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Comparison of bone transport and acute shortening methods in the treatment of gunshot defects of the tibial diaphysis

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Abstract

Introduction The use of high-precision, high-yield munitions in modern warfare has led to an increase in the number of wounded personnel with extensive defects of the tibial shaft. Effective methods for filling such defects are the methods of G.A. Ilizarov: bifocal or trifocal osteosynthesis with subsequent transport of fragments and (or) bone segments relative to each other (referred to as "bone transport method" in foreign literature), as well as acute, gradual, or combined shortening and subsequent lengthening.

Aim of the study: To compare the efficacy and safety of the bone transport (BT) method and the acute shortening with subsequent lengthening (ASL) method for filling (elimination) of gunshot defects of the tibial shaft.

Materials and methods The study included 60 male patients aged 18 to 59 years with gunshot defects of the tibial shaft ranging from 2 to 16 cm. They were divided into two groups comparable in main characteristics, depending on the treatment method applied. In the first group (30 subjects), the tibial defect was managed using the BT method, in the second group ($n = 30$) the ASL was applied.

Results In all patients of both groups, defects were eliminated, the length of the injured lower leg was restored, and the weight-bearing function of the limb was regained. According to the criteria of consolidation time at the docking site and maturation time of the regenerate, a statistically significant advantage of the ASL method was noted. The total treatment time and the external fixation index were greater in the BT group compared to ASL, but the differences were not statistically significant. The results on the ASAMI anatomical and functional scale were statistically significantly better in the ASL group. Substantial statistically significant differences between the groups were revealed in the number and types of minor and serious complications that developed during treatment. Non-union and invagination were observed only in the BT group. Differences regarding axis deviation of the segment and contracture of adjacent joints were not statistically significant.

Discussion The identified advantages of ASL are due to the absence of drawbacks that are characteristic of BT: prolonged absence of contact between bone fragments, technical difficulties and the long duration of moving a bone segment from one fragment to another and the necessity to achieve union simultaneously in two foci of bone damage (the defect zone and the regenerate zone).

Conclusion In the treatment of patients with gunshot defects of the tibial shaft, the use of BT and ASL methods ensured effectiveness with the possibility of achieving a positive result in up to 100 % of cases. The advantage of the ASL method in terms of safety indicators (type and number of complications) compared to BT was statistically significant.

Keywords: gunshot fracture, tibial diaphyseal defect, osteosynthesis, Ilizarov technique, bone transport, acute shortening

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INTRODUCTION

The widespread use of high-precision, high-power ammunition in current military conflicts has significantly increased the severity of limb injuries, complicated treatment, and worsened treatment outcomes [1, 2]. The anatomical features of the tibia pose additional challenges in the treatment of gunshot fractures of the segment. The problem is exacerbated by diaphyseal defects which form due to the impact of damaging factors on the segment, especially in the case of blast injuries [3]. The nature of tissue changes after a gunshot wound and the dynamics of the reparative processes in the wound, as well as the treatment aimed at necrotic tissue removal and at preventing infection progression, result in the formation of a bone defect [4]. Severe soft tissue damage complicates treatment, contributes to the development of complications, and affects the anatomical and functional outcomes [5].

The determining factor in choosing a treatment method for a gunshot fracture is the size of bone and surrounding tissue defects. Tetsworth et al. developed a classification and defined the size of a critical defect (⩾ 20 mm) [6]. Most researchers consider a defect to be critical if bone integrity cannot be restored without a specific surgical intervention.

To fill defects of the tibial shaft, free bone grafting with cancellous grafts [7], Ilizarov non-free bone grafting [8], the Masquelet induced membrane technique [9], free grafting with vascularized tissue complexes based on the fibula or other bones [10] are used, but the final treatment outcome of each of these techniques depends entirely on the condition of soft tissues. Microsurgical technologies assist a lot in repair of soft tissue defects. However, extensive cicatricial degeneration of the paravulnar tissues, typical of gunshot wounds, does not always allow for the creation of the necessary conditions for the application of a microvascular anastomosis and may result in flap necrosis, subsequent enlargement of the defect and pose an issue of amputation [11, 12].

Thus, for the successful treatment of patients with gunshot defects of the tibia, a method is required that is able to create conditions for the simultaneous elimination of bone and soft-tissue defects. The Ilizarov method, which provides dynamic control of the bone tissue regeneration process, offers wide possibilities for the treatment of patients with open and gunshot fractures, as well as their complications and consequences [13, 14]. The most common technique for gunshot fractures of the tibia with bone defects is the Ilizarov non-free bone grafting [15], known in the foreign literature as bone transport (BT). Its negative features include insufficient effectiveness of the impact on soft tissues for the purpose of wound closure and the development of cicatricial changes in the defect area, which hinder the achievement of contact between the transported fragments and slow down consolidation [16].

The Ilizarov techniques of acute, gradual or combined shortening followed by lengthening have not been so frequently used [17, 18], which, unlike BT, are characterized by shortening the limb segment in the area of the bone defect in order to achieve contact between the fragments as fast as possible [19]. The length of the shortened segment is restored by distraction after the signs of union in the area of contact of the fragments appear or after osteotomy of one or two fragments followed by distraction using bi- or polylocal osteosynthesis. A major advantage of acute shortening compared to BT is an early contact between the ends of the fragments with the possibility of simultaneous closure of the wound, which promotes rapid consolidation [20].

The available literature contains a few publications devoted to the use of acute shortening followed by lengthening (ASL) for gunshot fractures and gunshot defects [17]. The overwhelming majority of sources are studies of bone defect management for severe chronic infectious complications. In this regard, it is noted that the extent of possible correction is limited by the condition of the soft tissues and vascular bed. Most authors consider the presence of a defect of up to 5 cm to be an indication for the use of ASL, and those over 5 cm to be an indication for the use of BT.

A gunshot defect forms relatively fast before significant cicatricial changes in the soft tissues of the segment and vascular sclerosis develop. Given this, the possibility of safely repairing (eliminating) defects larger than 5 cm using ASL is promising.

Study hypothesis The ASL technique may be more effective and safer than the BT technique for eliminating gunshot defects of the tibia diaphysis longer than 4 cm (severe and massive defects according to the classification of Tetsworth et al. [6]) in the early stages after injury before the development of cicatricial changes in the soft tissues of the lower leg and fibrosis of the vascular bed.

Aim of the study: To compare the efficacy and safety of the bone transport (BT) method and the acute shortening with subsequent lengthening (ASL) method for filling (elimination) of gunshot defects of the tibial shaft.

MATERIAL AND METHODS

Study design: A single-center, open, prospective, comparative study approved by the institutional ethics committee of the Burdenko Main Military Clinical Hospital (Protocol No. 266 of May 24, 2023).

The study included 60 patients with gunshot defects to the tibia, divided into two groups of 30 patients (Table 1):

— Group 1: patients whose defects were treated using the BT technique;

— Group 2: patients whose defects were treated using the ASL technique.

Osteosynthesis in both groups was performed with the Ilizarov external fixator (EF), a wire-and-halfpin type.

Table 1

Basic characteristics of the groups

Parameters		Group 1 (BT), *n* = 30	Group 2 (ASL), *n* = 30	*p*
Age, years		33.0 ± 8.0	32.6 ± 9.2	0.835[1]
Bone defect size, mm		83.9 ± 30.3	82.7 ± 29.5	0.877[1]
Ratio of the defect size to tibia length, %		21.3 ± 7.6	21.1 ± 8.0	0.922[1]
Skin defect, cm^2 (interquartile range)		56.5 (80)	42.0 (103)	0.990[2]
Time to reconstructive surgery, days (interquartile range)		80.5 (46)	23.5 (26)	**< 0.001[2]**
Time of soft-tissue defect closure, days		73.2 ± 29.4	31.9 ± 20.1	**< 0.001[1]**
Bone defect size according to the classification of Tetsworth et al. [6], mm	21–40	3 (10.0 %)	3 (10.0 %)	0.876[3]
	41–80	13 (43.3 %)	12 (40.0 %)	
	> 80	14 (46.7 %)	15 (50.0 %)	

Notes: [1] — Student’s t-test; [2] — Mann – Whitney U test; [3] — Pearson's χ^2 test

Inclusion criteria: male gender; age from 18 to 59 years; critical-size gunshot defect of the tibia diaphysis longer than 2 cm; patient consent to participate in the study; dynamic follow-up study for at least 3 years.

Exclusion criteria: female gender; age under 18 and over 59 years; intra-articular fractures of the tibia, bone fractures of adjacent segments of the injured limb, severe concomitant injuries to other areas (head, spine, pelvis) that hinder or exclude the possibility of patient activation, chronic diseases that affect bone tissue regeneration; patient refusal to participate in the study; unavailable dynamic follow-up study.

Statistical analysis The analysis was performed in SPSS. The Shapiro–Wilk test was used to check the normality of quantitative variables. Normally distributed quantitative variables were described using the mean and standard deviation $\overline{x}$ (±), while abnormally distributed variables were described using the median and interquartile range Me (IQR). Comparison of quantitative variables with a normal distribution was performed using the Student's t-test for independent samples, and with an abnormal distribution using the Mann – Whitney U-test. Qualitative variables are presented as absolute values and percentages. Group comparisons for qualitative variables were performed using the Pearson χ^2 test. Differences were considered statistically significant at $p < 0.05$.

In the overwhelming majority of cases in both groups, there were severe ($n = 13$ for BT, $n = 12$ for ASL) and massive defects ($n = 4$ and $n = 15$, respectively). However, no statistically significant differences in these parameters were found between the groups ($p = 0.876$).

Bone defect sizes were comparable in both groups, both an absolute size and as a percentage of tibial length ($p = 0.877$ and $p = 0.922$, respectively). Bone defects in both groups typically had a dual nature: a primary defect resulting from injury and a secondary defect resulting from a series of surgical debridements aimed at removing necrosis and preventing (controlling) infection. The final defect size was determined after additional resection during reconstructive surgery to ensure contact between fragments during BT or ASL procedures. No statistically significant differences were observed between the groups in terms of the area of soft-tissue defects.

Patients in Group 1 underwent surgical treatment aimed at wound closure prior to BT with specific techniques. The following procedures were used: local tissue grafting (nine patients); split-thickness skin graft (six); free full-thickness skin flap (one); vascularized flap (six); and a combination of techniques (eight).

In 19 patients in Group 2, wound closure was performed using local tissues simultaneously with acute shortening (AS), local grafting was additionally used in eight patients, and split-thickness skin grafting was used in three patients. The need for an additional preliminary surgery in the BT group resulted in significant differences in the timing of reconstructive surgery. In the BT group, reconstructive surgery (osteotomy) was performed on average on day 80.5 (46), while in the case of ASL (approximation of fragments) it was performed on day 23.5 (26) ($p < 0.001$).

Based on the comparison of baseline characteristics, it can be concluded that the groups were homogeneous in all clinically significant aspects. The study patients were followed for at least one year after removal of the external fixator.

The decision on treatment tactics was made by the surgeon based on the clinical presentation, characteristics of each individual case. Total bone loss was calculated as the sum of the bone defect length and the magnitude of any limb length discrepancy, if any.

The effectiveness of the methods used was assessed based on clinical and radiographic studies. Total healing time was defined as the time from injury to removal of the external fixator after convincing radiographic evidence of consolidation of the fragments at the docking site and maturation of the distraction regenerate, as well as restoration of limb weight-bearing function. The radiographic maturation time of the distraction regenerate was determined according to the criteria of Fischgrund et al. [21]. In addition, the time of external fixation and the external fixation index (EFI) were calculated separately, which was calculated by dividing the time of external fixation by the length of the regenerate (months/cm).

Clinical outcomes were assessed based on anatomical and functional parameters in accordance with the scoring system of Paley et al. [22].

The safety of the method was determined based on complications that developed during treatment, categorised as minor (managed with conservative measures), serious (surgical treatment was used), or sequelae (not resolved during treatment) [23].

BT technique has three stages.

The first stage begins after the injury and involves preparing for bone fragment(s) transport in the defect area. The lower leg is fixed with a halfpin-based external fixator (EF); surgical debridement is performed to remove necrotic tissue, foreign bodies, and small bone fragments, and conservative treatment is administered to control infection and minimize the defect. The resulting wound and exposed bone fragment parts are closed using a skin grafting technique.

The second stage begins after the wound has healed and continues while the fragment is being transported. For this purpose, an Ilizarov halfpin-based fixator is placed, and an osteotomy of one or both fragments is performed. After 7–10 days, fragment(s) transport is performed.

The third stage of treatment starts when contact is achieved between the fragment(s) and/or fragments. During this transport of bone fragment(s), osteochondral formations at their ends, and in some cases, invagination occur. To create conditions for consolidation, the pseudoarthrosis area is resected, and the ends of the fragment(s) and the fragment are brought together and compressed. In cases of hypotrophic pseudoarthrosis, bone grafting is performed with free autograft. The third stage ends with bone union at the docking site between the fragment(s) and the fragment and the maturation of the regenerate(s).

ASL technique also has three stages.

The first stage begins at the moment of injury and involves preparing the wound for reconstructive surgery. The leg is fixed with a halfpin-based external fixator. Surgical debridement is performed, followed by conservative treatment aimed at controlling infection and minimizing the defect.

The second stage begins with reconstructive surgery (shortening) and is completed when convincing signs of bone union appear.

The third stage starts with osteotomy of one or two fragments and distraction to form the regenerate(s) until the segment length is restored. It ends with consolidation and ossification of the regenerate(s).

ASL intervention

Necrotic tissue remnants are excised, and the ends of the tibial fragments are resected until a "blood dew" appears perpendicular to the tibial axis to increase the stability of the osteosynthesis. If necessary, the fibula is resected to the length of the tibial defect. An Ilizarov halfpin-based fixator is applied to approximate the bone fragments. Once contact is achieved, the pulsation of the arteries in the foot is assessed, and pulse oximetry is performed to determine the state of blood circulation. If signs of ischemia are detected, partial separation of the fragments is performed until the ischemia is eliminated, followed by a gradual (2–3 cm per day) approximation until complete contact is achieved. Shortening of the tibia results in approximation of the wound edges and closure of the defect by grafting with local tissues.

RESULTS

The analysis of treatment time revealed considerable differences between the BT and ASL techniques. The consolidation time at the docking site was statistically longer in the BT group as compared with the ASL group (459.2 ± 99.6) days versus (217.7 ± 67.7) day, $p < 0.001$. This difference can be explained by the features of the BT technique in which an additional time for contact between the transported fragment and the docking site fragment and by the need to overcome osseochondral formation and invagination (Table 2).

The time of regenerate formation and maturation was also significantly longer in BT (326.8 ± 95.7) days versus (228.6 ± 93.5) days in ASL, $p < 0.001$. This difference, in our opinion, may be due to the fact that at least three centers of regeneration are formed in BT, the end of the fragment, the opposing end of the transported fragment, and the regenerate itself. Osteogenesis in these zones in reduced regenerative potential may not meet the needs of the body.

The total treatment time and fixation time did not show statistically significant differences between the groups ($p = 0.09$ and $p = 0.695$, respectively). However, on average, the duration of treatment was

45 days shorter in ASL patients. One of the important factors may be the delay in wound closure associated with the need for additional surgery at the initial stage of treatment. Accordingly, the EFI was also lower in ASL (45.8 (29.8)) compared to BT (50.0 (13.6)), while the Mann – Whitney criterion was 0.506.

Table 2

Treatment results

Parameters	Group 1 (BT), $n = 30$	Group 2 (ASL), $n = 30$	p
Consolidation time at the docking site, days	459.2 ± 99.6	217.7 ± 67.7	**< 0.001**^{1}
Time of formation and maturation of regenerate, days	326.8 ± 95.7	228.6 ± 93.5	**< 0.001**^{1}
Total treatment time, days	474.3 ± 95.0	429.0 ± 108.2	0.09^1
Fixation time, days	398.1 ± 108.9	388.5 ± 78.2	0.695^1
External fixation index, days/cm (interquartile range)	50.0 (13.6)	45.8 (29.8)	0.506^2
Anatomical results, ASAMI points (interquartile range)	4.5 (1.0)	5.0 (0.0)	**0.011**^{2}
Functional results, ASAMI, points (interquartile range)	3.0 (1.0)	4.0 (2.0)	**0.003**^{2}

Notes: ^{1} — Student's t-test; ^{2} — Mann – Whitney U test

In regard to the ASAMI score, the ASL group showed significantly better results. Thus, the median values of anatomical results in the ASL group were 5.0 (0.0) points versus 4.5 (1.0) points in the BT group ($p = 0.011$), and functional results were 4.0 (2.0) and 3.0 (1.0) points, respectively ($p = 0.003$).

The rate of complications differed significantly between the groups. Minor complications were more frequent in the BT group, (7.6 ± 2.7) cases per patient during treatment compared to (3.7 ± 2.4) in the ASL group ($p < 0.001$). Serious complications also prevailed in the BT group, 5.0 (3.0) cases versus 0 (1.0) in the ASL group (p < 0.001). Nonunion was observed only in the BT group, 23 (76.7 %) cases compared to their complete absence in the ASL group ($p < 0.001$). This critically important difference indicates a fundamental problem of the BT method, a high risk of pseudarthrosis at the docking site. Invagination was also characteristic only of the BT group, 19 (63.3 %) cases ($p < 0.001$), which is a specific complication of this method. This distribution of complications is explained by the long period of fragment transport after osteotomy until docking in the BT method and the need for additional surgical interventions to eliminate obstacles to union. Differences in the rate of other complications (axis malalignment and joint contractures) were not statistically significant. However, these complications affected the anatomical and functional results (Table 3).

To demonstrate the peculiarities of the Ilizarov techniques used for extensive defect management, we would like to show clinical reports.

Table 3

Complications

Complication type	Number		p
	Group 1 (BT), $n = 30$	Group 2 (ASL), $n = 30$	
Minor complications, number per patient	7.6 ± 2.7	3.7 ± 2.4	**< 0.001**^{1}
Severe complications, number per patients (interquartile range)	5.0 (3.0)	0 (1.0)	**< 0.001**^{2}
Nonunion, number (%)	23 (76.7)	0 (0)	**< 0.001**^{3}
Invagination, number(%)	19 (63.3)	0 (0)	**< 0.001**^{3}
Axial malalignment, number(%)	13 (43.3)	9 (30.0)	0.422^3
Knee and (or) ankle joint contracture, number(%)	24 (80)	17 (56.7)	0.209^3

Notes: ^{1} — Student's t-test; ^{2} — Mann – Whitney U test; ^{3} — Pearson's χ^2 test

Clinical reports

A 32-year-old patient (group 1) sustained injuries during combat operations: combined blast injury to the head and extremities; flame burns to the head, face, both hands, and both lower extremities, grades 2-3A-3B, S = 14 (6%); cerebral contusion; contusion of the left eyeball, penetrating corneal wound, scleral rupture, foreign body in the anterior chamber of the left eye; a through-and-through wound of the soft tissues of the left forearm; lacerated wound of the left hand, comminuted fracture of the middle phalanx of the 5th finger; **extensive lacerated wound of the left lower leg**, comminuted fracture of both bones in the upper and middle third with primary bone and soft tissue defect; traumatic shock, grade 3.

During the evacuation stages, treatment was aimed at stabilization of disorders and wound healing.

After stabilization of the condition and healing of the wounds on the left lower leg (Fig. 1), 72 days after the injury, an operation was performed: external transosseous compression-distraction osteosynthesis (Ilizarov method) of the left lower leg, osteotomy of the distal fragment of the left tibia. The tibial bone defect was 15 cm. On the 79th day after the injury, fragment transport was initiated to form a regenerate and fill the defect. On the 164th day after the injury (85 days after the osteotomy), in order to correct the position and direction of the fragment transport, the Ilizarov frame on the left lower leg was reassembled. The transport of the distal tibial fragment continued (Fig. 2).

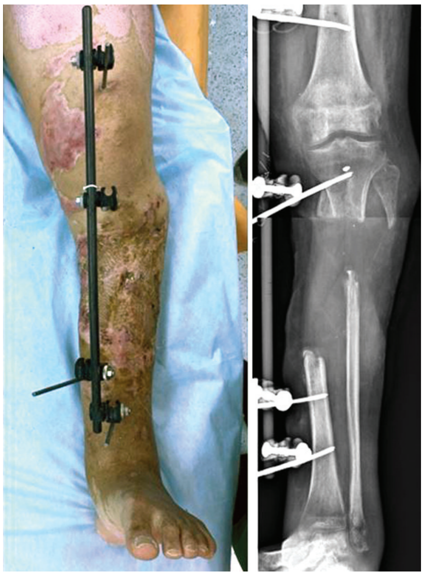

Fig. 1 Photo and radiograph of the left lower leg before the reconstructive operation

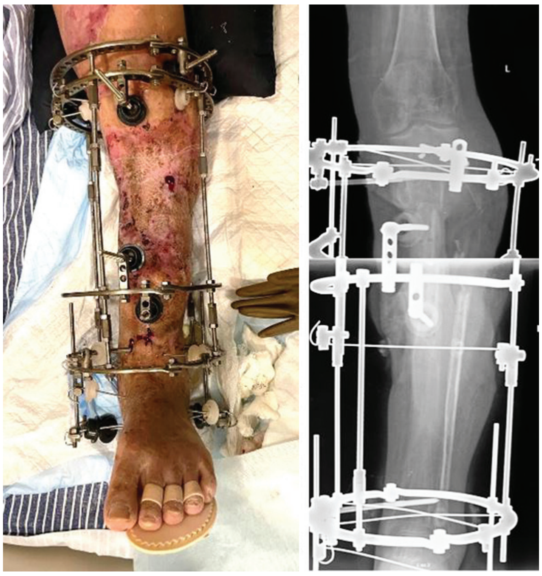

Fig. 2 Photo and radiograph of the left lower leg in the course of bone transport

On the 261st day after the injury (182nd day after osteotomy), contact was noted between the transported fragment and the proximal fragment through the invagination zone (Fig. 3). In order to ensure docking between the proximal fragment and the transported distal fragment, on the 262nd day after the injury (183rd day after osteotomy), resection of the invagination zone and the osteochondral area at the end of the proximal fragment and the transported fragment was performed, followed by open reduction of the fragments and reassembly of the Ilizarov fixator. Docking was achieved between the end parts of the proximal fragment and the transported fragment (Fig. 4). Subsequently, compression was produced between the proximal fragment and the fragment, and "regeneration training" was carried out using the "accordion" method.

Union between the proximal fragment and the transported fragment, as well as maturation of the regenerate, was noted on the 493rd day, and the Ilizarov fixator was removed (Fig. 5). Rehabilitation continued for 60 days (Fig. 6).

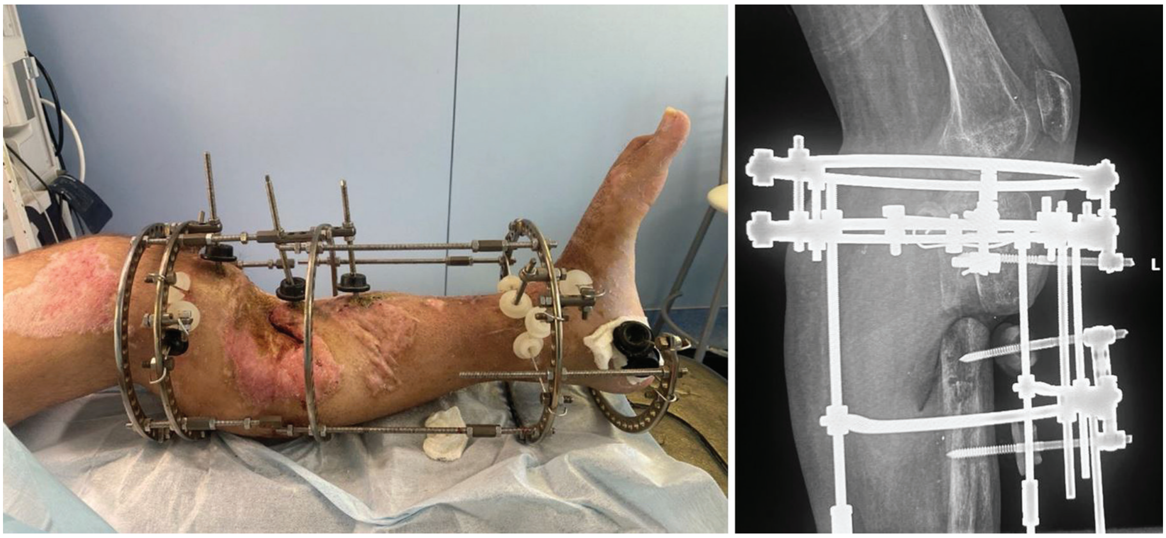

Fig. 3 Photo and radiograph of the left lower leg at the approximation of the proximal and transported fragments (invagination)

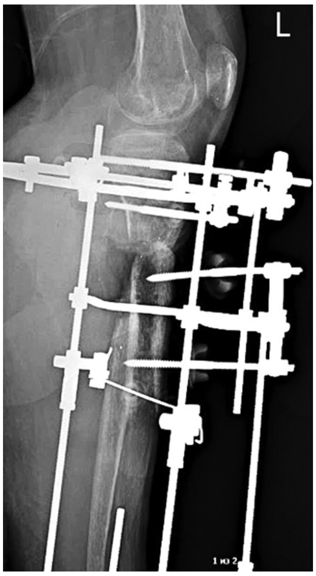

Fig. 4 Radiograph of the left lower leg following the surgery for invagination elimination, pseudarthrosis end resection and bone reduction, rearrangement of the Ilizarov fixator

Fig. 5 Full-length radiograph of the lower limbs upon treatment completion

Fig. 6 Patient weight-bearing on the left lower leg and its flexion in the left knee joint

The total treatment term was 553 days, external fixation duration was 43.7 days/cm, the ASAMI anatomical result was fair, and the ASAMI functional score was good.

A 44-year-old patient (group 2) sustained injuries while participating in combat operations: combined blast injury of the pelvis and both lower extremities; multiple shrapnel wounds of the perineum and lower extremities. **Extensive lacerated wound of the right lower leg, comminuted fracture of both bones in the upper and middle third with a primary bone and soft tissue defect** (Fig. 7). Extensive lacerated wound of the left foot associated with fractures of the 1st and 2nd metatarsal bones. Acute massive blood loss. Traumatic shock grade 2. Acute kidney injury.

During the evacuation stages, treatment was aimed at compensating for the disorders and wound healing.

After stabilization of the patient's condition and restoration of kidney function 34 days after the injury, a repeated surgical debridement of the wound was performed, including necrectomy of the tibia and fibula, external fixation of the right lower leg with the Ilizarov external fixator. The tibial bone defect was 11 cm (Fig. 8).

Signs of bone union were detected on day 126 after the injury (on the 92nd day after external fixator placement), and an osteotomy was performed in the lower third of the tibia (Figs. 9 and Fig. 10a).

The lengthening procedure continued 137 days after the shortening one (Fig. 10b) until the 263rd day after the injury (Fig. 10c). Bone union in the fracture contact zone was noted on the 192nd day after the initial surgery. Subsequently, "regenerate training" was performed using the "accordion" method. Maturation of the regenerate was noted 108 days after the cessation of lengthening. On the 371st day after the injury, the external fixator was removed. Rehabilitation continued for 60 days (Fig. 11).

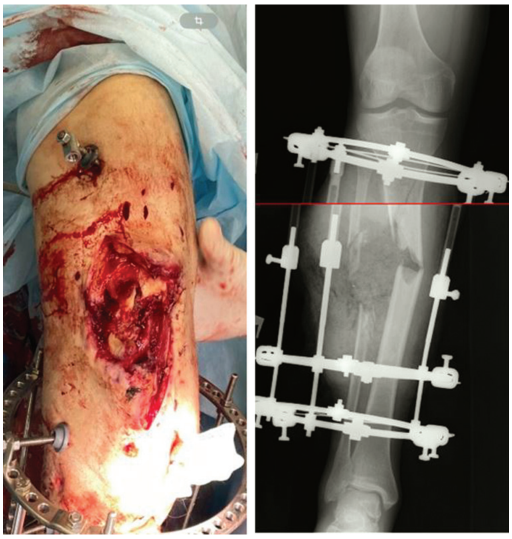

Fig. 7 Photo and radiograph of the right tibia upon admission

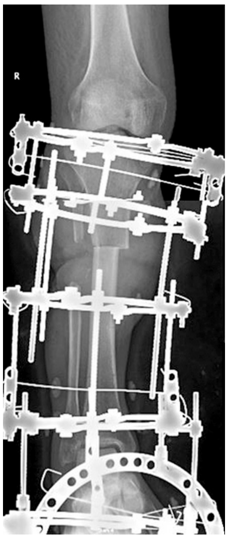

Fig. 8 Radiograph of the right tibia upon acute shortening phase

Fig. 9 Photo of the right tibia before performing osteotomy

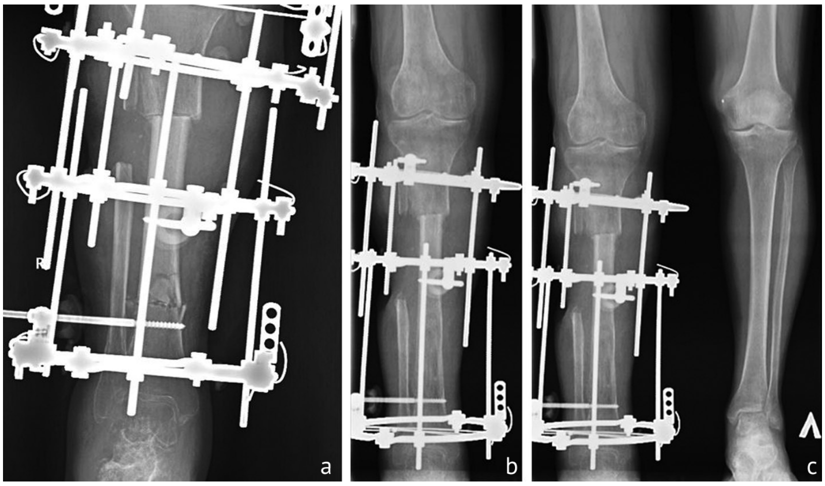

Fig. 10 Radiographs: (a) right tibia after osteotomy; (b) right tibia in the course of lengthening; (c) both tibias after lengthening of the right tibia

Fig. 11 Full-length radiograph and photo of the lower extremities upon treatment completion

Total treatment term was 431 days; EFI was 29.7 days/cm. Residual shortening made 2 cm. The anatomical ASAMI result was good and the functional ASAMI outcome was good.

DISCUSSION

In any pathology for which several treatment methods are available, the main issue is choosing the optimal method in each specific case. The size of the gunshot defect of the tibia serves as the main criterion for determining the indications for the choice of treatment tactics. In the available literature, we found recommendations according to which bone defects >10 cm should be corrected by BT [24], and bone defects < 8 cm by ASL [19]. These recommendations are based on a study of the experience of treating patients with the consequences and complications of open infected fractures. In such cases, reconstructive surgeries were performed a long time after the injury had been sustained and due to osteomyelitis, resulting in the formation of extensive cicatricial conglomerates in the bone defect area. Such changes cause technical difficulties during the surgery, increase the risk of intraoperative iatrogenic complications, ischemic disorders in the distal limb, and limit or make simultaneous approximation of fragments impossible. If ASL is used before fibrosis in the surrounding tissues has developed, safe fragment approximation is possible; it was confirmed by our observations and calculations. The maximum bone defect size in the BT group was 160 mm, while in the ASL group it was 140 mm, corresponding to 40% and 36.3% of the tibia length, respectively. Fragment approximation was achieved without distal ischemia. However, the elimination of the defect with BT technique during fragment transport occurs simultaneously with the formation of an interfragmentary scar, which may lead to nonunion at the docking site, invagination, and necessitates rearrangement of the external fixator and other surgeries aimed at combating complications.

Skin defects also have a significant impact on treatment decisions. Their size was comparable in both groups. BT requires preliminary preparation, including special wound closure procedures, which increases the work of the staff, the number of surgeries, and prolongs the overall treatment period. Our study revealed that the ASL technique is optimal, allowing for simultaneous bone deficiency elimination due to bone mass loss, coverage of the exposed bone, and wound closure.

When the fibula was intact and all other conditions were equal, we preferred BT, as this method preserves the true segment length, the relationships in the proximal and distal tibiofibular joints, and the relationship between the bone and tendon-muscle structures, which should positively impact the final functional outcome. Furthermore, fibula resection is an additional trauma and can lead to iatrogenic complications such as damage to arteries, veins, and nerve trunks. The presence of a fracture, and especially a fibula defect, predetermines greater freedom of choice and can serve as an additional justification for the ASL use. Attempts to manipulate fibula fragments during BT significantly complicate the procedure. However, in some cases, at certain BT stages, we also performed fibula osteotomy or resection to stimulate regeneration in the area of contact between fragments or regenerated bone.

Treatment strategy also determines timeframes. In our study, the total treatment duration in the BT group was longer than in the ASL group. This is due to a number of factors:

— Before starting BT, additional preliminary conservative and surgical treatment is necessary to close the wound; in ASL implementation, wound closure occurs immediately.

— The healing time at the contact zone of the fragments in ASL is slightly longer than that of a conventional fracture, 217.7 ± 67.7 days. In BT, the healing began upon reaching contact and was delayed due to the developed morphological changes similar to nonunion at the ends of the fragments, and took 459.2 ± 99.6 days. This, in turn, required 19 additional surgeries for invagination, 16 of which involved bone grafting.

— Fragment transport in BT is a more complex and time-consuming procedure, less comfortable for the patient than lengthening in ASL. The use of the BT method requires more care procedures by the medical staff and additional operations both during the actual transport to correct the fragment's position and direction of its movement (EFD rearrangement was performed in 24 patients) and during the docking of the fragments (bone grafting, elimination of invagination). In this regard, Tetsworth et al. introduced a planned bone grafting operation into the standard BT protocol when the contact is 1-cm distanced [25].

The specific features of the BT technique predetermine the development of specific complications common to all Ilizarov techniques.

The statistically significant advantage in the ASL technique in our study can be explained by the following factors:

— Early closure of a primarily infected gunshot wound prevents infection in the postoperative period and in the medium term.

— Early stable fixation of the external fixator (EF) system when contact between the fragments provides better conditions for bone and soft tissue healing.

— Transport of the bone fragment during BT further traumatizes the surrounding tissue, which also leads to complications, including those specific to BT (invagination, nonunion).

Managing complications make the treatment process more difficult and delays defect repair (removal and replacement of transosseous elements, rearrangement of external fixators, surgical debridement of suppurative foci, etc.).

Unlike other researchers, we found convincing, statistically significant differences in anatomical and functional outcomes between the groups. This is primarily explained by the differences between the observation groups in our study and those in the studies of other authors (groups of acute gunshot fractures with acute infection versus groups of sequelae and complications of open fractures with chronic infection and corresponding tissue degeneration of the segment). However, functional recovery largely depended on concomitant damage to functional tissues such as muscles, tendons, and nerves.

The results of our study demonstrate the fundamental advantages of the ASL technique over BT in the treatment of gunshot tibial defects:

— faster consolidation due to the immediate contact between the viable ends of the fragments;

— significantly lower complication rates;

— better functional outcomes with comparable overall treatment time.

CONCLUSION

The study results suggest that both methods of tibial shaft defect repair based on Ilizarov's discovery (bone transport or acute shortening and then lengthening) have the potential to achieve positive results, including in critical-size defects, when limb preservation is at stake after a gunshot fracture with an extensive defect of the bone and integumentary tissues.

However, in acute gunshot fractures of the tibia with primary and secondary soft-tissue defects and the tibia up to 40 % of its length, acute shortening followed by lengthening is preferable to the bone transport technique. The advantages of acute shortening include shorter treatment times, lower incidence of minor and major complications, a reduced number of planned and emergency surgeries and procedures during treatment, and simplified surgical techniques and treatment technologies.

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Ethical statement *All studies on humans were conducted in accordance with the ethical standards of the World Medical Association Declaration of Helsinki "Ethical Principles for Medical Research Involving Human Subjects" and the "Rules of Clinical Practice in the Russian Federation", approved by Order of the Ministry of Health of the Russian Federation dated June 19, 2003, No. 266.*

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