УДК 616.718.5-001.45-018.46-002:617.584-089.844](045)

DOI: http://dx.doi.org/10.15674/0030-59872025431-38

Analysis of the application of the Masculé technique in the treatment of critical tibial defects after gunshot wounds complicated by osteomyelitis

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Despite significant progress in the development of medicine, post-traumatic osteomyelitis remains one of the biggest problems in the treatment of patients in the orthopedic and traumatology specialty. The Masquelet technique has been most often used in the treatment of chronic osteomyelitis in recent years. Given the high relevance of this problem in foreign and domestic literature, we decided to analyze our own results of treatment of patients after gunshot, shrapnel or mine-explosive wounds of the lower extremities, namely with the presence of critical tibial defects complicated by osteomyelitis under the conditions of using the Masquelet technique. Purpose. To analyze the results of application and determine the clinical and laboratory dependencies of the Masquelet technique in the case of replacement of critical tibial defects after gunshot wounds complicated by osteomyelitis. Methods. The study analyzed 153 patients with critical tibial defects after gunshot wounds complicated by osteomyelitis. Results. With the correct use of the Masquelet technology, bone graft reconstruction was achieved in all patients, the average period was (168.08 ± 62.0) days. Among the shortcomings, it is worth noting the significant dependence of the consolidation period on the condition of the soft tissues, as well as on the pathological pathogen (the presence of Klebsiella pneumoniae or Pseudomonas aureginos in the wound). The terms of consolidation and reconstruction of the bone graft were significantly extended due to these factors. However, the issue of replacing critical bone defects of the tibia after gunshot wounds complicated by osteomyelitis requires further study and comparison of existing techniques.

Незважаючи на значний прогрес у розвитку медицини, посттравматичний остеомієліт залишається однією з найбільших проблем під час лікування пацієнтів в ортопедо-травматологічній спеціальності. Методика Masquelet в останні роки найчастіше використовується під час лікування хронічного остеомієліту. Зважаючи на високу актуальність цієї проблеми в закордонній та вітчизняній літературі, ми вирішили провести аналіз власних результатів лікування пацієнтів після вогнепальних, осколкових чи мінно-вибухових поранень нижніх кінцівок, а саме з наявністю критичних дефектів великогомілкової кістки, ускладнених остеомієлітом за умов використання методики Masquelet. Мета. Проаналізувати результати застосування та визначити клініко-лабораторні залежності Masquelet-техніки у разі заміщення критичних дефектів великогомілкової кістки після вогнепальних поранень ускладнених остеомієлітом. Методи. У дослідженні проаналізовано 153 пацієнти з критичними дефектами великогомілкової кістки після вогнепальних поранень, ускладнених остеомієлітом. Результати. За правильного використання технології Masquelet перебудови кісткового трансплантата вдалось досягнути у всіх пацієнтів, середній термін складав (168,08 ± 62,0) днів. Серед недоліків варто зауважити значну залежність термінів консолідації від стану м'яких тканин, а також від патологічного збудника (присутність у рані Klebsiella pneumonie або Pseudomonas aureginos). Терміни консолідації та перебудови кісткового трансплантата значно подовжувались через ці фактори. Проте питання заміщення критичних кісткових дефектів великогомілкової кістки після вогнепальних поранень, ускладнених остеомієлітом, потребує подальшого вивчення та порівняння існуючих методик. Ключові слова. Великогомілкова кістка, Masquelet, остеомієліт, критичний кістковий дефект, інфекція.

Keywords. Tibia, Masquelet, osteomyelitis, critical bone defect, infection

Introduction

Despite significant progress in the development of medicine, post-traumatic osteomyelitis remains one of the greatest challenges in the treatment of patients in the orthopedic and trauma specialties. The issue of treating patients with osteomyelitis became particularly urgent after the onset of large-scale military actions on the territory of Ukraine. The number of people with critical bone defects has significantly increased. Consequently, the use of various techniques for their reconstruction has become even more relevant. These include the Ilizarov technique, the Masquelet technique, the transfer of the fibula, and individual titanium 3D implants.

In terms of analyzing treatment methods for patients with critical bone defects caused by modern combat injuries, there is a scarcity of publications, and a general lack of summaries, forecasts, and overall analyses. In a multicenter study of complications following gunshot wounds among the civilian population in the USA, infectious complications occurred in 9.3 % of patients. [1] According to data from the National Military Medical Clinical Center “Main Military Clinical Hospital”, from February 2022 to June 2023, gunshot fractures with bone tissue defects made up 76 % of all cases (bone defects greater than 6 cm were 25 %), and osteomyelitis was recorded in 14 % of cases. [2–4]

The sharp rise in patients with osteomyelitis linked to tibial defects has prompted doctors to not only adopt new treatment methods but also to gain experience with techniques that have long been used in specialized centers.The Ilizarov technique has once again become relevant and widespread and is currently considered the only alternative treatment in many cases. In recent years, the Masquelet technique has become one of the most frequently used procedures in the treatment of chronic osteomyelitis [1]. It consists of two surgical stages: the first involves performing sequestrectomy, and the bone defect is filled with bone cement, which is pre-saturated with antibiotics to provide local antimicrobial action and promote the formation of a foreign body “reactive membrane” over 6–8 weeks; in the second stage, after infection control, the spacer is removed, and bone reconstruction is performed to address the defect.

Given the high relevance of this issue in both foreign and domestic literature, we decided to analyze our results in treating patients after gunshot, shrapnel, or mine-explosion injuries to the lower extremities, specifically those with critical defects of the tibia complicated by osteomyelitis, using the Masquelet technique.

Objective: To analyze the results of using the Masquelet technique and determine the clinical-laboratory dependencies when replacing critical defects of the tibia after gunshot wounds complicated by osteomyelitis.

Materials and Methods

Between 2014 and 2025, 153 patients with critical defects of the tibia after gunshot wounds complicated by osteomyelitis were treated at the Bone and Pus Surgery Department of the State Institution “National Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine”. The study was approved by the Bioethics Committee (Protocol No. 6 dated 14.07.2025) of the relevant institution, in accordance with the Helsinki Declaration of Human Rights and Biomedicine, as well as current legislation in Ukraine. All participating patients signed informed consent.

Inclusion criteria for our study included:

1. Lower extremity injuries resulting from combat actions: gunshot, shrapnel, or blast injuries;
2. Critical defect of the tibia. A critical defect is defined as a segmental bone defect that exceeds its diameter by more than twice. Thus, cases with a minimum segmental defect of 4 cm were considered;
3. Presence of osteomyelitis of the tibia, confirmed by clinical, radiological, and microbiological studies;
4. Cases where the Masquelet technique was applied for the replacement of critical tibial defects.

Exclusion criteria were:

1. Other than combat-related injuries of the lower extremity that led to critical tibial defects;
2. Lack of clinical-laboratory confirmation of the osteomyelitic process in the patient;
3. Violation of the Masquelet technique at various stages of treatment;
4. Incomplete treatment cases or inability to track long-term outcomes.

After applying the inclusion and exclusion criteria, we formed a group consisting of 39 patients (37 men, 2 women), with an average age of (39.28 ± 10.16) years (ranging from 19 to 65), and performed a retrospective analysis of their treatment outcomes. The average time since injury was (215.95 ± 114.83) days (ranging from 50 to 480). Prior to hospitalization to the department, patients underwent from 2 to 17 surgical interventions.

All patients were operated on according to the Masquelet technique, which involves the following process: The goal of the first stage of the intervention is to create a biological environment free from necrotic or infected tissue by completely removing all non-viable bone and soft tissues. Improper sanitation negatively affects the quality of the formed membrane and increases the risk of infectious complications. Removal of sclerotic bone is achieved when adequate bone bleeding is obtained, ensuring the viability of the remaining bone and clinically recognized by the presence of pinpoint bleeding within the medullary canal ("paprika sign", referred to in domestic literature as "blood dew"). After proper treatment, polymethylmethacrylate (PMMA) is implanted into the defect. The cement spacer should extend about one centimeter into the intramedullary canal and protrude circumferentially above the cortical layer of the proximal and distal fragments, covering the exposed bone ends by approximately 2 cm, similar to the morphology of a joint capsule. During polymerization of the spacer, an exothermic reaction occurs, so the spacer should be covered with a wet sponge or gauze to prevent thermal necrosis of surrounding tissues. Often, antibiotics are added to the specialized bone cement powder to improve the eradication of infection at the surgical site. PMMA spacers, filled with relatively low concentrations of vancomycin (1–4 g per dose of cement), do not hinder the proliferative, osteogenic, and angiogenic capacity of the induced membranes and may even enhance them. However, spacers saturated with relatively high concentrations of vancomycin (6–10 g per dose of cement) had a negative impact on osteoblast viability and proliferation, as well as angiogenesis [5]. After the completion of the first operation, a certain period of time is required to initiate a local cascade of foreign body reactions, leading to the formation of an autologous "induced" foreign body membrane around the PMMA spacer [6].

The osteogenic potential of the membrane has been found to peak and then decrease: the expression of VEGF (vascular endothelial growth factor) sharply drops after one month, while the expression of BMP-2 (bone morphogenetic protein-2) peaks after 4–6 weeks. These data indicate that the ideal time for performing the second stage is between 4 and 6 weeks after the first stage. However, due to the variety of injuries in clinical conditions, it is not always possible to predict the timing of the next stage, as wound healing is considered a necessary condition for proceeding with the second stage. An altered soft tissue environment can also delay the formation of the membrane, making it impossible to proceed to the final surgery. However, the clinically recognized consensus is that 4–8 weeks is the ideal waiting time between the two stages of the procedure [7].

It is important to note the role of stability in the fixation of bone fragments during the first stage of surgery. The formation of the membrane is only possible if absolute stability is achieved, and this is also a key factor in eradicating infection, as an unstable cement spacer may cause soft tissue trauma and lead to the recurrence of the infectious process.

At the second surgical stage, the membrane is identified and carefully incised, ensuring access through a longitudinal incision to avoid disturbing its vascularization. The cement spacer is removed in sections using osteotomes to prevent damage to the membrane. After this, a spongy autograft is harvested and implanted into the membrane to fill the defect. The bone graft should be tightly packed, and the membrane should be closed over the graft with sutures. At the second stage, final fixation of the bone fragments is used for stabilization, as rigid fixation promotes vascularization of the graft, and in conditions of instability, the rate of nonunion and graft resorption increases [8].

If there is insufficient autograft to fill the defects, allogeneic bone grafts or synthetic compounds (such as tricalcium phosphate particles, bioglass, etc.) can be added to increase the volume. The ideal ratio between autograft and allograft remains a subject of debate. However, generally, an optimal ratio of 70 % autogenous bone and 30 % volume expanders (allogeneic bone grafts, synthetic materials, etc.) is considered standard [9]. It should be taken into account that as the proportion of so-called volume expanders increases, the rate of nonunion and infection recurrence also increases.

All patients in our sample underwent reconstruction of critical bone defects according to the principles of the technique described above. All patients were monitored with radiological control of bone graft consolidation at 6–8 weeks, 3 months, and 6 months, and subsequently every 3 months from the second stage of the intervention. Union was confirmed clinically (absence of pain under axial load) and radiologically (presence of signs of bone graft consolidation). The average duration of bone graft consolidation in cases of critical defect replacement of the tibia was (168.08 ± 62.0) days (ranging from 100 to 370). However, at the same time, we observed reduced bone density in the newly formed bone, which persisted from 1 to 4 years after treatment completion. Therefore, physical activity limitations remain for a long period, as does the prohibition of planned fixation removal from the affected segment in patients with critical bone defects.

Results

Depending on the pathogen of the infectious process in the bone defect area, identified during microbiological testing, patients were divided into the following groups: *Klebsiella pneumonia* — 7 (17.95 %), *Pseudomonas aeruginosa* — 7 (17.95 %), *Staphylococcus aureus* — 18 (46.15 %), *Acinetobacter spp.* — 2 (5.13 %), *Escherichia coli* — 4 (10.26 %), and *Proteus mirabilis* in 1 patient (2.56 %) (Fig. 1).

Classification of Bone Defects

D1 — Incomplete defect (involving a maximum of three out of four cortical layers):

– A) Up to 25 % loss of the cortical layer;

– B) Loss of the cortical layer from 25 % to < 75 %;

– C) > 75 % to 99 % loss of the cortical layer.

D2 — Subcritical defect up to 2 cm (classified by the shape of the bone fragments' ends):

– A) Two oblique ends of the bone fragments;

– B) One oblique, the other transverse end;

– C) Two transverse ends of the fragments, i. e., segmental defect.

D3 — Segmental defect of critical size (> 2 cm):

– A) From 2 < 4 cm;

– B) From 4 < 8 cm;

– C) ≥ 8 cm.

According to the bone defect classification developed by the Orthopedic Trauma Association in 2021, all patients in our study belonged to the D3B and D3C groups [10]. Despite the fact that group D3A in the classification refers to critical defects, we optimized this classification in our practice, as defects up to 3–4 cm can be treated in a single stage and, in most cases, do not require multi-stage surgical intervention. These defects also do not meet the definition of a critical bone defect (a segmental defect that is 2–2.5 times the diameter of the damaged bone) [11].

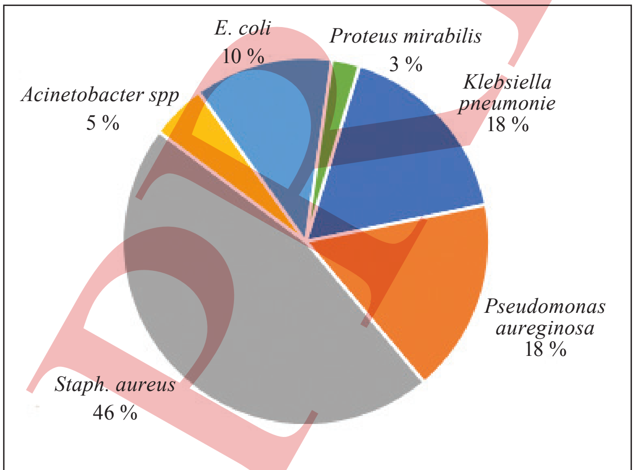

Fig. 1. Distribution of the patient group by pathogens of the pathological process

Depending on the size of the critical tibial bone defect, patients were divided into the following groups: defect size from 4 to 6 cm — 18 patients (46.15 %), from 6 to 9 cm — 13 (33.33 %), and 9 cm or more — 8 cases (20.51 %).

We also analyzed the nature of the soft tissue damage in these patients, specifically identifying the presence of skin defects, muscle injuries in the lower leg, and vascular-neurological disturbances. Thus, satisfactory skin condition was observed in 24 patients (61.54 %), significant scar transformation in 7 (17.95 %), and a defect requiring prior orthopedic replacement in 8 cases (20.51 %).

Damage to the main leg vessels and corresponding circulatory remodeling in the collateral type was noted in 12 patients (30.77 %). In 5 cases (12.82 %), damage to the fibular nerve was diagnosed, and in 2 cases (5.13 %), damage to the tibial nerve occurred. Ischemic contracture of the lower leg skeletal muscles was observed in 17 patients (43.59 %), while a muscle tissue defect was diagnosed in 5 patients (12.82 %).

The study of correlation relationships showed a moderate inverse correlation (ρ = –0.26) between the duration of consolidation and the time since injury, i.e., earlier use of the Masquelet technique was associated with delayed consolidation. A moderate direct correlation (ρ = 0.36) was observed between the duration of consolidation and the number of surgical interventions before the use of Masquelet, with a higher number of prior interventions, consolidation occurred faster. There was also a strong direct correlation (ρ = 0.8) between the duration of consolidation and the size of the defect: larger defects had slower consolidation, and the remodeling of the graft also took a longer period of time. The time since injury accounted for a significant number of surgical interventions, which indicates a moderate inverse correlation (ρ = –0.23). Additionally, it was established that with a higher number of interventions preceding the Masquelet technique (and a larger defect size), there was a moderate direct correlation (ρ = 0.34) between the number of surgeries prior to the Masquelet technique and the size of the bone defect.

The study also tracked the corresponding correlation relationships between the terms of bone graft consolidation and soft tissue damage: a moderate direct correlation (ρ = 0.36) was found between the duration of consolidation and the presence of skin and/or muscle defects; damage to the major arteries (in the presence of at least one of these factors) was associated with slower consolidation. A moderate inverse correlation ($\rho = -0.41$) was observed between the duration of consolidation and the preservation of limb innervation (in cases of fibular and tibial nerve damage) — consolidation occurred more slowly.

A moderate direct correlation was found between the number of surgical interventions and damage to the major arteries ($\rho = 0.39$) and muscle tissue defects ($\rho = 0.25$). Damage to the major arteries was accompanied by significant ischemia of surrounding soft tissues, requiring a greater number of interventions, including debridements, as well as for muscle tissue defects. Recurrences of the infectious process were observed in 6 patients (15.4 %), which required additional surgical interventions — re-sanitization and re-spacer insertion. After the second stage of treatment, critical graft resorption requiring repeat bone grafting was recorded in 3 patients (7.7 %).

Regarding the size of the bone defects, the authors noted the following: a moderate direct correlation was observed between this characteristic and the presence of skin defects, damage to major arteries, muscles, and nerves — large defects were associated with skin defects ($\rho = 0.38$), damage to major arteries ($\rho = 0.25$), muscles ($\rho = 0.55$), and nerves of the lower leg ($\rho = 0.55$).

When determining the relationships between different pathological pathogens and the duration of bone graft consolidation, as well as soft tissue damage, it was found that: a moderate direct correlation existed between the duration of consolidation and the pathogen identified during microbiological testing: in the presence of *Klebsiella pneumonia* ($\rho = 0.26$) and *Pseudomonas aeruginosa* ($\rho = 0.25$) — consolidation occurred more slowly; while a moderate inverse correlation ($\rho = -0.24$) was observed between the duration of consolidation and the detection of *Staphylococcus aureus* — consolidation occurred faster.

In cases of *Klebsiella pneumonia*, a moderate direct correlation was found between bone tissue defects ($\rho = 0.36$), skin defects ($\rho = 0.26$), and muscle tissue defects ($\rho = 0.42$). A moderate direct correlation ($\rho = 0.40$) was also noted between a higher number of surgical interventions prior to the Masquelet procedure when *Pseudomonas aeruginosa* was detected in microbiological testing.

Since *Staphylococcus aureus* is the most common pathogen in the entire group, accounting for 46 %, its presence was taken as the control group for comparing bone graft consolidation times.

The study found a significant ($p < 0.05$) difference in the duration of consolidation between the groups of patients in whom *Klebsiella pneumonia* or *Pseudomonas aeruginosa* was detected during microbiological analysis, compared to the *Staphylococcus aureus* group, with longer consolidation times in the *Klebsiella pneumonia* and *Pseudomonas aeruginosa* groups. At the same time, no significant difference was found in the duration of consolidation between the groups with *Klebsiella pneumonia* and *Pseudomonas aeruginosa* ($p = 0.45$). No significant difference was found in the duration of consolidation between the groups of patients in whom *Staphylococcus aureus* and other pathogens (except *Klebsiella pneumonia* and *Pseudomonas aeruginosa*) were detected.

Examples of control radiographic images immediately after the surgical interventions of the two-stage Masquelet procedure and 9 months after the second stage are presented in Figures 2–4.

Discussion

Considering the correlation between the duration of consolidation, the age of the injury, and the number of surgeries performed prior to the Masquelet procedure, it can be asserted that this technology involves radical surgical debridement. Indeed, the quality of the sanitation during the first stage of treatment is key to the success of this technique, especially in the presence of aggressive antibiotic-resistant microflora.

G. D. Chloros et al. claim that in case of infection, radical debridement of the bone is crucial, and the cement spacer helps create and maintain an aseptic environment until the second stage of treatment [12].

Another important factor is the presence of damage to the major arteries and the degree of trophic disturbances, which are accompanied by greater ischemia of the surrounding soft tissues and call into question the viability of certain structures, ultimately requiring more interventions (debridements and soft tissue defect replacements) to completely clear the wound of pathologically altered tissues. As a result, this leads to the elimination of the infectious process and healing of the soft tissues.

Thus, when comparing this with bone transport according to Ilizarov, where immediate debridement is not critical, the removal of all non-viable tissues, pathological granulations, and sequestrated bone fragments is mandatory during the sanitation stage when using the Masquelet technique. Proper debridement helps reduce the number of surgical interventions and the overall treatment time for patients with critical bone defects.

The key to successfully completing the second stage and achieving a positive outcome is the creation of a "foreign body membrane" around the cement-antibiotic spacer. Adequate formation of the membrane is only possible if the infection has been adequately controlled, which is ensured by the first stage of treatment.

The Masquelet technique requires good condition of the skin around the bone defect area [13]. T. Dugan and colleagues emphasize that bone reconstruction can only be performed after complete healing of any soft tissue injuries [14]. In the presence of skin and/or muscle defects, as well as damage to the major arteries, fibular, and tibial nerves, consolidation occurred significantly slower. In such cases, it is advisable to consider options for replacing the soft tissue defects or opt for an alternative treatment method.

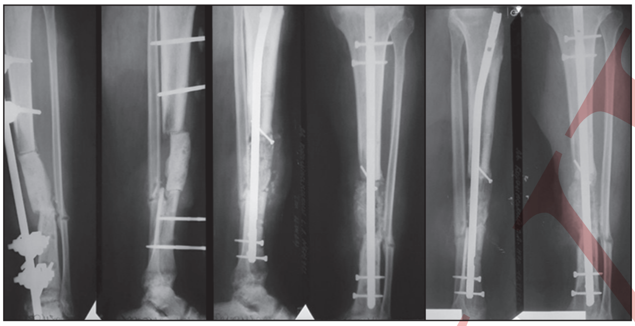

Fig. 2. Clinical case No. 1. Patient K, 35 years old, treated using the Masquelet technique, with a 9 cm defect in the tibia

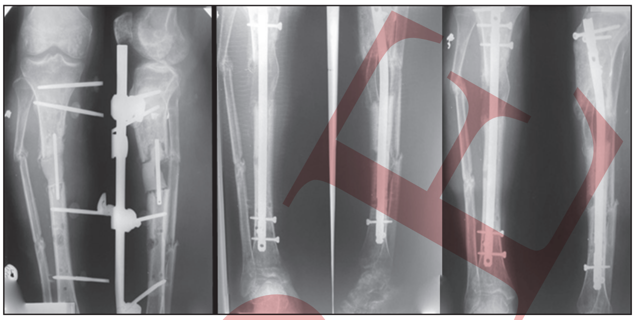

Fig. 3. Clinical case No. 2. Patient B, 42 years old, treated using the Masquelet technique, with a 5 cm defect in the tibia

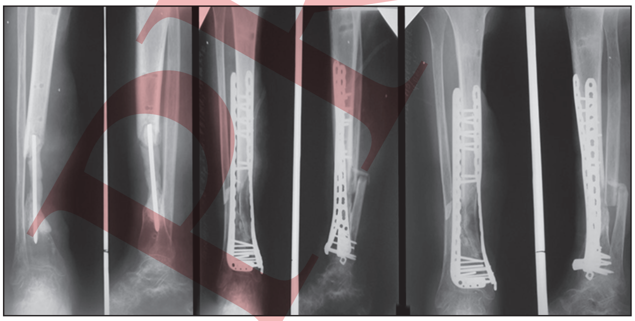

Fig. 4. Clinical case No. 3. Patient H, 29 years old, treated using the Masquelet technique, with a 7 cm defect in the tibia

A separate issue is the presence of multiresistant flora, which requires a special approach to treatment. The data presented also suggest that polystructural injuries with significant tissue defects were more often associated with the detection of the pathogen *Klebsiella pneumoniae*. The presence of *Klebsiella pneumoniae* and *Pseudomonas aeruginosa* in the wound disrupts the reparative osteogenesis processes, resulting in longer consolidation times when using the Masquelet technique. Additionally, in the case of Pseudomonas aeruginosa detection, the eradication of the pathogen requires more surgical interventions, leading to an increase in the concentration of antibiotics in cement spacers during the preparatory stages of treatment.

Conclusions

In our retrospective study, the Masquelet technique demonstrated its reliability as a method for replacing critical bone defects of the tibia after gunshot wounds complicated by osteomyelitis. When the technique was correctly applied, bone graft reconstruction was achieved in all patients, with the average healing time being (168.08 ± 62.0) days. According to our observations, the density of the regenerated bone reaches a level comparable to healthy bone at least one year after the second stage of treatment; however, in some cases, localized osteoporosis may still be observed for several years.

The advantages of the method include its effectiveness, which does not depend on patient compliance— something that is not possible with the Ilizarov technique — and the ability to achieve consolidation even for very large tibial bone defects exceeding 9 cm.

Among the disadvantages, it is worth noting the significant dependency of consolidation times on the condition of the soft tissues. In the presence of skin, muscle, and vascular or nerve bundle defects, consolidation times were significantly prolonged. Additionally, the presence of a pathological pathogen in the wound also impacts the healing process. *Klebsiella pneumoniae* or *Pseudomonas aeruginosa* significantly ($p < 0.05$) increase consolidation times and bone graft remodeling duration.

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

Prospects for Future Research. The issue of replacing critical bone defects in the tibia after gunshot wounds complicated by osteomyelitis requires further study and comparison of existing methods. A major limitation of our work was its retrospective nature, which limited more detailed examination of patients at different stages of treatment. Future research should involve prospective studies.

Funding Information. The authors declare that no financial support was received during the acquisition of results or the writing of this article.

Author Contributions. Hrytsay M. P. — conceptualization, methodology, study planning; Kolov H. B. — general editing, validity control, final approval; Polovyi A. S. — data collection, writing the original draft; Vyderko R. V. — preparation of illustrations; Hordii A. S. — supplementation of materials; Sabadosh V. I. — preparation of illustrations, supplementation of materials; Lysak A. S. — data analysis, formal (statistical) analysis, interpretation of results.

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The article has been sent to the editors	Received after review	Accepted for printing
07.08.2025	31.10.2025	14.11.2025

ANALYSIS OF THE APPLICATION OF THE MASCULÉ TECHNIQUE IN THE TREATMENT OF CRITICAL TIBIAL DEFECTS AFTER GUNSHOT WOUNDS COMPLICATED BY OSTEOMYELITIS

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