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Application of surgical technologies in the treatment of victims with long bone defects due to modern combat trauma. Message four. Bone plastic technology

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Objective. Evaluate the possibilities of using bone grafting to treat patients with long bone defects caused by combat injuries. *Methods.* This study is retrospective, based on the cohort principle. The formation of a specific study array was carried out using the method of irreversible randomization based on the successful performance of bone grafting. *Results.* The study found out that the need for bone grafting in the treatment of long bone defects in victims of modern combat limb trauma was only in 6.94 % of cases. This method was primarily used (in 74.22 % of cases) for patients aged 31–50, due to mine-blast injuries (58.33 %) and shrapnel wounds (41.67%). Most often, cavitary defects of long bones were localized on the tibia (41.66%) and femur (25.00 %). According to qualitative characteristics, medium cavitary defects of long bones (2–8 cm³) were found in 41.67 %, large (8–15 cm³) in 33.33 %, extra large (more than 15 cm³) in 16.67 % and small (up to 2 cm³) in 8.33 %. It was also found out that bone grafting was most often performed in 41.67 % using the technology of autoplasty with crushed cancellous bone, in 33.33 % using autoplasty with a three-layer graft, and in 25.00 % using autoplasty with cancellous bone with bioglass. *Conclusions.* Indications for bone grafting in patients with long-bone defects are determined through an integrated analysis of the defect's clinical-epidemiological and clinical-anatomical characteristics, with a specific surgical treatment method selected based on the size of the defect.

Мета. Проаналізувати можливості застосування методу реконструктивних кістково-пластичних втручань під час лікування постраждалих із дефектами довгих кісток скелета внаслідок бойової травми. *Методи.* Дослідження ретроспективне, засноване на когортному принципі. Формування конкретного масиву роботи відбувалося методом безповоротної рандомізації за ознакою успішного виконання кісткової пластики. *Результати.* Виявлено, що потреба у виконанні кісткової пластики під час лікування дефектів довгих кісток склала 6,94 %. Цей метод застосовувався здебільшого в 74,22 % у віці 31–50 років, через мінно-вибухові травми (58,33 %), уламкових ушкоджень (41,67 %). Найчастіше кавітарні дефекти довгих кісток локалізувалися на великогомілковій (41,66 %) та стегновій кістках (25,00 %), за якісною характеристикою зустрічалися середні кавітарні дефекти — 2–8 см³ (41,67 %), великі — 8–15 см³ (33,33 %), надвеликі — більше 15 см³ (16,67 %) та малі — до 2 см³ (8,33 %). Зафіксовано, що кісткова аутопластика виконувалася у 41,67 % з подрібненою губчастою кісткою, у 33,33 % — тришаровим трансплантатом, у 25,00 % — губчастою кісткою з біосклом. *Висновки.* Покази для виконання кісткової пластики в постраждалих із дефектами довгих кісток формуються на підставі інтеграційного аналізу клініко-епідеміологічних, клініко-анатомічних характеристик дефекту, причому для кожного розміру дефекту існує метод вибору технології оперативного лікування. *Ключові слова.* Довгі кістки, кавітарні дефекти, хірургічне лікування, кісткова пластика, бойові ушкодження.

Keywords. Long bones, cavitary defects, surgical treatment, bone grafting, combat injuries

Introduction

Modern combat trauma presents new forms of injury characterized by considerable diversity and complexity [1, 2], which, in turn, necessitate the use of new treatment approaches. This applies primarily to such a clinical and nosological form of modern combat injuries as musculoskeletal trauma [3, 4]. Long-bone defects are among the most severe, complex, and, unfortunately, relatively common complications of combat trauma, requiring comprehensive modern surgical treatment [5–10] and the use of the most widely adopted surgical techniques (Masquelet, bone transport). This study focuses on less commonly used surgical approaches for treating patients with long-bone defects resulting from modern combat trauma, specifically reconstructive bone grafting procedures.

It is worth noting that our review of the publicly available scientific literature revealed no systematic analyses of the use of these surgical techniques, but only isolated reports describing individual clinical cases. To date, there is no scientifically substantiated strategy for providing specialized care to patients with long-bone defects resulting from modern warfare.

Reconstructive bone grafting procedures should be viewed as a systematic approach: when microsurgical capabilities are limited, early coordination, high-quality initial wound management, timely stabilization, and rehabilitation-oriented treatment planning are of critical importance.

Objective: to analyze the potential for using reconstructive bone grafting procedures in the treatment of patients with long-bone defects of the skeleton resulting from combat trauma.

Materials and Methods

The study was conducted in accordance with the requirements of the Declaration of Helsinki and approved by the Bioethics Committee of the SI “Ukrainian Scientific and Practical Center for Emergency Medical Care and Disaster Medicine of the Ministry of Health of Ukraine”, Protocol No. 5 dated 07.07.2026.

The study was retrospective and based on a cohort design. The overall dataset comprised 519 cases of long-bone defects in patients with modern combat trauma recorded during 2020–2026, exceeding the sample size considered necessary and sufficient under the law of large numbers. The study population was formed using irreversible randomization based on successful bone grafting. We defined success as the maximum possible restoration of the anatomical

structure of the bone. The study sample comprised 36 cases of cavitary long-bone defects, which to some extent exceeded the minimum number of cases required for analysis and for obtaining reliable results using appropriate statistical analysis methods. It should be noted that the study population was formed according to the principle of treatment success, which made it possible to identify and assess factors influencing surgical efficacy.

We analyzed selected clinical and epidemiological characteristics of patients with long-bone defects who underwent reconstructive bone grafting, including age and mechanism of injury, as well as the clinical and anatomical characteristics of the defects, including their location and size. Successful bone grafting was achieved only in cases of cavitary defects.

Our review of the available scientific literature revealed no adequate or generally accepted classification of the size of cavitary long-bone defects. Therefore, the classification proposed by D. Paley [11] was modified and used in the present study.

Given the size of the study population and its subsequent stratification, nonparametric statistical methods were used, including the Wilcoxon test to compare calculated values with the critical values of the Mann–Whitney test at a confidence level of $p = 0.01$, as well as polychoric analysis to determine the direction, strength, and statistical significance of associations between the variables under study. The calculated Pearson statistic was compared with the critical F-value of 10.83. Given the limited sample size, the coefficient of mutual association in the polychoric analysis was calculated using the O. O. Chuprov correction. Elements of fractal analysis were also applied, specifically the calculation and qualitative assessment of distribution dispersion based on the maximum and minimum values of the variation series.

The methods used for data collection, study population formation, and statistical analysis met the requirements and criteria of evidence-based medicine and enabled the generation of reliable results. Overall, the methodological and software framework of the study was consistent with the principles of evidence-based medicine.

Results

In the overall study population, the need for bone grafting in the treatment of long-bone defects resulting from modern combat trauma to the extremities was 6.94 %. This technique is used relatively infrequently because its primary indication is the presence of cavitary defects of long bones. Bone grafting allowed restoration of the lost bone volume and stimu-

lated osteogenesis. All defects requiring bone grafting and successfully treated with this technique were cavitory in nature; its use for other types of defects was unsuccessful.

To assess the effect of age on the need for bone grafting following modern combat trauma, we performed a comparative analysis of patients with cavitory defects and those in the overall study population (Table 1). The age distributions differed between the two groups. No bone grafting procedures were performed in patients younger than 20 or older than 60 years. In the 21–30-year age group, the proportion was 16.67 %, representing an absolute difference of 42.58 % in the intensive rate, or 12.36 % below the corresponding figure for the overall study population. In the 31–40-year age group, the proportion was 41.66 %, representing an absolute difference of 30.37 % in the intensive rate, or 3.5 times higher than that of the overall study population. In the 41–50-year age group, the proportion was 33.33 %, which was 3.77 % higher in absolute terms in the intensive rate, or 10.17 % below the baseline level, compared with the overall study population. In the 51–60-year age group, the proportion was 8.33 %, representing an absolute difference of 2.96 % in the intensive rate, or 26.22 % below the baseline level, compared with the overall study population.

Thus, bone grafting for the treatment of cavitory long-bone defects resulting from modern combat trauma was performed predominantly in patients aged 31–50 years, who accounted for 74.99 % of cases. This age range represents a period in which involutional changes in bone tissue begin and progress, while sufficient regenerative potential remains to support adaptation and remodeling of the bone graft.

To assess the statistical significance of the distribution and the assumptions presented above, the nonparametric Wilcoxon–Mann–Whitney test

was applied. The results showed a U statistic of 47, exceeding the critical value of 3, indicating that the distribution was statistically valid and supporting the hypothesis of an effect.

To determine the need for bone grafting according to defect location, we analyzed the distribution of patients with cavitory long-bone defects and compared it with the distribution in the overall cohort of patients with injuries resulting from modern combat trauma (Table 2).

A difference in rank order was observed, along with substantial differences in the proportions between the comparison groups. For cavitory defects of the humerus, the proportion was 16.67 %, representing an absolute difference of 10.42 % in the intensive rate, or 1.67 times higher than the corresponding figure for the overall cohort.

Cavitory defects of the forearm also required bone grafting in 16.67 % of cases, representing an absolute difference of 1.04 % in the intensive rate, or 6.70 % above the baseline level compared with the overall cohort.

Bone grafting for femoral defects was performed in 25.00 % of cases in this comparison group, representing an absolute difference of 6.25 % in the intensive rate, or 33.33 % above the baseline level compared with the overall cohort. Patients with cavitory defects of the lower leg required bone grafting in 41.66 % of cases, representing an absolute difference of 17.71% in the intensive rate, or 29.83 % below the baseline level compared with the overall cohort.

Thus, patients with defects of the lower-leg bones had the greatest need for bone grafting. At the same time, this proportion was substantially lower than that observed in the overall cohort. The proportions for the other locations were higher than those in the overall cohort, particularly for the humerus, where cavitory defects requiring bone grafting were relatively common.

Comparative analysis of the distribution of patients by age

Table 1

Age (years)	Cohort of patients with cavitory defects		Total cohort of patients with long-bone defects	
	proportion (%)*	rank	proportion (%)*	rank
Under 20	0	5	8.06	4
21–30	16.67	3	29.03	2
31–40	41.66	1	11.29	3
41–50	33.33	2	37.10	1
51–60	8.33	4	11.29	3
Over 60	0	5	3.23	5
Total	100.00	—	100.00	—

To assess the statistical validity of the distribution and the likelihood of an effect of defect location on the need for bone grafting, the nonparametric Wilcoxon–Mann–Whitney test was applied. The Mann–Whitney statistic was 16, substantially exceeding the critical value $U_{st} = 0$. This finding supports the validity of the distribution and the hypothesis that defect location influences the need for bone grafting.

The genesis of cavitary defects requiring bone grafting is a complex and important aspect of the management of long-bone defects. To assess the effect of the mechanism of injury on the development of cavitary defects, we comparatively analyzed the distribution of patients with cavitary long-bone defects requiring bone grafting and the overall cohort of patients with long-bone defects resulting from combat trauma according to the mechanism of injury (Table 3).

The data presented in Table 3 show that cavitary long-bone defects requiring bone grafting occurred predominantly as a result of blast-mining trauma and explosive devices dropped from drones, accounting for 58.33 % of cases. This was 11.25 % lower in absolute terms for the intensive rate, or 16.17 % below the baseline level, than in the overall cohort. Defects resulting from fragment injuries accounted for 41.67 % of cases, which was 21.02 % higher in absolute terms for the intensive rate, or twice the baseline level.

It should be noted that cavitary long-bone defects were diagnosed predominantly following exposure to

high-intensity combat mechanisms of injury and, secondly, relatively often following secondary weapon effects, particularly fragments. Thus, although cavitary defects are associated with high-intensity injury mechanisms, their proportion was lower than that observed in the overall cohort of patients with long-bone defects.

The nonparametric Mann–Whitney rank analysis showed that $U_f = 9$ exceeded the critical value of 1. The distribution may therefore be considered objective, and the hypothesis of an effect may be regarded as statistically supported.

To analyze defect size, we used our modified version of the D. Paley classification, which takes into account the actual volume of the defect and is therefore applicable specifically to the assessment of cavitary long-bone defects (Table 4).

Medium-sized cavitary defects were the most common, accounting for 41.67 % of cases, followed by large defects at 33.33 %. Very large defects ranked third, accounting for 16.67 %, while small cavitary long-bone defects were recorded in only 8.33 % of cases. Thus, 74.99 % of cavitary long-bone defects were classified as medium or large. The ratio of the maximum to minimum values in the variation series was 5, indicating a high degree of dispersion and, indirectly, supporting the statistical validity of the distribution.

This raises the question of which bone grafting technique is optimal for the treatment of cavitary long-bone defects in patients with injuries resulting

Table 2

Analysis of the distribution of patients by defect location

Cavitary defect location	Cohort of patients with cavitary defects		Total cohort of patients with long-bone defects	
	proportion (%)*	rank	proportion (%)*	rank
Upper arm	16.67	3	6.25	4
Forearm	16.67	3	15.63	3
Thigh	25.00	2	18.75	2
Lower leg	41.66	1	59.37	1
Total	100.00	—	100.00	—

Table 3

Analysis of the distribution of patients by mechanism of injury

Mechanism of injury	Cohort of patients with cavitary defects		Total cohort of patients with long-bone defects	
	proportion (%)*	rank	proportion (%)*	rank
Blast injury, including explosive devices dropped from drones	58.33	1	69.57	1
Fragmentation injury	41.67	2	20.65	2
Combat-related road traffic accidents	0	3	9.78	3
Total	100.00	—	100.00	—

from modern combat trauma. Given that treatment success was used as the principal criterion in the present study, we analyzed the distribution of patients with cavitory defects according to the bone grafting technique used; the results are presented in Table 5.

Among patients with cavitory long-bone defects who underwent successful bone grafting, autologous grafting using cancellous bone accounted for the largest proportion, at 41.67 %. In 33.33 % of cases, bone grafting using cancellous bone combined with bioglass was performed. A three-layer autograft was used to replace the cavitory defect in 25.00 % of cases.

To determine the indications for specific bone grafting techniques in patients with cavitory long-bone defects, the study population was stratified according to the bone grafting technique and the “cavitory defect type” (Table 6).

Each bone grafting technique was associated with a specific defect size. Autologous grafting using cancellous bone was most often successfully performed for medium-sized cavitory defects of subtype A1.2 (80.00 %) and considerably less frequently for subtype A1.1 defects (20.00 %).

Autologous grafting using a three-layer graft was successfully performed predominantly for large defects of subtype A1.3, which accounted for 66.67 % of cases, and for medium-sized defects of subtype A1.2, which accounted for 33.33%.

Autologous grafting using cancellous bone combined with bioglass was required in equal proportions (50.00 % each) for large cavitory defects (subtype A1.3) and very large defects (subtype A1.4).

To verify the success of bone grafting according to the type of cavitory long-bone defect in patients with injuries resulting from modern combat trauma, we stratified the cases by bone grafting technique and cavitory defect type (Table 7).

It should be noted that each type of cavitory long-bone defect has bone grafting techniques capable of ensuring a successful surgical outcome. All patients with small cavitory defects (subtype A1.1) underwent autologous grafting using cancellous bone. Among patients with medium-sized defects (subtype A1.2), cancellous bone was used in 80.00 % of cases and a three-layer bone graft in 20.00 %. For large defects (subtype A1.3), autologous grafting with a three-layer graft and cancellous bone combined with bioglass were used in equal proportions. For very large defects, only autologous grafting with cancellous bone combined with bioglass was used.

To assess the significance of the association between defect size and the success of a given bone grafting technique in patients with cavitory long-bone defects resulting from modern combat trauma, polychoric analysis was performed (Tables 6 and 7). A positive ($\phi^2 = 0.99$), strong ($k = 0.6357$), and statistically significant association ($\chi^2 = 11.88$) was found between the success of a specific bone grafting technique and the size of the cavitory long-bone defect, with the observed values falling within the range of statistical significance.

In summary, bone grafting was performed exclusively in patients with cavitory long-bone defects, predominantly those younger than 50 years, in whom the regenerative potential of bone was preserved, most commonly involving the femur and lower-leg bones.

Analysis of the distribution of patients by the cavitory defect size

Table 4

Cavitory defect subtype	Quality characteristics	Proportion (%)*	Rank
A1.1 (up to 2 cm ³)	small	8.33	4
A1.2 (2–8 cm ³)	medium	41.67	1
A1.3 (8–15 cm ³)	large	33.33	2
A1.4 (over 15 cm ³)	very large	16.67	3
Total	—	100.00	—

Distribution of patients by bone grafting technique

Table 5

Bone grafting technique type	Proportion (%)*	Rank
Autologous bone grafting (cancellous bone)	41.67	1
Autologous bone grafting (three-layer bone graft)	25.00	3
Autologous bone grafting (cancellous bone) + bioglass	33.33	2
Total	100.00	—

Table 6

Distribution of study cases by cavitory defect type, stratified by bone grafting technique

Cavitory defect subtype	Autologous bone grafting (cancellous bone)		Autologous bone grafting (three-layer bone graft)		Autologous bone grafting (cancellous bone)+ bioglass	
	proportion (%)*	rank	proportion (%)*	rank	proportion (%)*	rank
A1.1 (up to 2 cm ³)	20.00	2	0	3	0	2
A1.2 (2–8 cm ³)	80.00	1	33.33	2	0	2
A1.3 (8–15 cm ³)	0	3	66.67	1	50.00	1
A1.4 (over 15 cm ³)	0	3	0	3	50.00	1
Total	100.00	—	100.00	—	100.00	—

Table 7

Distribution of study cases by bone grafting technique, stratified by cavitory defect type

Cavitory defect subtype	Autologous bone grafting (cancellous bone)	Autologous bone grafting (three-layer bone graft)	Autologous bone grafting (cancellous bone)+ bioglass	Total
A1.1 (up to 2 cm ³)	100	0	0	10
A1.2 (2–8 cm ³)	80	20	0	100
A1.3 (8–15 cm ³)	0	50	50	100
A1.4 (over 15 cm ³)	0	0	100	100

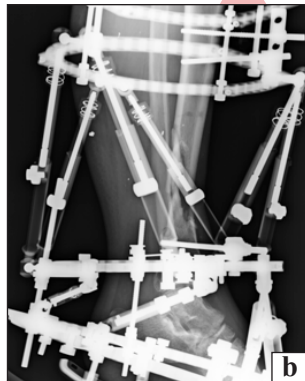
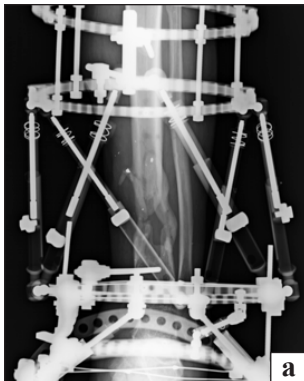


Fig. 1. Radiographs of patient B: (a) anteroposterior and (b) lateral views.

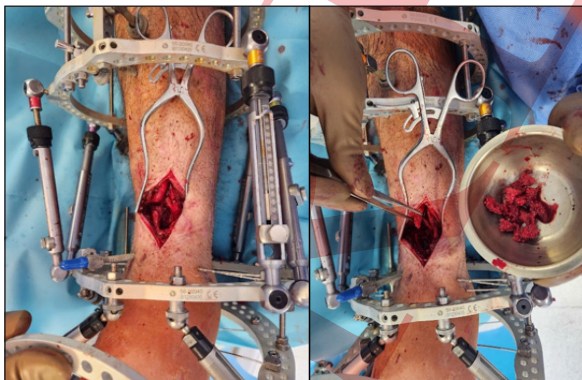


Fig. 2. Intraoperative photograph showing bone grafting with an autologous pelvic bone graft.

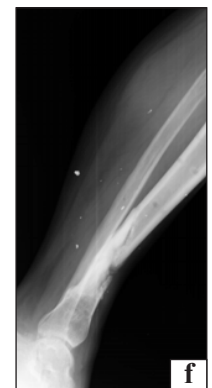
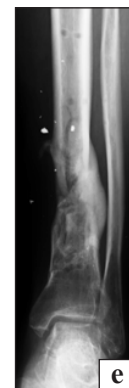
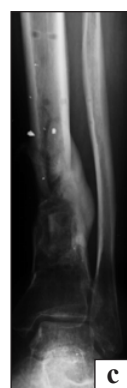
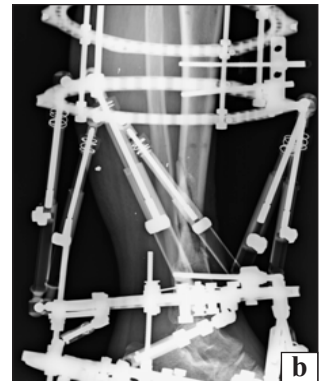
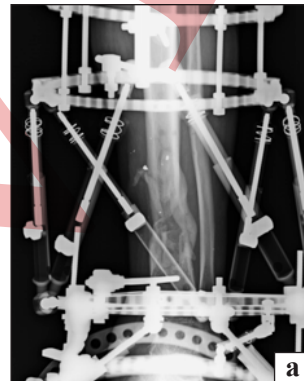


Fig. 3. Radiographs obtained after bone grafting: (a) anteroposterior and (b) lateral views; at 2.5 months: (c) anteroposterior and (d) lateral views; at 5 months: (e) anteroposterior and (f) lateral views.

Clinical Case 1. A 50-year-old patient B. was admitted with a gunshot, fragmentary, blind wound of the right lower leg. A cavitory bone defect and

a soft-tissue defect were identified. During the initial stage of medical care, wound debridement was performed and the fragments were stabilized using

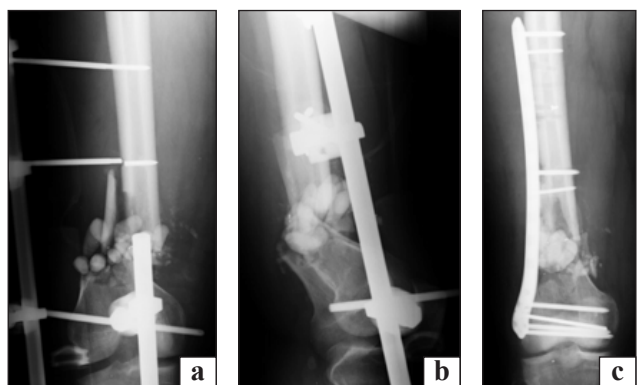


Fig. 4. Radiographs of patient S.: (a) anteroposterior and (b) lateral views; (c) radiograph after filling the defect with a cement spacer and plate fixation.

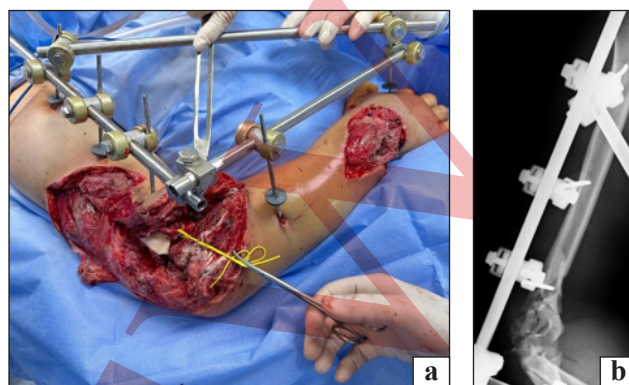


Fig. 7. (a) Intraoperative appearance and (b) radiograph.

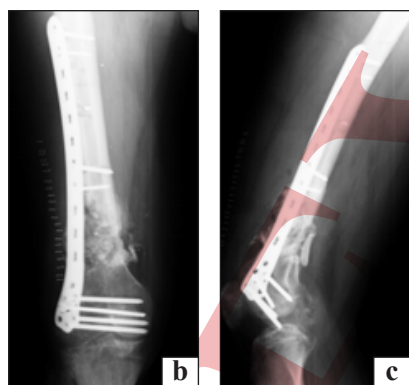


Fig. 5. (a) Intraoperative photograph showing bone grafting with an autologous pelvic bone graft; radiographs obtained after grafting: (b) anteroposterior and (c) lateral views.

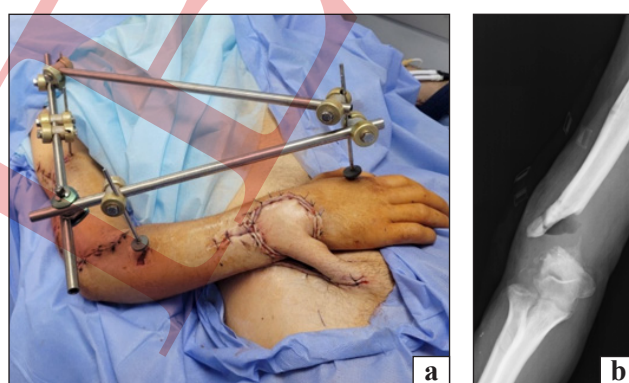


Fig. 8. (a) Clinical appearance and (b) radiograph obtained 3 months after bone grafting.

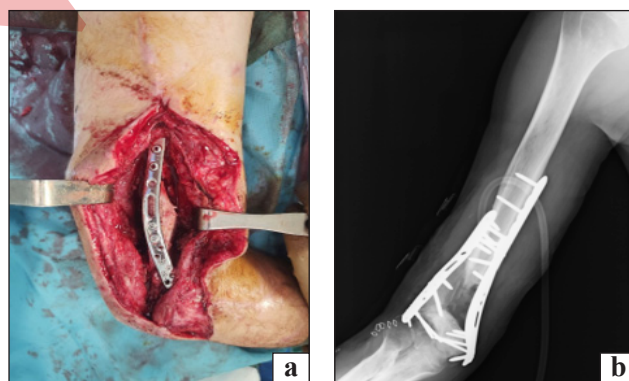


Fig. 9. (a) Clinical appearance of the injured limb after bone grafting; radiographs: (b) anteroposterior and (c) lateral views.

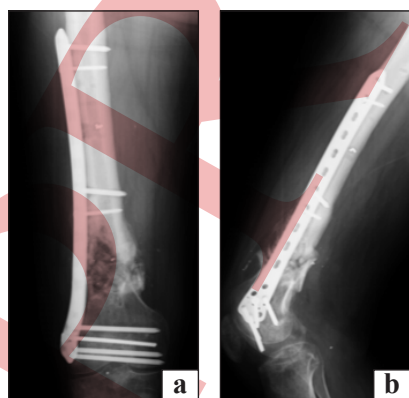


Fig. 6. Radiographs obtained 3 months after bone grafting.



an external fixation device (Fig. 1a, b). Two weeks after the injury, bone grafting was performed using morselized cancellous bone combined with bioglass at a ratio of 3:1 (Fig. 2). Postoperative imaging showed adequate filling of the cavitory defect with the autograft (Fig. 3). Follow-up radiographs were subsequently obtained at 2.5 and 5 months. The follow-up radiographs (Fig. 3, c–e) demonstrated substantial restoration of the bone structure.

Clinical Case 2. A 44-year-old patient S. was admitted with a femoral injury resulting from blast-mining trauma. A cavitory defect of the distal femur was identified. During the initial stage of medical care, wound debridement was performed and a rod external fixation device was applied (Fig. 4, a, b); at the second stage, the femoral fracture was stabilized with a plate and the cavitory defect was filled with a cement spacer (Fig. 4, c). Six weeks later, the spacer was removed and bone grafting was performed using morselized cancellous bone harvested from the anterior pelvic region (Fig. 5). Follow-up radiographs obtained at 3 months (Fig. 6) demonstrated restoration of the bone structure.

Clinical Case 3. A 25-year-old wounded patient K. was diagnosed with multiple injuries of the right upper extremity, including a cavitory defect of the distal humerus. During the initial stage of medical care, wound debridement was performed and a rod external fixation device was applied (Fig. 7, a, b); at the second stage, delayed closure of the arm wound was performed, together with soft-tissue reconstruction of the forearm defect using a groin flap (Fig. 8, a, b). At the third stage, 3 months later, the distal humeral fracture was stabilized with plates, with reconstruction of the lateral column using a three-cortical graft harvested from the iliac wing (Fig. 9, a, b).

Discussion

The study found that bone grafting was used in 6.94% of cases in the treatment of patients with long-bone defects resulting from modern combat trauma. This figure is somewhat higher than that reported in the international scientific literature [9, 12]. Notably, all defects in patients who underwent successful bone grafting were cavitory in nature. In our view, this may be attributed to the specific effects of the mechanisms of injury in these patients. Bone grafting was performed predominantly in patients aged 21–50 years (91.67 %), which may be explained by the preservation of bone regenerative potential. In terms of anatomical location, the humerus and femur were the most favorable sites.

The application of our modified D. Paley classification showed that the most common cavitory defects were medium-sized defects of 2–8 cm³ (41.67 %) and large defects of 8–15 cm³ (33.33 %), while very large defects (> 15 cm³) accounted for 16.67 %. Bone grafting was generally associated with satisfactory outcomes for defects measuring 2–15 cm³, which accounted for 75.00 % of the study population. These findings are unique to patients with combat trauma.

The mechanisms underlying defects successfully treated with bone grafting were blast trauma in 58.33 % of cases and fragment injuries in 41.67 %; the latter was twice as frequent as in the overall study population.

These findings support the view that cavitory defects may result from both direct and indirect effects of combat-related mechanisms of injury. This is consistent with the international scientific literature [2, 13, 14] and substantially expands the current understanding of the pathogenesis of these injuries.

We analyzed the provision of medical care and surgical treatment of patients with cavitory long-bone defects who underwent bone grafting using the following techniques: autologous grafting with cancellous bone (41.67 %), cancellous bone combined with bioglass (33.33 %), and a three-layer graft (25.00 %). Cancellous bone autografting was successfully used in 80 % of patients with defects measuring 2–8 cm³; cancellous bone combined with bioglass was used for defects larger than 8 cm³; and three-layer grafting was used for defects measuring 2–15 cm³.

It should be emphasized that the effectiveness of reconstructive bone grafting procedures depends on adherence to key organizational principles. Experience in the management of combat trauma under resource-limited conditions has demonstrated that interdisciplinary limb-preservation models can be successfully implemented, although infection, non-union, and inadequate rehabilitation remain major challenges. The authors of these studies emphasized the importance of coordinated multidisciplinary collaboration, even in frontline settings [15, 16].

Conclusions

Bone grafting in the treatment of patients with long-bone defects was successful only for cavitory defects. The mechanisms of injury were predominantly both direct (blast trauma) and indirect (fragment injury) effects of combat-related mechanisms of injury.

In summary, successful bone grafting in patients with long-bone defects resulting from modern combat trauma requires clearly defined indications

for specific surgical techniques based on the clinical and epidemiological characteristics of the patient and the clinical and anatomical characteristics of the defect. Nevertheless, the final choice of surgical technique should always be made at the treating physician's discretion. The most favorable sites for successful bone grafting in patients with long-bone defects are the femur and tibia.

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

Prospects for further research. Future studies will focus on evaluating other surgical techniques for the treatment of bone defects resulting from modern combat trauma.

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APPLICATION OF SURGICAL TECHNOLOGIES IN THE TREATMENT OF VICTIMS WITH LONG BONE DEFECTS DUE TO MODERN COMBAT TRAUMA. MESSAGE FOUR. BONE PLASTIC TECHNOLOGY

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