УДК 616.717/.718-001.5-073.7(045)

DOI: http://dx.doi.org/10.15674/0030-59872025417-24

Destruction of bone and surrounding tissues in case of gunshot fractures of long bones of the extremities (clinical and radiological classification). *First report*

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Objective. To determine the nature of the destruction of the bone and surrounding tissues in gunshot fractures of the long bones of the extremities and to create their clinical and radiological classification. Material and methods. 123 cases with gunshot fractures of the long bones of the extremities (127 fractures) were studied. The number of intermediate fragments, the magnitude of their transverse displacement, the length of the bone destruction zone, the shape and size of the soft tissue wound were studied. During the operation, the state of the anatomical connection of the fragments with the periosteum and muscles was assessed. Based on known data on the mass and speed of traumatic agents, calculations of their energy that occur during the action of a bullet and a hit by a moving car were made. Results. 97 % of the victims had multifragment fractures, among them 50 % had 2–3 intermediate fragments, 30 % — 4–6 and 22 % — 7 or more, or a primary bone defect was formed. Based on the number of formed intermediate fragments, the magnitude of their transverse displacement and the presence (or absence) of anatomical connection with living tissues, we distinguished three types of gunshot fracture: 1 — with slight or moderate transverse displacement of the intermediate and main fragments (within the diameter of the bone and with preservation of the longitudinal orientation); 2 — with significant transverse displacement of one or more intermediate fragments (in the direction of the projectile movement) with loss of anatomical connection with the periosteum and formation of a parietal defect of the bone and a wound of medium or large size; 3 — with excessive transverse displacement of all intermediate fragments (in the direction of the projectile movement) with loss of their anatomical connection with the periosteum and formation of a complete transverse defect of the bone. It was found that in the majority (66%) of gunshot fractures, despite the presence of a soft tissue wound, the intermediate and main fragments retain an anatomical connection with the periosteum and muscles, and this is of great importance in choosing treatment tactics.

Мета. З'ясувати характер руйнування кістки й оточуючих її тканин за вогнепальних переломів довгих кісток кінцівок і створити їх клініко-рентгенологічну класифікацію. Методи. Досліджено 123 особи з вогнепальними переломами довгих кісток кінцівок (127 переломів). Вивчали кількість проміжних уламків, величину їхнього поперечного зміщення, протяжність зони руйнування кістки, форму та розміри рани м'яких тканин. Під час операції оцінювали стан анатомічного зв'язку уламків з окістям і м'язами. На підставі відомих даних про масу і швидкість травмуючих агентів проведено розрахунки їхньої енергії за умов дії кулі чи удару автомобілем, який рухається. Результати. У 97 % постраждалих були багатоуламкові переломи, серед них 50 % мали 2–3 проміжні уламки, 30 — 4–6 і 22 % — 7 і більше проміжних уламків, або утворився первинний дефект кістки. На підставі кількості утворених проміжних уламків, величини їх поперечного переміщення та наявності (або відсутності) анатомічного зв'язку з живими тканинами нами виділено три типи вогнепальних переломів: 1 — із незначним або помірним поперечним переміщенням проміжних і основних уламків (у межах поперечника кістки і зі збереженням повздовжньої орієнтації); 2 — зі значним поперечним переміщенням одного або декількох проміжних уламків (за напрямом руху снаряда) зі втратою анатомічного зв'язку з окістно-м'язовим футляром та утворенням пристінкового дефекту кістки і рани середніх або великих розмірів; 3 — із надмірним поперечним переміщенням усіх проміжних уламків (за напрямком руху снаряда) з втратою ними анатомічного зв'язку з окістно-м'язовим футляром та утворенням повного поперечного дефекту кістки. Висновки. Виявлено, що за більшості (66 %) вогнепальних переломів, не дивлячись на наявність рани м'яких тканин, проміжні й основні уламки зберігають анатомічний зв'язок з окістям і м'язами, це має важливе значення вибору тактики лікування. Ключові слова. Вогнепальні переломи, морфологія, класифікація.

Keywords. Gunshot fractures, morphology, classification

Introduction

Fractures caused by projectiles with a reserve of kinetic energy are different from those we are used to seeing in peacetime, as they are associated with the action of a high-energy carrier. From the experience of recent years, it is evident that fractures of long bones caused by bullets or shrapnel occur in the following forms: comminuted (26 %), shattered (69 %), and with the formation of a primary bone defect (5 %) [1]. Our previous analysis of gunshot fractures showed that they approached types B (40 %) and C (47 %) in terms of the fracture plane and the number of fragments, according to the AO classification (Fracture and Dislocation Classification Compendium) [3]. However, some types of gunshot bone destruction were not accounted for, such as fractures that involve the presence of a bone defect.

In scientific articles on the treatment of gunshot fractures, the Gustilo-Anderson classification for open fractures is used, which was proposed in 1976 [4] and later refined in 1984 [5]. Regarding the relationship between the nature of the fracture plane and the extent of soft tissue damage, the authors of the classification note that for types I and II of open fractures, there is one transverse or oblique plane, while for type III, there are several planes and the formation of intermediate fragments. It should be noted that this classification is based on the experience of treating open fractures in peacetime, among which fractures with a single fracture plane are most common.

The morphology of a gunshot fracture is inextricably linked to the destruction of the surrounding soft tissues, and all of this must be considered and evaluated as a whole. From our point of view, having a uniform mechanism of injury and similar patterns of destruction, gunshot fractures require a separate classification that would divide them by severity, healing prognosis, and would also serve as a basis for choosing the treatment method.

Objective: To investigate the nature of bone destruction and the surrounding tissues in gunshot fractures of long bones in the limbs and create a clinical-radiological classification for them.

Materials and Methods

The study was conducted in compliance with the requirements and provisions of the Helsinki Declaration on human rights, the Constitution and basic health protection laws of Ukraine, and all ethical standards regarding clinical research (Protocol No. 256 dated 17.11.2025, State Institution Professor M. I. Sytenko Institute of Spinal Pathology and Joint Diseases of the National Academy of Medical Sciences of Ukraine). All patients signed informed consent.

The study is based on the experience of treating 123 patients with gunshot fractures of long bones in the limbs at the State Institution Professor M. I. Sytenko Institute of Spinal Pathology and Joint Diseases of the National Academy of Medical Sciences of Ukraine (93 cases) and the Communal Non-profit Enterprise M.I. Kononenko Chuhuiv Central Hospital (30 cases). By the localization of the affected segment, the distribution was as follows: lower leg 38 (34 %), thigh 30 (24 %), shoulder 30 (24 %), forearm 25 (18 %). Among them, in 4 cases, two segments were affected in different combinations (a total of 127). These patients were admitted urgently either directly from the trauma site (36 cases) or within 3-12 days after the injury for continued treatment with an external fixation device.

Clinical evaluation of the shape and size of the wound channel or defect

Among the variety of gunshot wounds, we consider it rational to distinguish three variants. The *tunnel form* of the wound channel has the following characteristics:

– the length of the channel exceeds or corresponds to the size of the skin wound;

– the volume of soft tissue defect is not large, disappearing into the depth due to the adhesion of the walls, and the edges of the skin wound can be approximated with sutures;

– it can be either a blind or a through wound.

Sectoral form of the defect, which extends either to the soft tissues only or to both the soft tissues and the destroyed bone. The characteristics of this form are:

– the possibility of visual control over almost the entire wound surface;

– tissue deficiency and difficulty in approximating the wound edges.

A combination of both variants is possible when the entry tunnel part of the wound channel transitions into a sectoral form (*tunnel-sectoral form*).

During the initial examination of a gunshot fracture, it is not always possible to measure and assess the extent of soft tissue destruction, especially when the channel has a tunnel form. The main objective parameter is the size of the skin wound, which we propose to classify as small (up to 3 cm), medium (4–10 cm), and large (over 10 cm), taking its largest longitudinal dimension as the basis.

Characteristics of bone destruction and fragment displacement based on radiographic data

Since most fractures were comminuted and could be classified as types B and C, we focused on the following signs:

1. The number of intermediate fragments, their shape, and size;

2. The extent of the maximum transverse displacement of the main fragments (Fig. 3) relative to each other. This was measured with the fragments fixed by an external device and expressed as a percentage of the transverse size of the bone;

3. The extent of the maximum transverse displacement of intermediate fragments (Fig. 3) relative to the surface of the main fragments, also expressed in relative units. Special attention was given to the presence of rotational displacement of fragments, which could indicate their detachment from soft tissues. If there was a transverse displacement of the intermediate or main fragment relative to the bone's transverse diameter, it was considered insignificant or moderate; if it exceeded the full transverse diameter, it was considered significant; and if it went beyond the surface of the segment, it was considered excessive.

4. The extent of the bone destruction zone (Fig. 1) was also determined as a percentage relative to the length of the segment.

Additional information about the extent of internal soft tissue destruction and the state of the anatomical connection between intermediate fragments, the periosteum, and muscles was obtained during the primary surgical treatment of the wound. During the procedures to remove metal projectiles, an attempt was made to visually and palpably assess the size of muscle destruction, as well as the condition of intermediate fragments that were found far from their natural position. It is worth noting that the ability to inspect destruction in the case of a tunnel wound channel is limited, so palpatory examination was relied upon. When necessary, in cases where metal objects needed to be removed, the wound channel was rationally expanded, and the condition of the tissues was visually assessed.

The study materials were statistically processed using both parametric and non-parametric analysis methods in Microsoft Office Excel 2016 electronic spreadsheets. The statistical analysis was carried out using the STATISTICA 10.0 software. For describing quantitative indicators, the measurement results were calculated using descriptive statistics methods: mean (M) and its standard deviation (SD), minimum and maximum values. To compare independent groups in cases of small sample sizes and absence of normal distribution of data, the Mann–Whitney U test was used. To study the relationship between phenomena, where the quantitative data distribution deviated from normal, the non-parametric method of Spearman's rank correlation coefficient was applied [6].

Results and Discussion

The analysis revealed the following distribution of gunshot fractures by the number of fragments:

- No intermediate fragments (single plane fracture) — 4 (3 %);
- 1–3 intermediate fragments — 63 (49.6 %);
- 4–6 intermediate fragments — 38 (30 %);
- 7 or more intermediate fragments — 11 (8.7 %);
- Presence of a primary bone defect — 11 (8.7 %).

Most of the fractures were comminuted fractures (97 %). Among these, 49.6 % had 1–3 intermediate fragments, and as the number of fragments increased, the frequency of such fractures decreased. It is also important to note that in 8.7 % of fractures, a bone defect was formed, preceded by a condition with a large number of intermediate fragments displaced in the direction of the projectile's motion, accompanied by soft tissue destruction. In 2 of the injured patients, the intermediate fragments were lost during the previous stages, while in the remaining 9, they were removed during repeated surgical wound debridements.

A characteristic feature of comminuted gunshot fractures of long bones was that the destruction occurred through the formation of cracks and splits, mainly oriented in the longitudinal direction, resulting in intermediate fragments with an elongated shape. This can be explained by the fact that cracks form along the interosteonal substance [7], and osteons in long bones, as known, are oriented in the longitudinal direction. As for the extent of bone destruction, the fractures were distributed as follows: 54 % of gunshot fractures affected 25% of the segment length, 43 % were in the range of 26–50 %, and 3 % had a length greater than 50 % of the segment length. Thus, we can see that significant bone destruction is associated with the formation of mainly longitudinal splits.

Displacement of main fragments

After the main fragments were joined by the external fixation system, in most fractures (76 %), a transverse displacement occurred that did not exceed the transverse diameter of the bone at this level. In the remaining 24 %, the displacement exceeded the transverse diameter. This was the position achieved during the primary surgical treatment of the wounds and fixation of the fragments with the external pin apparatus. As a rule, the fragments were aligned by traction of the segment, restoring its anatomical axis. This position of the main fragments was considered acceptable.

Magnitude and direction of intermediate fragment displacement and the nature of soft tissue destruction

The displacement of the intermediate fragments varied, and thus, we identified three clinical groups of gunshot fractures.

The *first group* consists of fractures where both intermediate and main fragments retain moderate displacement in width, creating an expansion of the damaged part of the bone, up to about 50 % (Fig. 1). In this case, the intermediate fragments maintain their longitudinal orientation and show no significant rotational displacement. Most of these fractures were combined with a blind or through-and-through tunnel-shaped soft tissue wound of small or medium size — 80 cases (63 %). This group also includes gunshot fractures with a single fracture plane (4 cases, or 3 %), with minor or moderate transverse displacement of the fragments.

The *second group* is characterized by intermediate fragments (or one of them) being displaced transversely to a significant or excessive extent, exceeding the full transverse diameter of the bone and extending beyond its boundaries. These fragments lost their longitudinal orientation or rotated around their longitudinal and transverse axes. The radiological signs indicated possible periosteum detachment from the intermediate fragments displaced in this manner (Fig. 2). Based on the characteristics and size of the wounds (medium or large), it was observed that the direction of fragment displacement corresponded to the trajectory of the projectile. The viability of the intermediate fragments was evaluated during the surgical wound treatment. If a fragment was detached from the soft tissues and surrounding necrosis had developed, it was removed, leading to the formation of a wall defect. However, another portion of the intermediate fragments remained connected to the periosteum and muscles by their outer surface, forming a kind of bridging structure between the main fragments. This variant of bone destruction was recorded in 32 cases (25 %).

The *third group* consisted of 11 cases (8.7 %) where all or most of the intermediate fragments were displaced beyond the segment, detached from the soft tissues, leading to the formation of a total bone defect (Fig. 3). In the case of the last two variants, the fracture was accompanied by a soft tissue wound, which had a tunnel-sectoral or sectoral shape of medium or large size. For a general representation of these types of gunshot fractures, a schematic illustration is provided (Fig. 4).

The numerical values of the transverse displacement of intermediate fragments in the first and second groups of patients were calculated using the non-parametric Mann-Whitney U-test. In the first group (n = 80), the average displacement was (27.1 ± 14.6) % (range 1–56), while in the second group (n = 32) it was (78.2 ± 14.0) % (range 57–100). A statistically significant difference was observed between the groups for this parameter (U = 0, Z = –6.32; p = 0, p < 0.05), which is an expected result, as a prior biased distribution by groups was made.

The number of intermediate fragments in group 1 (n = 80) averaged (2.9 ± 2.2) pieces (range 0–9), while in group 2 (n = 32) it was (4.4 ± 2.5) pieces (range 0–9). A statistically significant difference was found between the groups for this parameter, calculated using the Mann-Whitney U-test (U = 286.5; Z = –2.26; p = 0.02; p < 0.05).

A moderate direct correlation was observed between the magnitude of the maximum transverse displacement of intermediate fragments and the total size of the wound in both groups (r = 0.44; p < 0.05).

The extent of bone destruction in group 1 (n = 80) averaged (24.2 ± 9.5) % (range 6–44), in group 2 (n = 32) it was (30.2 ± 9.6) % (range 13–48), and in group 3, it was (20.5 ± 7.6) % (range 6–32). There was no statistically significant difference between the groups for this parameter (Mann-Whitney U-test: U = 248.00; Z = –1.92; p = 0.05; p > 0.05). This value is not a criterion for group classification, but in all cases, it influences the choice of method for connecting the main fragments.

A moderate direct correlation was found between the extent of bone destruction and the number of intermediate bone fragments in all groups (r = 0.37; p < 0.05).

It was observed that the nature of bone destruction in gunshot fractures significantly differs from fractures occurring in peacetime, particularly those caused by high-energy projectiles (such as vehicles moving at high speeds). For the latter, the characteristic fracture pattern is a transverse single-plane fracture or a fracture that forms one intermediate triangular-shaped fragment (so-called “bumper fracture”).

Building on known facts, let us explore the specific features of the mechanogenesis of bone destruction in gunshot fractures. First, we will calculate and compare the kinetic energy carried by bullets from common types of firearms [8] and a passenger car in motion using the well-known formula $E = mv/2$ (see Table).

The calculations show that a passenger car weighing 1300 kg moving at a speed of 60 km/h carries 7 to 12 times more kinetic energy than a bullet from a firearm with an initial velocity of 800–954 m/s.

Fig. 1. Photographic prints of the injured limb and X-ray of a 45-year-old patient Ts. who sustained a gunshot fracture of the middle third of the left tibia with moderate transverse displacement of the intermediate fragments and a blind tunnel wound of medium size. First clinical group.

Fig. 2. Photographic prints of the limb and X-ray of a 25-year-old injured patient H. who had several displaced, non-viable intermediate fragments removed during the primary surgical treatment, in the direction of the entry wound, which was closed after cleaning by suturing the edges. After 2 months, periosteal bone regeneration (indicated by the arrow) had formed over the remaining intermediate fragments. Second clinical group.

This fact leads us to assume that the magnitude of kinetic energy itself is not the cause of fragmentation during bone destruction. As we can see, a bullet or metal shrapnel primarily destroys bone by creating numerous longitudinal cracks, which, as they expand, lead to the fragmentation of the bone. According to fracture mechanics theory [9], this is the most common form of brittle failure: “the result of the avalanche-like growth of microcracks (at speeds up to 1/3 of the speed of sound), when elastic deformation reaches a magnitude that atomic bonds break...”. There is also quasi-brittle failure, which is characterized by a certain zone of plastic deformation before cracks appear. According to [7, 10], compact human bone fails in a brittle manner. The authors note that the nature of this process depends on the deformation rate: at low deformation speeds, the failure process can be considered viscous, while at high deformation rates, it is distinctly brittle. Thus, we can hypothesize that in the case of a gunshot fracture, under the influence of high projectile speed, high-speed stress and deformation occur in the bone, leading to brittle failure and the formation of many fragments. Interestingly, the authors of this theory note a direct correlation between the amount of energy expended and the number of cracks (fractures) formed [9].

From a mechanical standpoint, it is crucial to differentiate between the processes of bone destruction and the subsequent damage to soft tissues. J. J. Amato et al. [11] and G. R. Baum et al. [12] experimentally and clinically demonstrated that when a projectile with high velocity strikes bone, the resulting fragments gain kinetic energy and act as secondary projectiles that damage soft tissues. However, this is only possible if the fragments accumulate enough energy to damage the periosteum, muscles with their fascial sheaths, aponeuroses, and skin. These structures, in contrast to bone, have distinct physical and

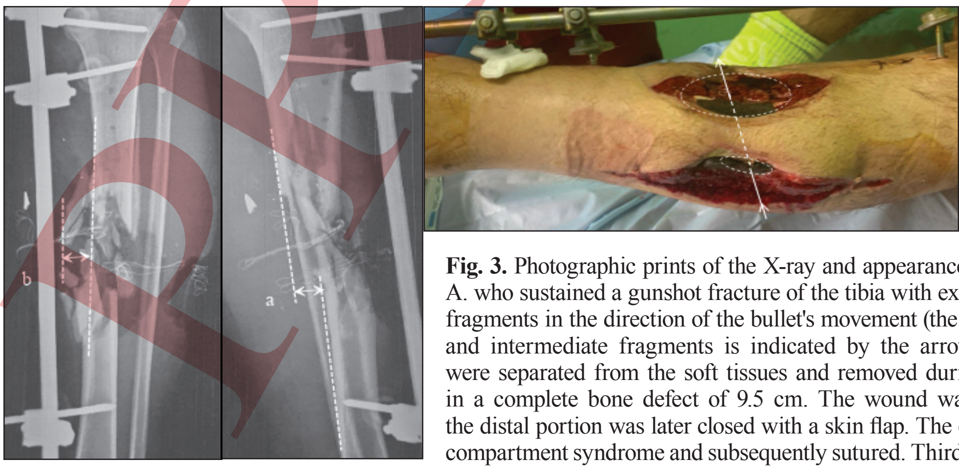

Fig. 3. Photographic prints of the X-ray and appearance of the tibia of a 45-year-old patient A. who sustained a gunshot fracture of the tibia with excessive displacement of intermediate fragments in the direction of the bullet's movement (the transverse displacement of the main and intermediate fragments is indicated by the arrows). Seven intermediate fragments were separated from the soft tissues and removed during the primary treatment, resulting in a complete bone defect of 9.5 cm. The wound was classified as tunnel-sectoral, and the distal portion was later closed with a skin flap. The entrance wound was enlarged due to compartment syndrome and subsequently sutured. Third clinical group.

Table

The kinetic energy of a moving car and bullets from different types of firearms

Source of kinetic energy	Weapon caliber (mm)	Mass of kinetic energy carrier (g)	Speed (m/s)	Amount of energy (J)
Car	—	1 300 000	16.6 (60 km/h)	17 911 400
AK 47	7.62	7.9	800	2 528 000
AK 74	5.45	3.4	914	1 420 173
M 193	5.56	3.6	954	1 638 208

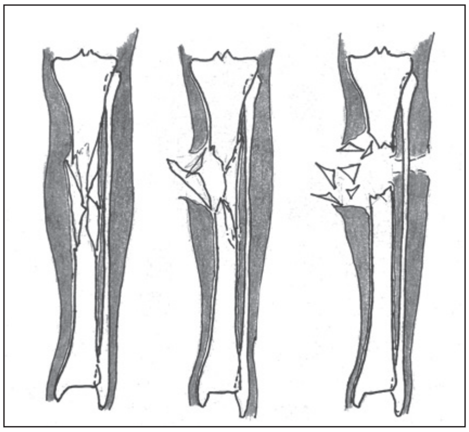

Fig. 4. Schematic representation of types of gunshot fractures.

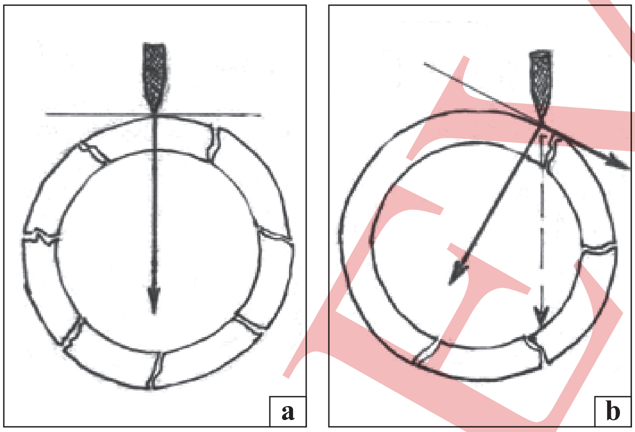

Fig. 5. Schematic representation of the distribution of the bullet's force impulse under central impact (a) and when acting at an angle (b).

mechanical properties and can withstand similar forces, but with different outcomes. For example, the periosteum, which contains a strong fibrous layer with longitudinally arranged collagen and elastin, demonstrates viscoelastic behavior and can endure tensile stress up to 26.67 MPa [13], unlike the brittle nature of bone. This means that the periosteum can deform plastically and elastically to some extent, absorbing the energy carried by the fragments without sustaining significant damage.

It is important to note that in 63 % of cases (the first clinical group), the intermediate fragments formed during a gunshot fracture did not undergo significant displacement. This may indicate that the periosteal-muscular sheath around the fractured bone was preserved, possibly with some tears. We can hypothesize that this portion of fractures occurred under conditions where the kinetic energy of the projectile was not maximized due to several factors, such as the projectile passing through the segment with minimal contact with the bone or its relatively low velocity. Therefore, in these cases of gunshot fractures, the soft tissue damage was relatively less, primarily caused by the projectile itself.

The second and third types of gunshot fractures showed signs of significant destruction of the periosteal-muscular sheath, leading to partial or complete defects in the diaphyseal walls. This was the result of the action of greater kinetic energy, enough to crush the bone, detach the fragments from the periosteum, and displace them a considerable distance. It is essential to understand that only part of the projectile's energy may be used to destroy the bone, particularly in through-and-through wounds. We propose that the effect of energy transfer from the projectile to the bone depends on the angle of the applied force relative to the bone's surface. It is known from mechanics that when a force is applied to an inclined surface, the force is distributed according to the parallelogram law — part of the force acts perpendicular to the surface, and the other part acts parallel to the inclined surface. Since long bones have a circular or triangular cross-section, there is a high likelihood that the projectile's forces act at an angle, producing a tangential vector that displaces the epicenter of bone destruction and the adjacent tissues in the corresponding direction. This can explain the asymmetrical destruction, leading to the formation of a partial defect. In cases where the projectile's force is large and directed perpendicularly to the surface of the bone (toward the bone's center), total destruction may occur, creating a full transverse defect (Figure 5).

In our view, there are significant differences between the clinical types of gunshot fractures that must be considered for predicting the healing process and determining the appropriate treatment strategy for these fractures.

In the case of the first type, the axial alignment of the fragments remains satisfactory after closed reduction and fixation of the main fragments with an external apparatus. The preservation of the anatomical connection of most of the periosteal-muscular sheath with the main and intermediate fragments is a key factor for the formation of periosteal bone regeneration, which can cover the entire area of bone destruction during further apparatus-based treatment.

The second type differs from the previous one by a significantly larger volume of damaged soft tissues and a partial (periosteal) bone defect. This type requires additional treatment measures for wound cleaning and closure, as well as various actions aimed at achieving bone union of the main fragments.

The third type of gunshot fracture differs from the previous types in that it results in a complete bone defect of varying size, requiring a different treatment approach, such as reconstructive and restorative surgeries or amputation.

Conclusions

Gunshot fractures caused by bullets or shrapnel are characterized by the presence of a destruction zone in the bone with the formation of intermediate fragments. Depending on the amount of kinetic energy transferred, these fragments may move, causing detachment from the surrounding soft tissues.

Diaphyseal gunshot fractures of long bones in the extremities, depending on the degree of displacement of the intermediate fragments and whether or not they maintain their anatomical connection with soft tissues, can be divided into three types:

– Type I – With slight or moderate transverse displacement of the intermediate and main fragments (within the bone's transverse diameter and maintaining longitudinal orientation), which preserve anatomical connection with the periosteal-muscular sheath and do not extend beyond it. In this case, the soft tissue wounds require minimal treatment (can be closed with secondary sutures).

– Type II – With significant transverse displacement of one or more intermediate fragments (in the direction of the projectile's movement), losing their anatomical connection with the periosteal-muscular sheath, and resulting in a periosteal bone defect and a medium or large wound.

– Type III – With excessive transverse displacement of all intermediate fragments (in the direction of the projectile's movement), losing their anatomical connection with the periosteal-muscular sheath, and forming a complete transverse bone defect.

Conflict of Interest. The authors declare no conflict of interest.

Prospects for Further Research. A second report is planned, in which an analysis of treatment outcomes based on the proposed classification will be conducted.

Funding Information. The authors state that there are no financial interests related to the writing of this article.

Authors' Contributions. Popsyushapka O. K. — Proposed the research methods and classification criteria, analyzed the material, and drafted the article; Lytvyshko V. O. — Conducted clinical studies on the shape and size of the wounds and analyzed the radiological material; Malik R. V. — Performed statistical analysis, created an electronic questionnaire for registering gunshot fracture signs; Doluda Y. A. — carried out information search and created illustrations; Mikhanovsky D. O. — Conducted clinical studies, analyzed wound sizes, participated in creating the classification, and calculated kinetic energy.

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The article has been sent to the editors	Received after review	Accepted for printing
24.07.2025	11.03.2025	10.10.2025

DESTRUCTION OF BONE AND SURROUNDING TISSUES IN CASE OF GUNSHOT FRACTURES OF LONG BONES OF THE EXTREMITIES (CLINICAL AND RADIOLOGICAL CLASSIFICATION). *FIRST REPORT*

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