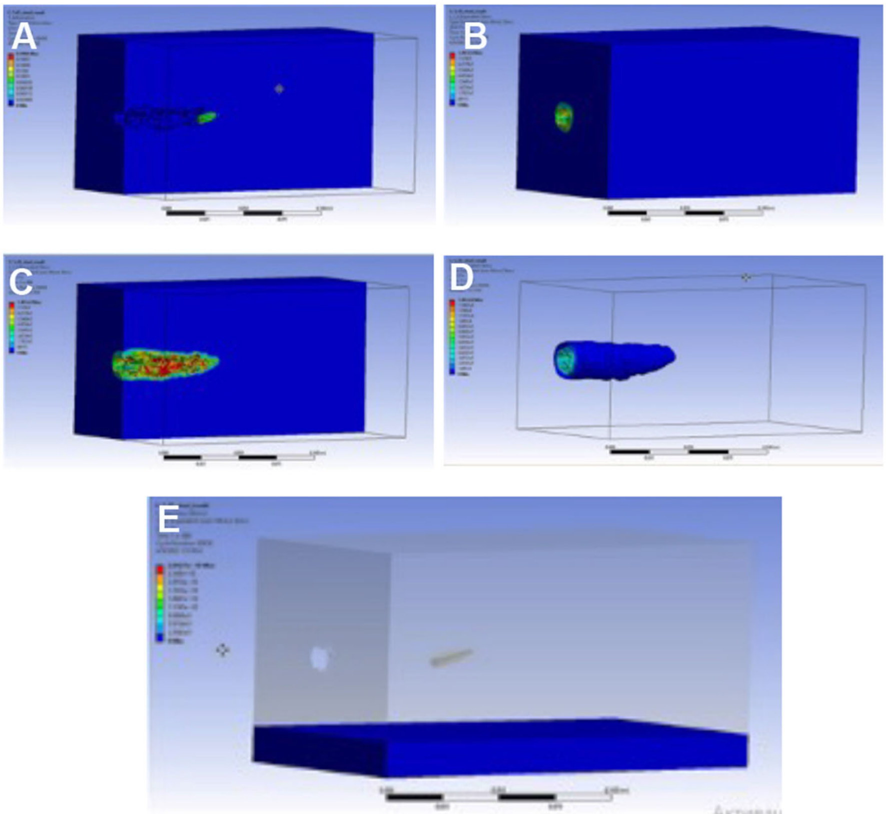

Fig. 4. Numerical model of passing a bullet 5.45x39 PS (7N6M) through a block of ballistic plasticine, t=0.0001 s: A – deformation, B – equivalent strain (inlet), C – equivalent strain (cut), D – equivalent strain (surface, which describes the volume of tissues affected by the kinetic energy of the bullet), E – the trajectory of the bullet

Simulation of the damaging effect of a bullet caliber 5.45 mm 7N6M 0.0005 s after the shot is shown in Figure 5.

Simulation of the damaging effect of an expansive bullet of 5.45 mm V-max caliber 0.0001 s after the shot is shown in Figure 6.

The simulation of the damaging effect of the 5.45 mm V-max expansive bullet 0.0002 s after the shot is shown in Figure 7.

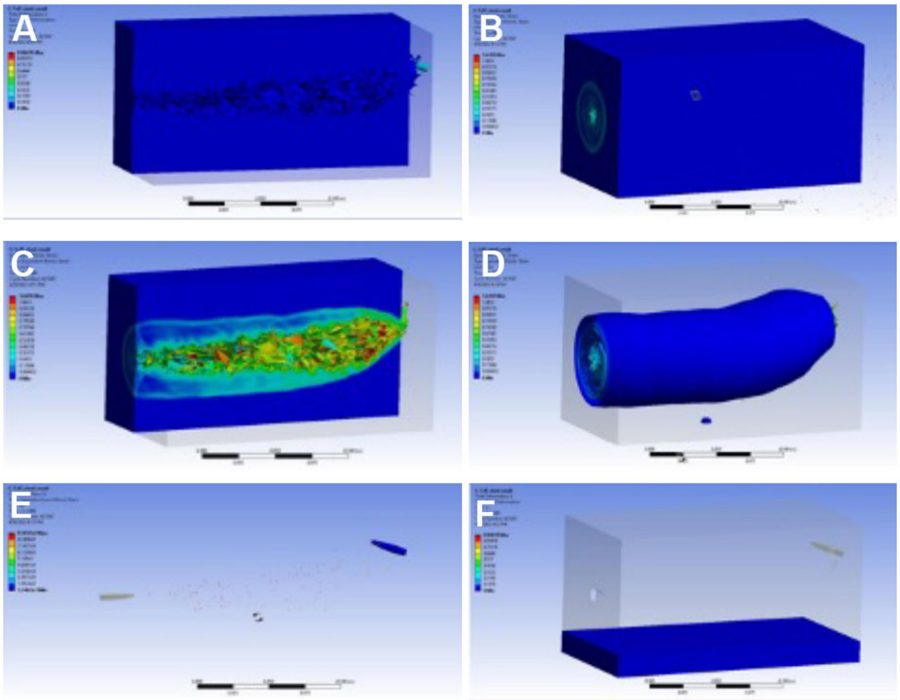

Fig. 5. Model of passing a bullet 5.45x39 PS (7N6M) through a block of ballistic plasticine, t=0.0005 s: A – deformation, B – equivalent strain (inlet), C – equivalent strain (cut), D– equivalent strain (surface, which describes the volume of tissues affected by the kinetic energy of the bullet), E – the equivalent strain of the bullet, F– the trajectory of the bullet

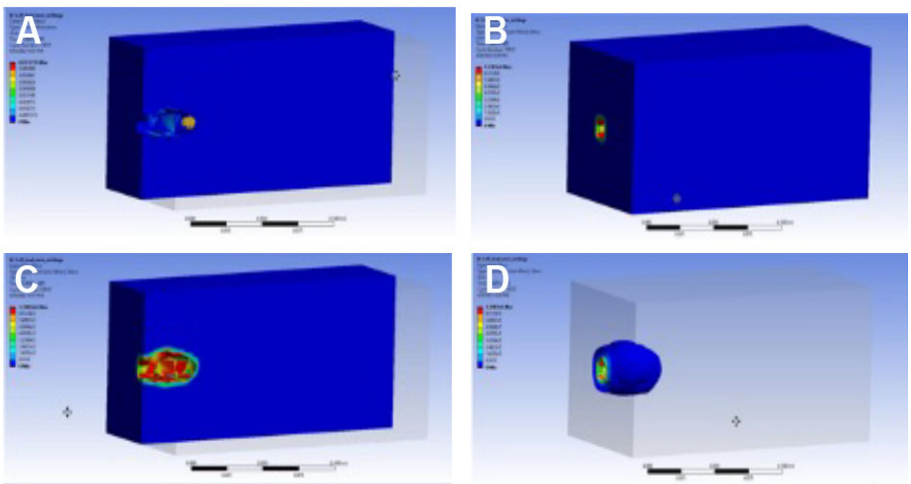

Fig. 6. Model of passing a bullet 5.45x39 V-max through a block of ballistic plasticine, t=0.0001 s: A – deformation, B – equivalent strain (inlet), C – equivalent strain (cut), D – equivalent strain (surface, which describes the volume of tissues affected by the kinetic energy of the bullet)

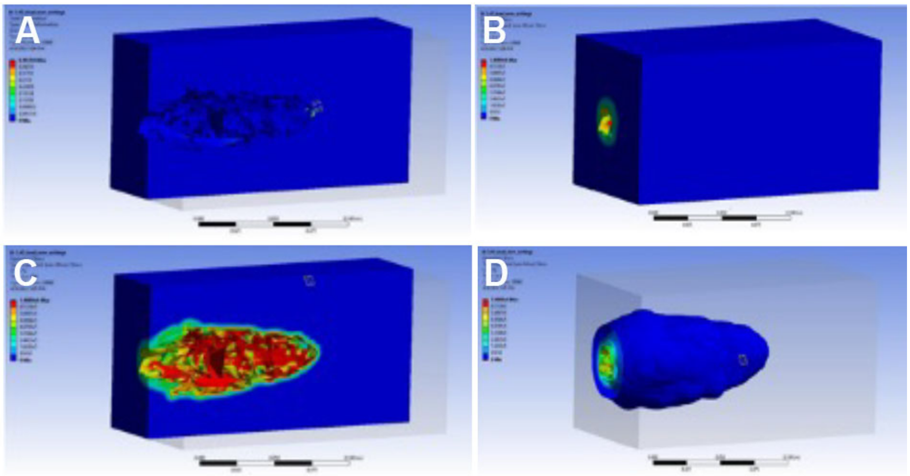

Fig. 7. Model of passing a bullet 5.45x39 V-max through a block of ballistic plasticine, t=0.0002 s: A– deformation, B – equivalent strain (inlet), C – equivalent stress (cut), D – equivalent strain (surface, which describes the volume of tissues affected by the kinetic energy of the bullet)

To compare the severity of the wound between the expansive and ordinary bullets, the value of the equivalent strain acting on the walls of the wound canal is shown in Figure 8.

Verification of the obtained results

The experimental research was carried out on the basis of the shooting range of the Kyiv Scientific Research Expert Forensic Center of the Ministry of Internal Affairs of Ukraine with the involvement of specialists of the State Scientific Research Expert Forensic Center of the Ministry of Internal Affairs of Ukraine for conducting experiments. Special certified ballistic plasticine (ROMA PLASTILINA No. 1, Ballistic Testing Backing Material), produced in the USA, was used as a ballistic material as an imitator of biological tissues. Ballistic plasticine gave us the opportunity to evaluate not only the nature and extent of damage after a shot but also to determine the number of properties of the bullets themselves (expansive properties, fragmentation, and the number of fragments, fragments, fragments, their sizes, ability to change shape). The experiments were conducted under normal environmental conditions (temperature 250C, relative humidity 72%, atmospheric pressure 738 mm Hg/st). Blocks of ballistic plasticine were heated to a temperature of 28-320C before firing.

The results of experiments with different types of bullets are shown in Figure 8 and their modeling is in Figure 9.

5,45x39 ПС (7Н6М)

5,45x39 V-max

Fig. 8. The results of the test showed that the numerical modeling data is in line the behavior of the 5.45x39 PS (7H6M) bullet, performing a U-turn and exiting the outside of the block (left figure) in a place shifted relative to the central axis of the block. The expansive bullet 5.45x39 V-max destroys the block immediately, and the length and shape of the wound channel match with the the numerical modeling data (right figure)

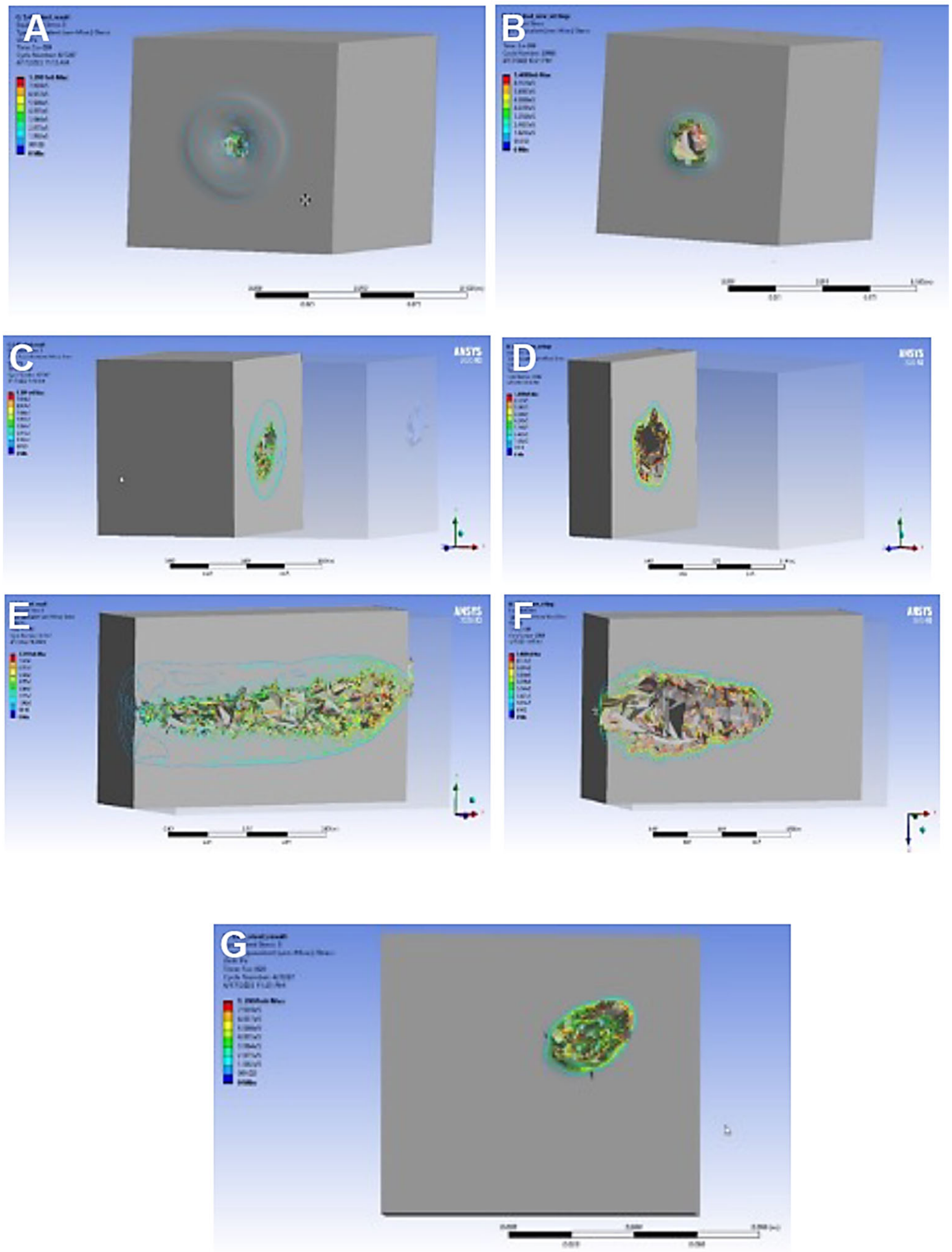

Fig. 9. Comparative characteristics of the values of equivalent strain acting on the walls of the wound canal: a – bullet 7N6M, inlet, maximum value – 2 atm; b – bullet V-max, inlet, maximum value – 4 atm; c – the middle of the wound canal in the direction of movement of the bullet 7N6M, maximum value – 6 atm; d – the middle of the wound channel in the direction of movement of the bullet V-max, maximum value – 9 atm; e – cut of the wound channel of the bullet 7N6M, maximum value – 10 atm; f – cut of the wound channel bullets V-max, maximum value – 14 atm; g – outlet of the bullet 7N6M, maximum value – 10 atm

The obtained results of numerical simulation showed that the injury by the expansive bullet V-max has a much larger area of tissue damage.

Mathematically, this can be explained by the fact that the expansive bullet has a soft core that deforms and transfers all the kinetic energy to the tissues immediately after penetration into the tissues. The loss of kinetic energy of the bullet (ΔE, J) is defined as the difference between the kinetic energy at the time of injury (Ec, J) and the residual energy of the bullet when leaving the material (Er, J):

$$\mathbf{\Delta E} = \frac{\mathbf{m}}{\mathbf{2}}\left(\mathbf{v}_{\mathbf{c}}^{\mathbf{2}} - \mathbf{v}_{\boldsymbol{\gamma}}^{\mathbf{2}}\right)$$

Equation legend: Vc – the contact velocity, m/s; Vγ – velocity at the time of outlet, m/s; m – the mass of the bullet, kg.

Taking into account that the initial velocity of the bullet is 1185 m/s at a mass of 3.9 g, we obtain energy 2740 J. All this energy acts at the area of the wound canal with a depth of 150 mm.

Injury with a conventional 7N6M bullet is characterized by the fact that it passes through the block and loses only part of the kinetic energy. The simulation results showed that the velocity of the bullet at the outlet is 220 m/s. Taking into account the initial velocity of the bullet 918 m/s with a mass of 3.4 g, we obtain the kinetic energy acting on the walls of the wound canal with a depth of 200 mm of about 830 J.

Features of the geometric shape of the bullet (the center of mass is shifted to the tail of the bullet) provide a rectilinear motion of the bullet at a depth of 100 mm, after which the bullet loses speed and rotates 180°. It is at this point that the main part of the energy is transferred, which accordingly causes significant damage to organs and tissues that are on the pathway of the bullet.

The simulation results showed that the strain of the expansion bullet at the inlet will be 4 atm and the usual bullet 2 atm. The main difference when injured by an expansive bullet is that the maximum strain falls on the entire wound canal immediately after the injury (can reach 14 atm). When injured by an ordinary bullet type 7N6M, the maximum strain occurs at the area of the bullet's turn, closer to the outlet (can reach 10 atm).

The conducted numerical simulation has shown the features of expansive and conventional bullet wounds, which improves the understanding of the nature and extent of tissue damage during gunshot wound surgery.

CONCLUSIONS

1. Expanding bullet 5.45x39 V-max passes through the ballistic simulator, and transfers all kinetic energy to the tissues (2740 J) at a depth of 150 mm, whereas a 5.45x39 PS (7N6M) bullet transfers a maximum of kinetic energy (830 J) at 180° rotation at a depth of 200 mm.
2. Engineering simulation proved that the strain of the expanding bullet in the area of the inlet was 4 atm, and the ordinary bullet up to 2 atm.
3. In case of injuries by an expanding bullet, the maximum strain falls on the entire wound canal immediately after the injury (may reach 14 atm), and in case of injuries by a conventional bullet type 7N6M bullet, the maximum strain occurs at the area of the bullet's turn, closer to the outlet (may reach 10 atm).
4. Engineering simulation of wound ballistics in biological tissue simulators allows to determine the features of wound canal formation and tissue response to damage of bullets having different kinetic energy, which contributes to the choice of adequate surgical management during surgery for gunshot wounds.
5. Engineering simulation might be used as a useful scientific tool in addition to clinical investigations, pathomorphological and immunohistochemical studies of damaged biological tissues, adding a piece of important research information about the gunshot wounds formation and identifying features of the damaging effect of different types of military munition. Taken together, engineering numerical modeling for wound ballistics provides important data that could be potentially applied for better surgical management of gunshot injury.

Contributors:

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