REVIEW ARTICLE

PHYSIOLOGICAL AND BIOLOGICAL EFFECTS OF A GUNSHOT WOUND

Fizjologiczne i biologiczne efekty rany postrzałowej

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Abstract

The paper was inspired by reports on the Russian-Ukrainian war in terms of the ammunition used by the Russian army despite the introduced restrictions in this regard. The aim of the paper was to analyse and describe phenomena that occur during soft tissue penetration by a bullet. The paper presents a synthetic description of the ongoing research and the development of the discipline of wound ballistics. The beginnings of experiments that provided the basis for the development of a research and numerical apparatus for the description of wound ballistics are discussed. Further parts of the paper describe the phenomena occurring in soft tissue during bullet penetration, discusses the process of creating a permanent channel and a temporary cavity, depending on the type and technical parameters of bullets used, as well as present sample images from the conducted experiments. The presented description concerns only the mechanism of the projectile-soft tissue interaction and does not take into account other destruction factors, such as fragments from artillery shells, rockets, grenades or mines. The severity and profile of injuries change as a result of bullet rotation. When the projectile rotates at a 90-degree angle, it crushes the tissue with its side surface. This also results in an increase in force. It should be borne in mind that the rate of energy transfer along the wound channel is not uniform throughout the body, as the projectile may change trajectory or undergo fragmentation during penetration. Additionally, human tissue is not homogeneous. A temporary cavity may develop depending on several factors, such as the shape, velocity, calibre of the projectile, the penetrated organs through or near which the trajectory of the projectile passes, and the pressure or shock wave that may cause both proximal and distal injuries.

Streszczenie

Inspiracją do powstania pracy były doniesienia o tym, co się dzieje na wojnie rosyjsko-ukraińskiej w zakresie amunicji stosowanej przez stronę rosyjską, pomimo obowiązujących obostrzeń w tej kwestii. Celem artykułu jest analiza oraz opisanie zjawisk, które występują podczas penetracji tkanki miękkiej przez pocisk. W pracy przedstawiono syntetyczny opis prowadzonych badań i rozwoju dyscypliny, jaką jest balistyka rany. Omówiono początki eksperymentów, które dały podstawy do opracowania aparatu badawczego i numerycznego do opisu balistyki rany. W dalszej części opisano zjawiska zachodzące w tkance miękkiej podczas penetracji przez pocisk, omówiono proces tworzenia się kanału trwałego oraz jamy chwilowej w zależności od rodzaju użytych pocisków i ich parametrów technicznych oraz przedstawiono przykładowe zdjęcia z przeprowadzonych eksperymentów. Przedstawiony opis dotyczy tylko mechanizmu interakcji pocisk–tkanka miękka, nie uwzględnia innych czynników rażenia, takich jak odłamki po uderzeniu pocisków artyleryjskich, rakiet, granatów czy też min. Ciężkość obrażeń i ich profil zmienia się w wyniku obrotu pocisku. Gdy obraca się pod kątem 90 stopni, miażdży tkankę boczną powierzchnią. Skutkuje to również wzrostem siły. Należy pamiętać, że szybkość transferu energii wzdłuż kanału rany nie jest jednolita w całym ciele, ponieważ pocisk w czasie penetracji może zmieniać trajektorię czy też fragmentować. Ponadto tkanka ludzka jest niejednorodna. Jama chwilowa może powstać w zależności od kilku czynników: kształtu, prędkości, kalibru pocisku, penetrowanych narządów, przez które lub w pobliżu których przechodzi trajektoria lotu pocisku oraz ciśnienia lub fali uderzeniowej, która może powodować zarówno bliższe, jak i dalsze obrażenia ciała.

Keywords: bullet; gunshot; permanent wound channel; temporary cavity; wound ballistics

Słowa kluczowe: pocisk; postrzał; kanał trwały; jama chwilowa; balistyka rany

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Historical outline

The field of wound ballistics is about 1,000 years old, or at least that is how old the first records of the ancestor of the modern gun, a small wrought-iron or bronze cannon secured with a leather strap, are. The gun of that time used an iron ball about 0.09 m in diameter as a projectile. Black gunpowder weighing about 0.1 kg was used as propellant [1]. The gun, which was 0.34 m long and weighed 3.5 kg, was called the Heilongjiang hand cannon by Chase and Needham [2–3]. From that moment on, the evolution of propellants and the ammunition used in these guns began, giving rise to the development of a new scientific discipline known as wound ballistics. The 1830s can be considered as the time when it began, while the first significant breakthrough occurred in the 1870s, when Emil Theodor Kocher, a Swiss surgeon, developed a hydrodynamic theory for the effect of gunshot wounds, which was the foundation for the development of the discipline. In 1895, he was the first scientist to use gelatin to conduct a ballistic experiment, the purpose of which was to simulate the penetration of soft tissue by a bullet [4]. The innovative design of the experiment using the technical solutions available at that time, combined with Kocher's interest in wound ballistics, provided the foundation for the development of rational principles constituting the scientific basis for modern wound ballistics.

Louis Anatole La Garde, a Colonel in the US Army Medical Corps, was another person who contributed to the development of the discipline. In the 1890s, he conducted ballistic experiments to demonstrate that higher-velocity hard core bullets caused less damage when penetrating soft tissue than larger-caliber soft core projectiles [5]. La Garde focused his research on the transfer of kinetic energy of a moving bullet to soft tissue. He concluded that the energy transfer in soft tissue depends on the projectile velocity at impact [5].

In 1901, General John T. Thompson and Colonel Louis Anatole La Garde found that the kinetic energy of a bullet is not always the main factor determining the severity of injury in a permanent cavity created by a bullet as it penetrates the soft tissue [5–7]. Furthermore, they both confirmed that large-caliber bullets can cause more damage than their small-caliber counterparts [5].

General Julian Hatcher, who developed a model that took into account momentum rather than kinetic energy (Hatcher's model), was another person who contributed to the development of wound ballistics. Hatcher realized that bullets fired from handguns caused less internal damage outside the permanent wound tract than rifle bullets [8].

Lindsey and Mendelson were researchers who performed histopathological and biophysical measurements in the 1950s (before the Vietnam conflict), based on which they developed models of correlations between absorption of energy and tissue damage as functions of the depth of the wound tract [7].

In the late 1970s and early 1980s, Swedish scientists Janzon and Seeman [9] attempted to determine if quantitative relationships existed between energy and tissue damage using the amount of debrided tissue as an index of tissue damage [9]. All these attempts and studies gave impetus to the significant development of the work by Colonel Martin L. Fackler from the US Army, who was the first to compare material imitating human tissue (ballistic gelatin) with living tissue (experiment on pigs). This way, he established and introduced into the literature a model of 10% gelatin, which allowed for research in a medium imitating human muscle tissue [10, 11]. He was the first to introduce calibration of ballistic gelatin to ensure consistency between manufactured gelatin batches and to compare the results of ballistic tests. For this purpose, he used an air gun, from which he fired pellets at a specific speed at a gelatin block. This was steel pellets with a uniform shape, which prevented deviation from a given direction, deformation and fragmentation. The proposed calibration method allowed for correlating data from various previously conducted experiments [12].

Physiological and biological effects of gunshot wounds in a living organism

Mechanisms of injury

Wound ballistics can be defined as a study of the interaction between a projectile and the tissue [13]. The biological effect of this interaction can be determined based on:

- design parameters of the projectile: weight, shape, material, construction, calibre, speed;
- soft tissue parameters: density, elasticity, viscosity, structure, anatomy.

These parameters are schematically presented in Figure 1. A projectile moving through the air is subject to aerodynamic drag (air resistance) and gravity, with gravity having constant direction and magnitude, and with variable air resistance. In order for the aerodynamic drag force not to cause the projectile to tumble, the gyroscopic phenomenon is used for stabilization, which requires that the projectile has a high rotational velocity (typically about 200,000 rpm). Lateral drift of the bullet, directed to the right for bullets spinning clockwise and to the left for bullets spinning counterclockwise, is an additional effect related to the gyroscopic phenomenon. The drift is very slight and is of practical significance only when shooting at long distances.

The amount of projectile's kinetic energy to inflict damage (penetration centre) depends largely on the energy at impact, which in turn depends on the velocity at impact and the mass of the projectile.

Additional factors that determine projectile behaviour during penetration in the medium depend on its design: i.e. the material it is made of, projectile deformation of fragmentation.

The bullet kinetic energy at impact with the target can be determined using the following formula:

$$E_i = \frac{m \times V^2}{2} \qquad (1)$$

where: V – bullet velocity, m –bullet weight,

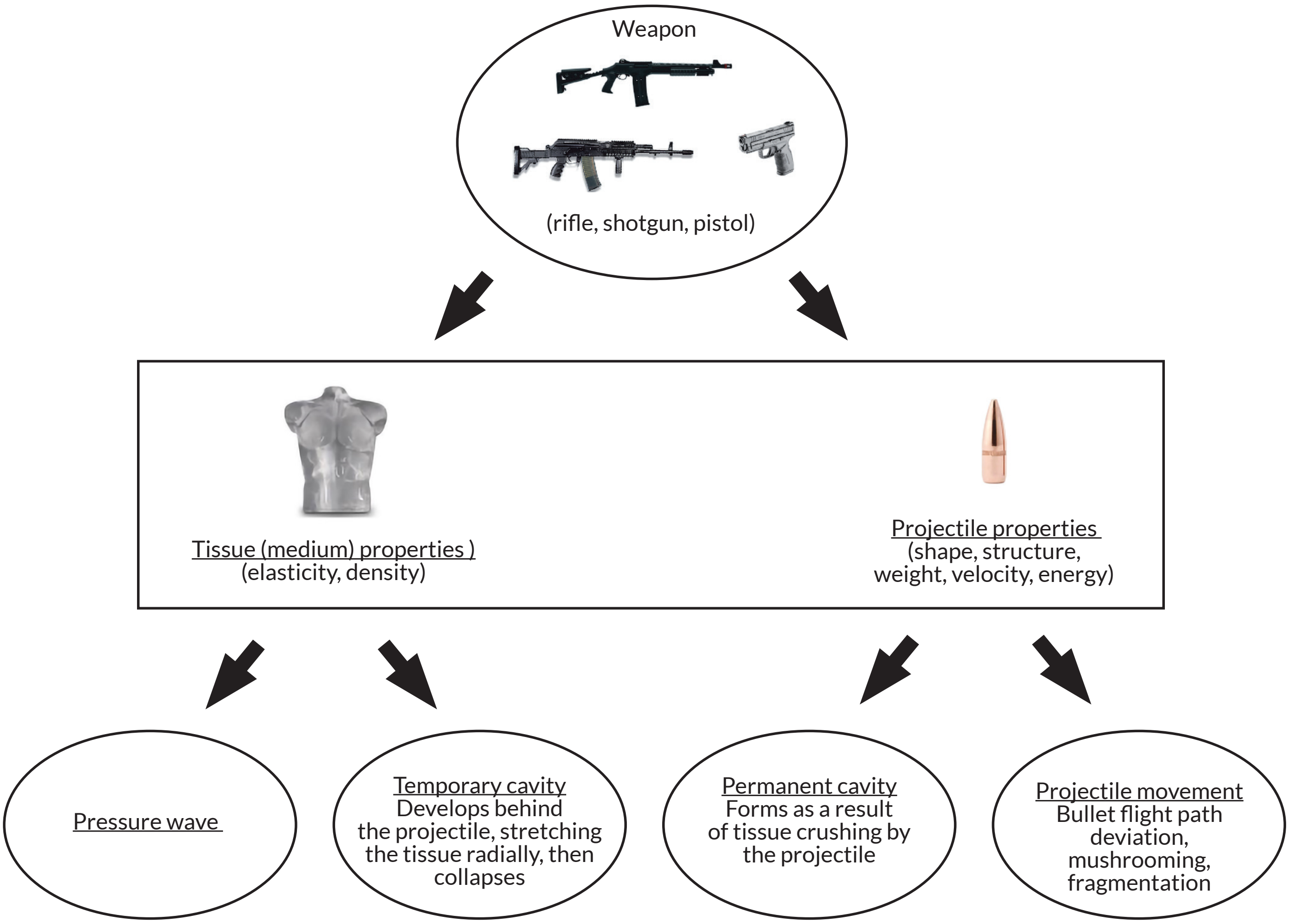

Figure 1. Factors affecting wound severity. Own elaboration

The energy balance of a bullet in a medium imitating soft tissue can be expressed as follows:

$$E_r = E_i - E_{def} - E_d \quad (2)$$

where: E_r – residual kinetic energy of the bullet, E_i – impact energy, E_{def} – kinetic energy used by bullet deformation, E_d – kinetic energy dissipated in the medium.

The kinetic energy dissipated in the penetration medium may be described using an equation proposed by Martel and presented by Kneubueh [14]:

$$Ed = Cv \times V \quad (3)$$

where: CV – material constant of the penetration medium, V – volume of the permanent wound tract.

The kinetic energy of a bullet passing through soft tissue decreases, which is caused by a significant reduction in its velocity. The bullet slows down, converting kinetic energy into work, which is performed during crushing, tearing, and stretching of the soft tissue in front of and around the bullet's penetration path, with the penetrated tissue being simultaneously driven outward in a radial direction, thus creating a temporary cavitation with a diameter much larger than the calibre of the penetrating bullet. This phenomenon was first described by Woodruff and presented by Jussili [7]. It is schematically shown in Figure 2.

The unstable motion od a projectile, its deformation and fragmentation increase the amount of energy dissipated, thus increasing the size of the temporary cavity. In the initial period of penetration, the diameter of the inlet hole increases rapidly, then the temporary cavity undergoes a series of gradual pulsations and contractions of smaller amplitude before finally resolving, leaving a permanent cavity (channel), which arises from crushed and fragmented tissue. Examples of temporary and permanent cavitations are shown in Figure 3 and Figure 4.

A penetrating projectile can cause soft tissue damage via two different mechanisms: crushing and stretching [16–18].

Crushing mechanism, permanent cavitation

Soft tissue in the trajectory of the moving projectile is crushed and torn away by the dynamic pressure generated in front of the tip of the moving projectile. This causes tissue breakdown, and consequently formation of a permanent wound channel [16, 17, 19].

The higher the velocity of the projectile, the further the tissue will move away from it, as the level of tissue stress

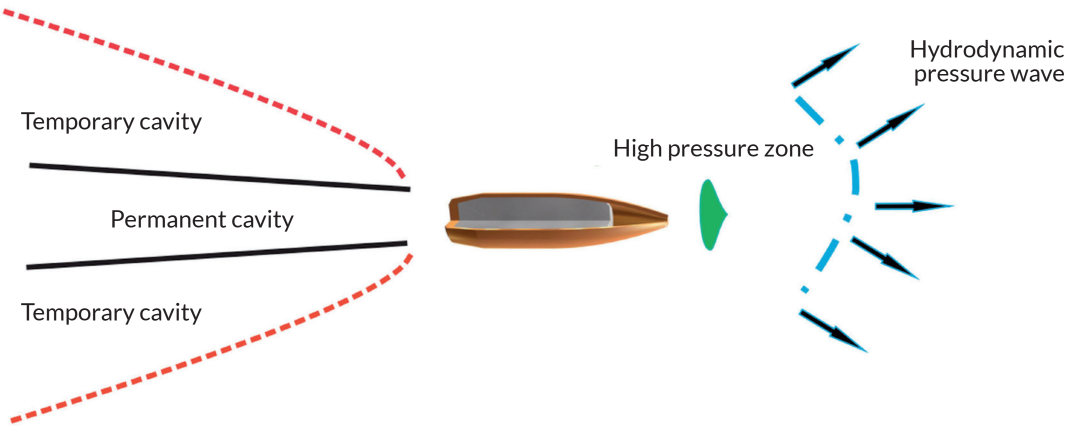

Figure 2. Schematic drawing of the phenomenon that occurs as a result of human tissue penetration by a projectile. Own elaboration based on Fackler [15]

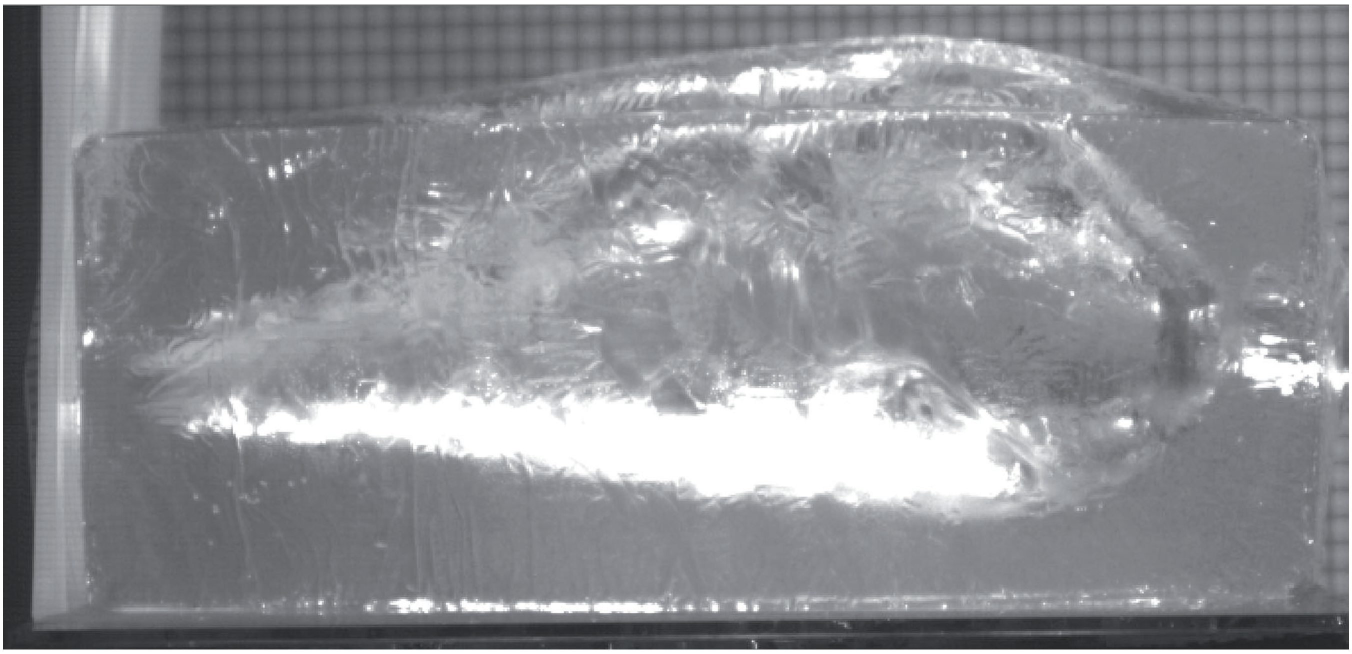

Figure 3. Temporary cavity in ballistic synthetic gelatin created by a .308 Win caliber bullet. Photo by G. Motrycz

in relation to its elastic limit depends on the amount of stored energy (a function of the projectile resistance force). In order for permanent damage to occur and a permanent cavity to form, the tissue or organ must move as a result of bullet penetration. After exceeding the elastic threshold of the tissue or organ, permanent damage (cracks, tears) caused by stress occurs.

Stretching mechanism, temporary cavitation

When analysing a temporary cavitation mechanism, a distinction should be made between high-velocity projectiles (usually rifle bullets) and low-velocity projectiles (intended for a pistol or revolver). However, it should be remembered that these terms are imprecise and can sometimes be misleading, as subsonic rifle bullets reaching a speed of 325 m/s, which are intended for short-barrel rifles with silencers, are also available on the market. The bullet loses kinetic energy during target penetration, which results in significant differences in forces on the tissue and wound profiles.

As pointed out by Fackler: *'Kinetic energy'… reveals nothing about the magnitude, type and location of tissue disruption… The force interactions between penetrating projectile and tissue remain hidden behind the abstract 'kinetic energy' discussions*" [6, 20]. This force (force of interaction between the projectile and the tissue) is the local rate of change of kinetic energy at a given penetration depth. The value of this force (interaction of the projectile with the tissue) is the local rate of change of the value of kinetic energy at a given penetration depth. The quantity of kinetic energy lost by the projectile is equal to the work done on the tissue. The rate of energy loss in the body as the bullet penetrates equals the force at each point (tissue). The magnitudes of the forces on the tissue allow for determining

Figure 4. Permanent cavity in ballistic synthetic gelatin created by a .308 Win caliber bullet. Photo by G. Motrycz

the extent of tissue damage. The area under the curve for the relationship between force and penetration depth equals the total energy lost by the bullet as it penetrates. The total energy lost is less than the impact.

The onset of energy transfer by a non-ricocheted bullet penetrating soft tissue is as shown in Figure 5. Depending on its design and penetration depth, there is a change in the point of curve of the force as a function of displacement.

The increase in the force shown schematically in Figure 5 can only occur in the case of an increase in the penetrated area resulting from the deviation (deviation of the axis of projectile from its trajectory, i.e. a rotational moment caused by the inhibitory force on the front part of the projectile).

As already mentioned, soft tissue penetration depends on multiple factors. These include:

- design and material of the bullet – bullets with high hardness and strength do not undergo plastic deformation during penetration, while soft bullets are deformed or defragmented;

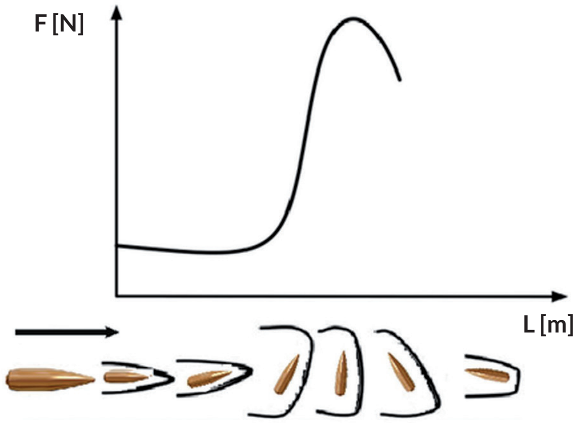

Figure 5. Schematic diagram of the force (F) course as a function of projectile length (L) in soft tissue. Own elaboration

- bullet outline – spitzer bullets tend to quickly lose stability in soft tissue, which causes them to tumble and lose speed faster than round nose bullets;
- bullet velocity – depending on the velocity, the bullet may break, which means that the shape of the temporary cavity and the nature of the bullet deformation may change.

It is mainly spitzer bullets, the design of which is associated with poorer or difficult mushrooming, that lose stabilization. Despite its streamlined shape, the bullet starts to tumble as a result of the loss of stabilization in the tissue, which is about 890 times denser than air, leading to more severe damage.

In the case of full metal jacket rifle bullets resistant to deformation, with a low ballistic coefficient, the trajectory during soft tissue penetration will not change, the flight path will be stable, and the damage will be smaller.

Conclusions

- The severity (profile) of injury changes as a result of bullet rotation. When the bullet rotates at a 90-degree angle, the force increases, translating into kinetic energy transfer to the tissue.
- The rate of energy transfer along the wound tract is not uniform in the tissue, as the bullet may change its trajectory (tumble) or fragment as it penetrates. Additionally, the penetrated tissue is not uniform.
- The shape of temporary cavitation depends on the shape of the bullet, its velocity, calibre, the penetration site in the tissue (organs) through or near which the bullet passes, and the pressure of the shock wave, which can cause both proximal and distal injuries.
- Wounds caused by shrapnel, mine or rocket fragments have a different shape due to the additional effect of pressure and temperature.
- The wound profile will be different for a tactical vest. When penetrating soft tissue, the bullet will have less kinetic energy, but there will be chest injuries caused by costal cartilage fractures.

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