ОРИГІНАЛЬНІ СТАТТІ

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Application of surgical technologies for the treatment of victims with defects of long bones due to modern combat trauma. Report three. Bone transport technologies

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Objective. To provide a full description of the indications for the use of bone transport technology in victims with long bone defects due to combat trauma. Methods. The current state of domestic and international treatment strategies, as well as research achievements regarding bone transport methods (antegrade, retrograde, and antegrade-retrograde) were reviewed. The medical histories of 62 patients with long bone defects who were successfully treated using bone transport technology were studied. Results. It was found out that antegrade bone transport is most often used for the surgical treatment of victims with such defects — 54.84 %. In the general array of victims who were treated with bone transport technology, patients aged 21–50 years prevail — 77.42 %. It should be noted that the use of this technology prevailed in cases of damage to the long bones of the lower limb — 96.78 %. It can also be stated that the bone transport technology for the treatment of long bone defects is inherent in conditions of defect sizes from 5 to 15 cm. Conclusions. The use of bone transport technology in the surgical treatment of victims with long bone defects due to combat trauma to achieve a successful clinical and anatomical result requires a clear comprehensive formation of indications based on age, anatomical features, as well as assessment of the defect, the criteria being the age of the victim (up to 50 years) and the defect size of 5 cm or more. Each subtype of bone transport technology has a specific localization of defects for its successful use: antegrade bone transport for defects due to combat trauma of the forearm (100 %) and lower leg (56.82 %), retrograde — thigh (62.5 %), antegrade-retrograde — only on the lower leg.

Мета. Надати повноцінну характеристику показів для застосування технології кісткового транспорту в постраждалих із дефектами довгих кісток унаслідок бойової травми. Методи. Розглянуто сучасний стан вітчизняних і міжнародних стратегій лікування, а також дослідницькі досягнення щодо способів транспортування кісток (антеградний, ретроградний та антеградно-ретроградний). Вивчено історії хвороби 62 пацієнтів із дефектами довгих кісток, яких успішно проліковано зі застосуванням технології кісткового транспорту. Результати. Виявлено, що для оперативного лікування постраждалих із такими дефектами найчастіше застосовується антеградний кістковий транспорт — 54,84 %. У загальному масиві постраждалих, яким було застосовано технологію кісткового транспорту, здебільшого хворі віком 21–50 років — 77,42 %. Зауважимо, що використання цієї технологія переважало в разі ураження довгих кісток нижніх кінцівок — 96,78 %. Також можна стверджувати, що технологія кісткового транспорту для лікування дефектів довгих кісток притаманна за умов розмірів дефектів від 5 до 15 см. Висновки. Застосування технології кісткового транспорту в хірургічному лікуванні постраждалих із дефектами довгих кісток унаслідок бойової травми для досягнення успішного клініко-анатомічного результату потребує чіткого комплексного формування показів, заснованого на вікових, анатомічних ознаках, а також оцінюванні дефекту, критеріями є вік постраждалого (до 50 років) та розмір дефекту від 5 см та більше. Кожен підтип технології кісткового транспорту застосовується за певної локалізації дефектів для її успішного використання: антеградний кістковий транспорт за дефектів унаслідок бойової травми кісток передпліччя (100 %) та гомілки (56,82 %), ретроградний — стегна (62,5 %), антеградно-ретроградний — лише на гомілці. Ключові слова. Довгі кістки, дефекти, хірургічне лікування, технології кісткового транспорту, бойові ушкодження.

Keywords. Long bones, defects, surgical treatment, bone transport technologies, combat injuries

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Introduction

The increase in high-energy and explosive injuries during wartime has led to a rise in the number of severe trauma cases with serious consequences. These injuries may potentially be associated with a range of complications, such as bone infections or prolonged hospitalization.

Firearm-related fractures of long bones resulting from combat trauma are characterized by zones of destruction with the formation of multiple bone fragments that may migrate after detaching from the soft tissues. Therefore, bone transport technology is an important method for treating patients with long bone defects caused by combat trauma. Its principles help reduce the time required to bridge the bone ends across the defect zone and enable early bone grafting, providing an effective solution for nonunion problems. This technique is also becoming increasingly widespread among orthopedic surgeons, as it minimizes the need for large soft tissue and autologous bone grafts. In addition, it can adequately control infection and allows simultaneous reconstruction of both bone and soft tissue defects.

The relevance of this research topic has been demonstrated in our previous reports, where bone transport technology in combat trauma was applied in 54.35 % of cases [1], and has been reflected in numerous domestic and international scientific publications [2–5]. However, most publications addressing this issue primarily focus on medical-technical aspects. In the available scientific sources reviewed and analyzed by us, we found a limited number of articles addressing the clinical and organizational aspects of bone transport technology in patients with long bone defects due to combat trauma, including the verification and justification of indications for its use.

Purpose: to provide a comprehensive characterization of the indications for the use of bone transport technology in patients with long bone defects resulting from combat trauma.

Materials and Methods

We reviewed current domestic and international treatment strategies, as well as research developments regarding methods of bone transport (antegrade, retrograde, and antegrade–retrograde).

The literature search was conducted using PubMed, Web of Science, and Google Scholar, including original studies, reviews, clinical cases, and meta-analyses, covering the period from 2016 to 2025. A total of 430 articles were identified. Inclusion criteria: studies related to bone transport technology. Exclusion criteria: duplicate content articles and studies of the same type without significant differences. Overall, 16 studies in Ukrainian and English were included in the analysis.

The study was approved by the local bioethics committee (Protocol No. 3 dated 02.04.2026) of the State Institution "Ukrainian Scientific and Practical Center of Emergency Medical Care and Disaster Medicine of the Ministry of Health of Ukraine", in accordance with ICH GCP, the Declaration of Helsinki on Human Rights and Biomedicine, and current legislation of Ukraine. All participating patients were informed about the study design and conditions and provided written informed consent.

The study population was stratified according to the subtype of bone transport technology, namely antegrade, retrograde, and antegrade–retrograde techniques. The application of specific subtypes of bone transport in patients with long bone defects due to combat trauma was analyzed depending on age, anatomical location, and defect size, followed by comparative analysis. Full parametric (rank-based) and non-parametric statistical methods were applied, along with elements of fractal analysis.

To assess injury characteristics and the condition of long bone defects, medical history, radiometric changes over time, and treatment outcomes were analyzed according to the location and size of the defect.

Results

In nearly 90 % of the cases analyzed, bone defects were located in the diaphyseal regions of long bones, consistent with the characteristics of bone transport. First, we performed a distribution of the overall cohort of patients with long bone defects treated using bone transport technology according to its subtype (Table 1).

Analysis of the data in Table 1 showed that, in the overall cohort of patients with long bone defects, antegrade bone transport was most frequently used for surgical treatment — 54.84 % (ranked first). Retrograde bone transport was used in 38.71 % of combat-related bone defect cases, while the least frequently used method was a combination of retrograde

Table 1

Analysis of the distribution of the patient cohort according to the bone transport technique subtype

Bone transport technique subtype	Percentage (%)	Rank
Antegrade	54.84	1
Retrograde	38.71	2
Antegrade-retrograde	6.45	3
Total	100.00	—

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and antegrade bone transport — 6.45 %. The ratio between the highest and lowest proportions was 8.5, indicating a high dispersion of the distribution and indirectly supporting its validity. Thus, antegrade bone transport remains the method of choice for treating long bone defects in patients with combat-related trauma.

To determine the influence of age on the use of bone transport technology in patients with long bone defects resulting from combat trauma, we analyzed the patient cohort distribution, and the results are presented in Table 2.

The study found that, in the overall cohort of patients with long bone defects due to combat injuries treated with bone transport technology, the most common age group was 41–50 years — 37.10 % (ranked first), followed by individuals aged 21–30 years (29.03 %), while the lowest proportion was observed in patients over 60 years of age — 3.23 %. In summary, this technology was predominantly used in patients aged 21–50 years (77.42 %). The ratio between the highest and lowest proportions was 11.49, indicating high dispersion and indirectly supporting the validity of the distribution.

In the overall cohort of patients treated with bone transport for long bone defects, a distribution was performed according to the "injury localization" parameter, and the results are presented in Table 3.

Analysis of the data in Table 3 leads to the conclusion that bone transport technology in patients with long bone defects due to combat injuries was most frequently applied to the tibia — 83.26 %, and 5.7 times less frequently to the femur. Overall, it was used in 96.78 % of cases involving the lower extremities and only 3.22 % in the upper extremities, exclusively in the forearm. Thus, bone transport technology is more appropriate for long bone defects of the lower limbs. The ratio between the highest and lowest proportions was 25.55, indicating very high dispersion and indirectly supporting the validity of the distribution.

To determine the relationship between the use of bone transport technology and the size of the bone defect in patients injured during combat, we analyzed the distribution of the cohort according to defect size, and the results are presented in Table 4.

It was found that bone transport technology was most frequently used for defect sizes ranging from 5 to 10 cm — 38.71 % (ranked first). The second most common group, with a slightly lower proportion (37.10 %), included defects measuring 10.0–14.99 cm. A notably low proportion of cases (3.22 %) was observed in defects smaller than 5 cm. Based on these data, it can be concluded that bone transport technology for surgical treatment of long bone injuries in combat trauma is predominantly indicated for defect sizes between 5 and 15 cm.

To determine the relationship between bone transport subtypes and the injured segment, we analyzed the study cohort according to the "bone transport technology subtype" and "limb segment" parameters. The results of this analysis are presented in Table 5.

Data in Table 5 showed that in patients with long bone defects of the forearm, only antegrade bone transport was used in 100 % of cases. For femoral bone defects, retrograde bone transport was predominantly used — 62.50 %, while antegrade transport was used in 37.5 % of cases. In tibial bone defects, in contrast to the femur, antegrade bone transport was preferred more frequently — by a factor of 1.56. In addition, it is noteworthy that in 6.82 % of tibial defect cases, a combination of antegrade and retrograde

Table 2

Analysis of the distribution of the patient cohort by age group

Age (years)	Percentage (%)	Rank
Up to 20	8.06	4
21–30	29.03	2
31–40	11.29	3
41–50	37.10	1
51–60	11.29	3
Over 60	3.23	5
Total	100.00	—

Table 3

Analysis of the distribution of the patient cohort by injury location

Defect location	Percentage (%)	Rank
Humerus	0	4
Forearm	3.22	3
Femur	14.52	2
Tibia	82.26	1
Total	100.00	—

Table 4

Analysis of the distribution of the patient cohort by defect size

Defect size (cm)	Percentage (%)	Rank
2.5–4.99	3.22	4
5.0–9.99	38.71	1
10.0–14.99	37.10	2
Over 15.00	20.97	3
Total	100.00	—

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bone transport techniques was applied. Thus, based on these data, it can be concluded that specific bone transport subtypes are characteristic of particular anatomical segments.

On the other hand, the study cohort was also analyzed according to the "injured limb segment" parameter in relation to the applied bone transport technique (Table 6).

Analysis of the data in Table 6 revealed that antegrade bone transport in patients with long bone defects resulting from combat trauma was most frequently applied to the tibia — in 86.21 % of cases, while it was used in the femur and forearm 8.3 times and 25 times less frequently, respectively.

Retrograde bone transport for the surgical treatment of long bone defects was also predominantly used in tibial defects (76.19 %), while femoral involvement accounted for 23.81 %, which is 3 times less; notably, this technique was not used at all in the forearm.

A combination of bone transport techniques (antegrade and retrograde) in our study was observed only in tibial defects, and was not encountered in other segments in a statistically significant number of cases.

Based on the above data, it can be concluded that the use of bone transport techniques for the surgical treatment of bone defects in combat-related injuries is most characteristic for tibial defects.

To assess the reliability of the data in Table 6, a polychoric analysis was performed, which demonstrated a positive ($\varphi^2 = 0.0571$), moderate ($C = 0.2325$), and statistically significant association ($\chi^2 = 3.03$) between the variables "bone transport subtype" and "defect localization," although the level of significance also suggests the influence of additional factors.

For didactic purposes, clinical examples of the application of different bone transport subtypes in patients with long bone defects due to combat injuries are presented below.

Clinical Case No. 1

Application of antegrade bone transport in long bone defects. A 48-year-old patient sustained an isolated injury (mine-explosive trauma). Comminuted fracture of the right tibial bones in the distal third with a soft tissue defect and injury to the anterior tibial artery. Tourniquet syndrome duration was 4 hours. The patient was admitted for staged treatment on day 4 after injury (Fig. 1); immediate wound debridement and surgical revascularization were performed, and a bone defect measuring 12.5 cm was identified.

The next stage included soft tissue management, VAC therapy, and split-thickness skin grafting (Fig. 2).

On day 15, a cement spacer was implanted (Fig. 3).

Three months after injury, correction of the transport segment was performed, the cement spacer was

Table 5

Analysis of the distribution of the study cohort by limb segment across groups according to the bone transport technique subtype

Subtype	Limb segment					
	forearm		femur		tibia	
	percentage (%)	rank	percentage (%)	rank	percentage (%)	rank
Антеградна	100.00	1	37.5	2	56.82	1
Ретроградна	0	2	62.5	1	36.36	2
Антеградно-ретроградна	0	2	0	3	6.82	3
Total	100.00	—	100.00	—	100.00	—

Table 6

Analysis of the distribution of the study cohort by bone transport technique subtype across limb segment groups

Сегмент	Bone transport technique subtype					
	antegrade		retrograde		antegrade-retrograde	
	percentage (%)	rank	percentage (%)	rank	percentage (%)	rank
Forearm	3.45	3	0	3	0	2
Femur	10.34	2	23.81	2	0	2
Tibia	86.21	1	76.19	1	100.00	1
Total	100.00	—	100.00	—	100.00	—

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removed, and the fixation method was converted to a circular external fixation device (Fig. 4).

Nine months after injury, conversion from circular external fixation to an LPC plate was performed (Fig. 5).

At 18 months after injury, the patient demonstrated a satisfactory treatment outcome at follow-up (Fig. 6).

Clinical Case No. 2

Application of Retrograde Bone Transport. A 32-year-old patient was admitted to the State Institution "Ukrainian Scientific and Practical Center for Emergency Medical Care and Disaster Medicine of the Ministry of Health of Ukraine" 3 months after staged treatment, presenting with combined soft-tissue and bone defects measuring 7.3 cm and a wound showing signs of infection (Fig. 7a, b). Surgical wound debridement and placement of a cement spacer were performed.

Two weeks later, repeat wound debridement, spacer exchange, and soft-tissue reconstruction using a rotational muscle flap were carried out (Fig. 8), after which the patient was discharged for outpatient follow-up.

Five weeks after admission, or 4 months after the injury, a critical bone defect measuring 8.4 cm, compromised soft tissues, and persistent infection were identified (Fig. 9a). It was decided to replace

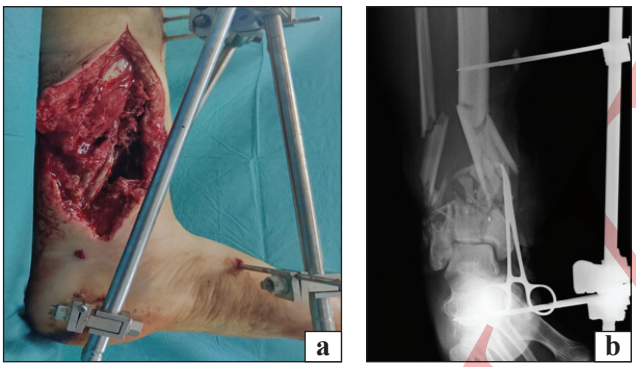


Fig. 1. Photographic images: (a) injury at admission, (b) radiographic images at admission

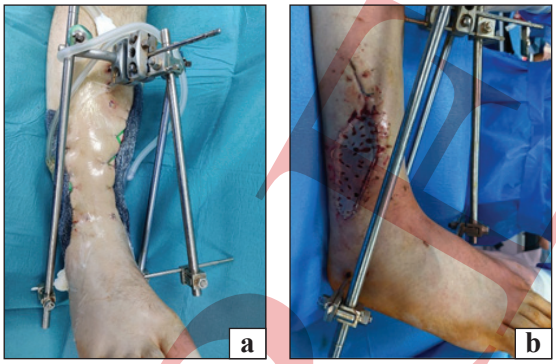


Fig. 2. General view after wound management — VAC therapy (a), after split-thickness skin grafting (b)

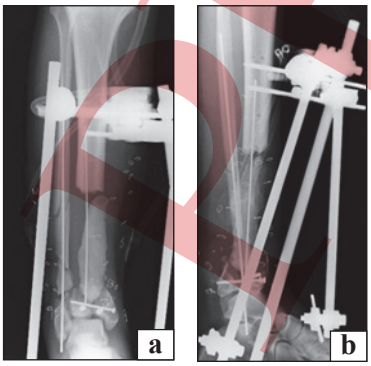


Fig. 3. Radiographic images on postoperative day 15, anteroposterior view (a), lateral view (b)

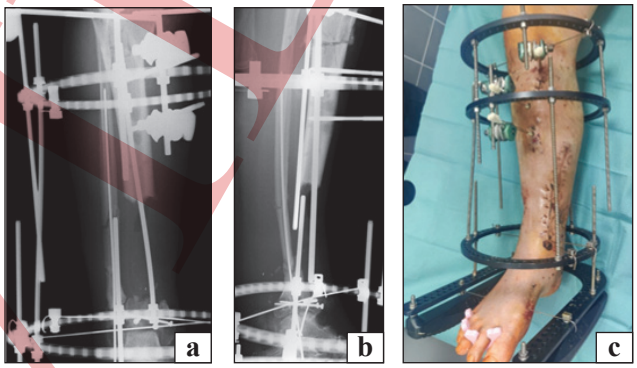


Fig. 4. Radiographic images at 3 months (a, b), clinical appearance of the limb (c)

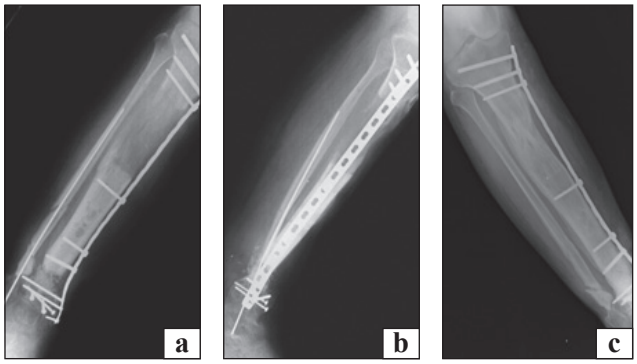


Fig. 5. Radiographic images at 9 months (a, b) and at 18 months (c)

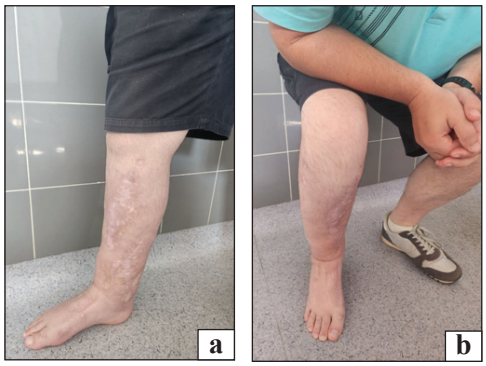


Fig. 6. Clinical photographic images of the injured limb at 18 months

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the monolateral external fixator with a circular external fixator (Fig. 9b), perform retrograde bone transport into the open wound, and use a local fasciocutaneous (“light”) flap for definitive soft-tissue coverage.

Figure 10 shows a radiographic image of the injured limb 1 year after the injury. Removal of the external fixator is planned within the next 1–2 months.

Discussion

The results of this study showed that among the bone transport techniques used, antegrade bone transport was the most common (54.84 %), followed by retrograde bone transport (38.71 %), whereas combined antegrade-retrograde bone transport was used infrequently (6.45%). Overall, these findings are consistent with those reported in the international literature [6–8]. Bone transport was performed most successfully in patients younger than 50 years with long-bone defects (77.42 %), which may be explained by the greater regenerative capacity of bone tissue in this age group. It should also be noted that bone transport was used predominantly for long-bone defects of the tibia resulting from combat-related injuries, considerably less often for the femur, and only rarely for the forearm (3.22 %). It was not used for humeral defects. In our opinion, this distribution is attributable to both the anatomical characteristics of the affected bones and the technical aspects of the surgical procedure. Data on the management of combat-related injuries of this nature remain limited and are therefore of particular value.

We also analyzed the use of bone transport according to the size of long-bone defects resulting from combat trauma. Bone transport was used in 75.81 % of patients with defects measuring 5–15 cm, with

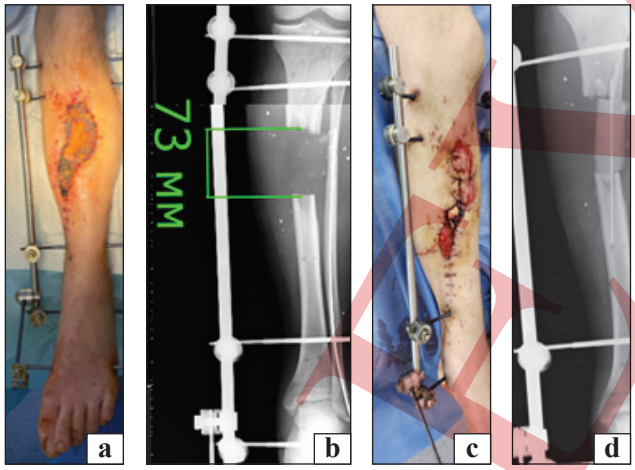


Fig. 7. Clinical photographic images of the injured limb (a) and radiograph at admission (b). Images after debridement and spacer placement (c) and radiographic image (d)

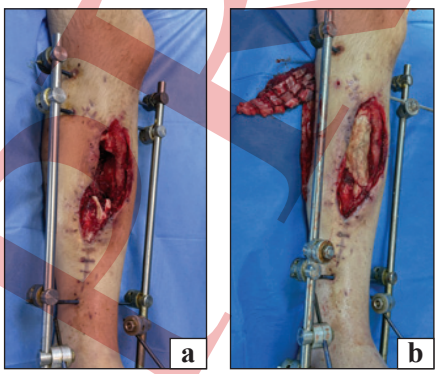


Fig. 8. Clinical photographic images at 2 weeks after treatment (a, b)



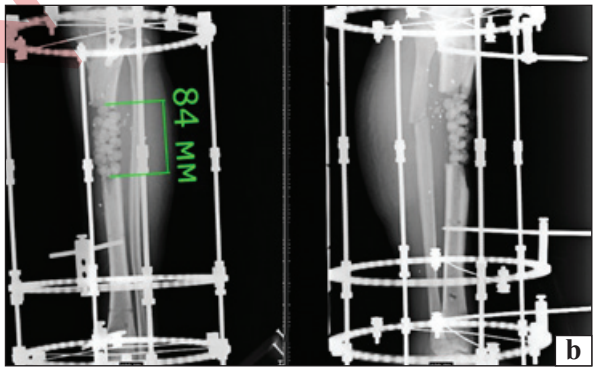


Fig. 9. Clinical photographic images of the wound at 5 weeks (a), radiograph after conversion from monolateral external fixator to circular external fixator (b)

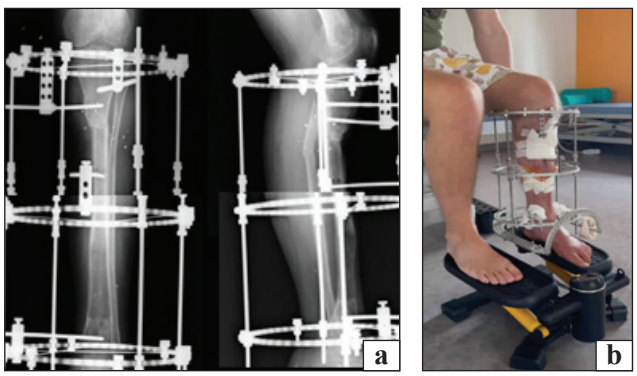


Fig. 10. Radiographic images at 1 year (a), clinical images of the patient’s limbs under functional loading (b)

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nearly equal proportions for defects of 5–9.99 cm (38.71 %) and 10–14.99 cm (37.10 %). In patients with very large defects exceeding 15 cm, bone transport was performed in 20.97 % of cases, whereas it was used only rarely (3.22 %) for defects smaller than 5 cm.

These findings indicate that bone transport is the treatment of choice for the surgical management of large and very large long-bone defects resulting from combat injuries. Although this conclusion has been reported previously by several authors [10–15], quantitative data describing the distribution of defect sizes have generally not been provided.

In a meta-analysis by K. Aktuglu et al., which included 27 studies, the pooled bone union rate was 90.2 %, demonstrating satisfactory functional outcomes in patients with critical-sized tibial defects treated using bone transport techniques [9].

In their meta-analysis, H. Wen et al. demonstrated that the use of bone transport techniques for the treatment of bone defects offers several advantages, including a shorter duration of external fixation, reduced overall healing time, fewer complications, and improved limb function [16].

The successful application of bone transport techniques, including each specific subtype, in the surgical management of long-bone defects resulting from combat injuries requires adherence to well-defined indications and selection criteria.

Conclusions

The use of bone transport in the surgical treatment of patients with long-bone defects resulting from combat trauma requires a comprehensive and well-defined set of indications to achieve successful clinical and anatomical outcomes. These indications should be based on patient age, anatomical factors, and careful assessment of the bone defect.

The key indications and selection criteria for the successful use of bone transport are patient age younger than 50 years and a bone defect measuring at least 5 cm.

Each subtype of bone transport has specific indications based on defect location. Antegrade bone transport was most successfully applied for combat-related defects of the forearm (100 %) and tibia (56.82%), retrograde bone transport for femoral defects (62.5 %), whereas combined antegrade-retrograde bone transport was used exclusively for tibial defects.

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

Future Research. Future studies are planned to evaluate other surgical techniques for the management of bone defects resulting from contemporary combat injuries.

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Author Contributions. S. O. Huriev — study conception, definition of the research objectives, and overall supervision; Hariian S. V. — preparation of the main manuscript and drafting conclusions; Kushnir V. A. — analysis of the study materials and compilation of the reference list; Tsybulskyi O. S. — data collection.

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APPLICATION OF SURGICAL TECHNOLOGIES FOR THE TREATMENT OF VICTIMS WITH DEFECTS OF LONG BONES DUE TO MODERN COMBAT TRAUMA. REPORT THREE. BONE TRANSPORT TECHNOLOGIES

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