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Research Article

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Repair Of Critical Defects of the Humerus After Combat Trauma Using a Combination of Bioceramics and Bone Autograft with the Use of Stable Orif in the Second Stage of the Masquelette Method

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ABSTRACT
In recent years, Ukrainian traumatologists have been facing a significant number of cases involving the consequences of combat-related injuries, particularly large segmental bone defects of critical size. The treatment of such injuries has become an immense burden for our healthcare system and medical professionals.

Keywords: Critical Defects, Bioceramics, Bone Defect, Induced Membrane

Introduction

In recent years, Ukrainian traumatologists have been facing a significant number of cases involving the consequences of combat-related injuries, particularly large segmental bone defects of critical size. The treatment of such injuries has become an immense burden for our healthcare system and medical professionals. These injuries carry serious clinical and socio-economic implications, with treatment outcomes often limited by high complication rates, repeated surgical interventions, and unsatisfactory functional recovery [1,2].

Currently, there is still no consensus regarding the definition of critical-sized bone defects, the selection of reliable experimental models, or the optimal surgical approaches for their management [3-5]. In this work, we review the current perspectives on this issue, focusing on the definition of critical-sized bone defects, the application of the induced membrane technique, and the use of stable osteosynthesis combined with bone grafting.

Aim

To demonstrate the versatility, safety, advantages, and limitations of reconstructing critical bone defects following combat-related injuries using a combination of ceramic material and autogenous cancellous bone grafts, applied in the second stage of the Masquelet technique with various types of internal osteosynthesis, based on the example of treating post-gunshot humeral fractures.

Materials and Methods

Definition of "Critical" Bone Defect

The etiology of bone defects is diverse, and there are many classifications that take into account the size of the defect; however, there is no unified definition of what constitutes a critical-sized bone defect [6,7].In general, a "critical size" defect is considered one that does not heal spontaneously despite surgical stabilization and requires further surgical intervention, such as autologous bone grafting [8,9].The most common definitions in the literature describe a critical defect as one greater than 1–2 cm in length and involving more than 50% loss of the bone circumference [10,11]. However, the anatomical location of the defect and the condition of the surrounding soft tissues play an important role in healing potential. There are many factors influencing the spontaneous healing ability of bone defects, including their critical size, anatomical location, soft-tissue environment, the patient's age, and comorbidities [12-15].

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Summarizing the above, critical-sized bone defects require reconstruction, and the gold standard remains an autogenous bone graft harvested from the iliac crest. However, there are numerous limiting conditions, making it essential to determine which defects require additional procedures and which alternative biological methods of treatment should be selected.

Many factors influence the choice of treatment method. According to the literature, as shown by Haines et al., in open tibial shaft fractures with defects greater than 2.5 cm treated with intramedullary nailing, the defect size and infection were the main determinants of the outcome [6,15].

The study concluded that spontaneous union did not occur in more than half of the patients. A review of the literature allows us to confidently state that, to date, there is no consensus regarding the definition and treatment of critical-sized bone defects.

Induced Membrane (Masquelet) Technique

When analyzing treatment methods for critical bone defects, the following approaches are most commonly discussed: bone transport using external fixation devices according to the Ilizarov method or other external fixators, vascularized bone autografting, implantation of artificial biomaterials, and the induced membrane (Masquelet) technique [14,16,6].

The induced membrane technique allows for control of the post-traumatic bone cavity, reduction of infection risk, stabilization of bone fragments during soft-tissue healing, and the formation of a biologically active membrane that stimulates bone regeneration.

This is a two-stage technique:

- Stage I involves adequate surgical debridement of the bone and soft-tissue defect, stabilization of bone fragments, and placement of a polymethylmethacrylate (PMMA) spacer containing antibiotics at the site of the bone defect. The PMMA spacer induces the formation of a biologically active pseudomembrane that preserves the space for subsequent bone grafting.
- Stage II generally consists of filling the defect after spacer removal with various types of bone grafts and, if necessary, correcting the metal fixation [8,17-18].

Stafford and Norris demonstrated that combining intramedullary canal reaming autografting with the Masquelet technique for segmental bone defects achieved a union rate of 70% at 6 months and 90% at 12 months in 25 cases, with an average defect length of 5 cm [6,19,11]. To minimize the required graft volume and prevent central necrosis, some authors recommended using a mesh framework and intramedullary nail to fill the medullary canal [13,20,21].

We selected the induced membrane technique for reconstruction of critical bone defects due to the following advantages: better postoperative quality of life compared with bone transport using external fixation devices, and a lower rate of postoperative complications. The technique of vascularized fibular grafting was used when microsurgical vascular anastomoses were feasible and was most commonly performed for reconstruction of forearm bone defects.

Use of Bioceramics

The use of bone-grafting materials in the management of critical bone defects remains a pressing issue, for which no clear criteria currently exist. This applies to the indications for allograft or composite use. Although autogenous cancellous bone grafting yields the best results, in clinical practice traumatologists often face the problem of insufficient autograft volume (especially considering the critical size of defects). Furthermore, large-volume autografting is associated with local aseptic necrosis [3,16,10].

To address these challenges, alloplastic materials such as bioceramics and bioglass are increasingly employed [22,13,7].

In our practice, bioglass was used to fill cavitary defects of non-critical size or those located in metaphyseal areas (due to its shorter resorption period compared with bioceramics). For critical diaphyseal defects of the humerus, a mix of bioceramics and autogenous cancellous bone was preferred, as it allowed:

- An increase in graft volume
- Addition of osteoinductive properties to the bioceramic material.
- Synchronization of bioceramic resorption time with bone consolidation periods.

The bioceramic material used to fill the membrane consisted of porous granules (3–4 mm) composed of three biocompatible phases: 65 wt.% hydroxyapatite, 30 wt.% β-tricalcium phosphate, and 5 wt.% α-tricalcium phosphate, doped with silicon to provide osteoinductive properties. To maintain the shape of the graft and allow impaction, polymer and titanium meshes were used as structural frameworks.

Practical Material

To evaluate treatment outcomes for critical bone defects, we selected patients with post-combat humeral injuries treated with a mixture of bioceramics and autogenous cancellous bone graft using internal fixation during the second stage of the Masquelet technique.

The study included 27 patients with critical humeral bone defects ranging from 4 to 13 cm in length (mean 6.9 cm), involving the full diameter of the bone. Treatment was carried out using the two-stage Masquelet technique.

Stage I involved

- Secondary surgical debridement of the lesion site
- Removal of non-viable bone fragments and infected tissue
- Implantation of a PMMA spacer with gentamicin to fill the cavity.

Depending on the condition of the skin and soft tissues, bone fragment fixation was achieved using:

- External fixation devices (3 patients)
- Bridge plating with plates (7 patients)
- Intramedullary nails (5 patients)
- Combined fixation with locked intramedullary nail and plate (12 patients)
- Soft-tissue reconstruction with a skin-fascial flap was performed in 8 patients.

Stage II included

- Removal of the cement spacer while preserving the induced membrane.
- Trimming of bone edges and reaming of the medullary canal (as in pseudarthrosis surgery).
- Filling of the defect with a mixture of autogenous cancellous bone and bioceramics.

In 3 cases, external fixation was converted to internal fixation; in 6 patients, additional plating was performed. In 13 patients, local titanium or polymer meshes were used as frameworks to contain the graft material.

Results

During the period of 2022–2025, 27 patients with the consequences of combat-related injuries resulting in critical bone defects of the humerus, accompanied by associated soft-tissue damage, underwent combined treatment using the induced membrane technique (Masquelet method) and bone grafting with a mixture of autogenous cancellous bone and bioceramic material.

Treatment was performed in the Traumatology Department of "Dobrobut" Medical Center, a tertiary–quaternary level healthcare facility in Kyiv, Ukraine, as presented in Table 1.

Table 1: Treatment was performed in the Traumatology Department of "Dobrobut" Medical Center, a tertiary–quaternary level healthcare facility in Kyiv, Ukraine

№	Age	Localisation	Area cm	Length cm	Observation period months
1	26	с/3	6/2,5	7	15
2	31	с/3	10/3	11	22
3	45	н/3	1,5/5	6	15
4	41	с/3	9/2,5	8,5	18
5	22	с/3	11,5/2,5	12	14
6	25	в/3	3/3	4	15
7	30	с/3	8/2,5	8	10
8	35	с/3	12/2,5	13	19
9	33	н/3	4/2	4	17
10	27	с/3	7/3	8	11
11	51	н/3	2/3	4,5	10
12	27	с/3	9,5/2,5	10	16
13	28	с/3	7/3	7,5	23
14	57	н/3	2,5/5	5,5	12
15	21	с/3	3/9	9	10
16	28	н/3	2,5/3,5	4	8
17	26	в/3	3/5	4,5	26
18	34	н/3	4,5/6	5,5	15
19	45	с/3	2,5/8	8	12
20	27	с/3	2/7	7	8
21	28	с/3	3/5	4,5	14
22	37	н/3	3,5/6,5	6,5	9
23	34	с/3	2,5/8	7,5	17
24	53	с/3	3/4	4	14
25	39	н/3	3,5/5	4,5	18
26	29	в/3	2,5/5	5	10
27	24	с/3	2,5/8	8	7
	33,4			6,9	16,5

Given the specific nature of medical care in recent years, the study included patients with combat-related injuries (MWT); all were male, with a mean age of 33.4 years. The average length of the humeral bone defect was 6.9 cm, involving the entire bone diameter. Defects were classified by localization as follows: upper third – 3 patient, middle third – 16 patients (majority), and lower third – 8 patients.

First Stage

Upon admission, patients underwent general clinical laboratory testing, evaluation of local soft-tissue condition in the affected area, and microbiological cultures to determine bacterial flora and antibiotic sensitivity. In the absence of local septic signs and with negative microbiological results, the first stage of surgical treatment was performed, consisting of conversion of external fixation to internal fixation.

According to AO recommendations, for diaphyseal comminuted fractures and bone defects, preference was given to locked intramedullary osteosynthesis (BIOS) with cavity filling by a PMMA spacer containing gentamicin. For fractures of the metaepiphyseal region, fixation was typically performed using two angular stable locking plates (LCP) [14,19].

When necessary, neurolysis and neurorrhaphy were performed in collaboration with micro- and neurosurgeons, and skin grafting was conducted to close soft-tissue defects.

In the presence of septic complications, staged surgical wound management was performed, including necrosectomy, sequestrectomy, lavage, and drainage, often with pulse lavage and, if needed, VAC therapy. After achieving stable improvement—absence of local infection for at least four weeks and normalization of clinical laboratory blood tests for 2–3 consecutive weeks—the patient proceeded to the stage of fixation conversion, skin grafting, and the first stage of the induced membrane technique.

Second Stage

The second stage was initiated on average 6–8 weeks after the first surgical procedure provided that no local septic manifestations had been observed for at least the previous four weeks and that general clinical blood parameters remained within normal limits for a minimum of two to three weeks

During the second stage the PMMA spacer was replaced with a plastic mixture of bioceramic material and autogenous cancellous bone. In three patients in addition to intramedullary osteosynthesis angular stable locking plates LCP were used for supplementary fixation. To maintain the plastic graft mixture in a compact configuration a resorbable polymer mesh was used as a structural framework in three patients and a titanium mesh in four patients. The latter provided greater mechanical rigidity

and allowed impaction of the graft mixture resulting in increased material density.

In the presence of neurological symptoms caused by radial nerve injury simultaneous nerve revision neurolysis and when necessary neurorrhaphy were performed at this stage.

Postoperative Evaluation and Complications

Patients were evaluated at 3, 6, 12 and 18 months following the reconstructive procedure or conversion of fixation method. Each follow up included assessment of the condition of the skin and postoperative scars the range of motion in adjacent joints the presence of neurological deficits and radiographic evaluation in dynamics.

Serious complications were defined as infections unresponsive to antibiotic therapy and wound sanitation refractures without reinjury migration or instability of fixation devices requiring additional surgery and persistent joint stiffness in adjacent joints.

Outcomes

The mean follow-up duration after transplantation of the autologous bone–bioceramic mixture was 16.5 months. The average bone defect length was 6.9 cm.

During the second stage and postoperative follow-up, local septic complications occurred in 6 cases, requiring wound sanitation. The mean time to bone consolidation was 8.7 months. In 5 patients, a limb-length discrepancy of 1–3 cm compared to the contralateral side was observed. 3 patients exhibited persistent radial nerve injury, necessitating additional surgical procedures involving mioplasty for complete restoration of hand and finger function. In 3 cases, minor residual deformities were observed as marginal local bone defects at the interface between native bone and graft mixture. In these cases, secondary local bone formation procedures using stem cell therapy were performed to stimulate osteogenesis.

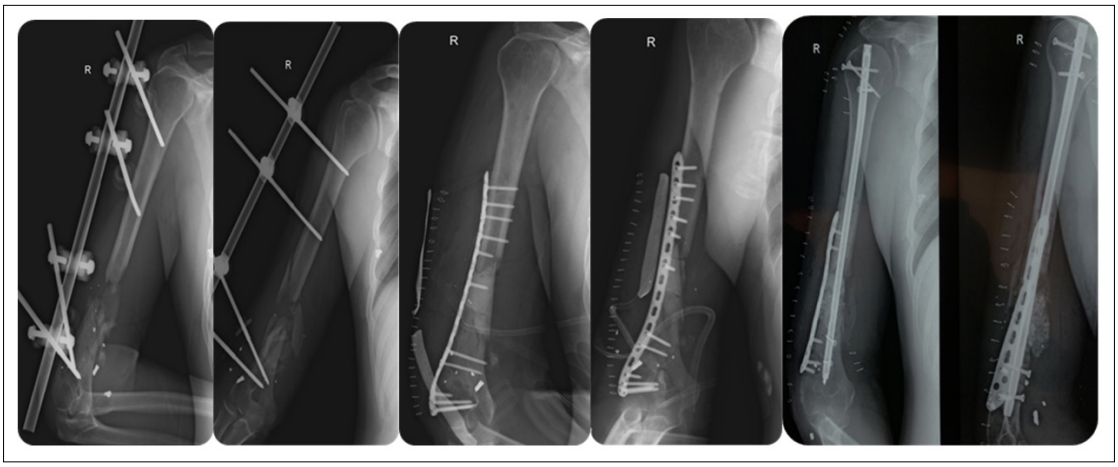
Case report 1

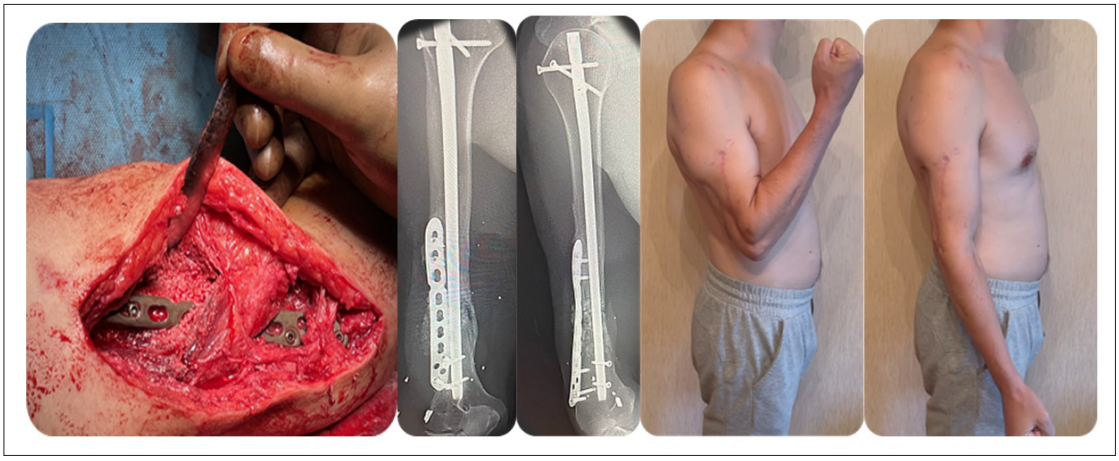
A patient with a combat-related injury and a bone defect measuring 5.7 cm in the diaphysis of the humeral, initially stabilized with an external fixation device (EFD) (first two images).

During the first stage of the Masquelet technique, the fixation was converted from external to internal using an angular stable plate (LCP). Simultaneously, necrosectomy and sequestrectomy were performed, and the bone defect was filled with a polymethylmethacrylate (PMMA) spacer containing gentamicin (images 3 and 4).

At the second stage-changing the LCP to the blocking intramedullary nail (BIOS) and other plate and formation of the induced membrane-the PMMA spacer was replaced with a plastic mixture of autogenous cancellous bone and bioceramic material (postoperative radiographic control shown in image 5-6).

Next foto intraoperative, we can see plastic material in the wound, follow-up radiographs taken 12 months after the second surgical stage demonstrated progressive bone consolidation (images 7-8), and next two shows us volume of movements.





Case report 2

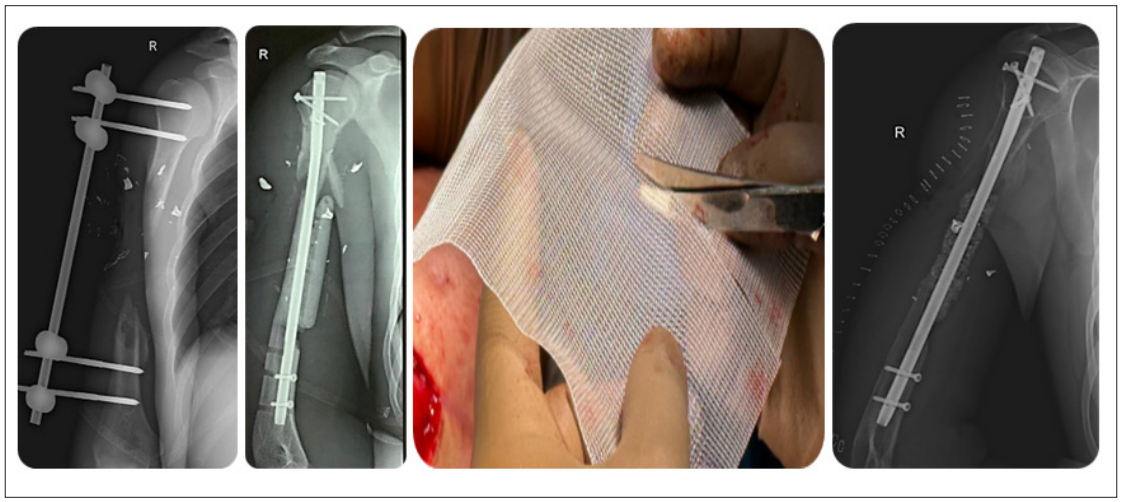
A patient with a combat-related injury and an 8 cm bone defect in the middle third of the humeral diaphysis, initially stabilized with an external fixation device (EFD) (image 1).

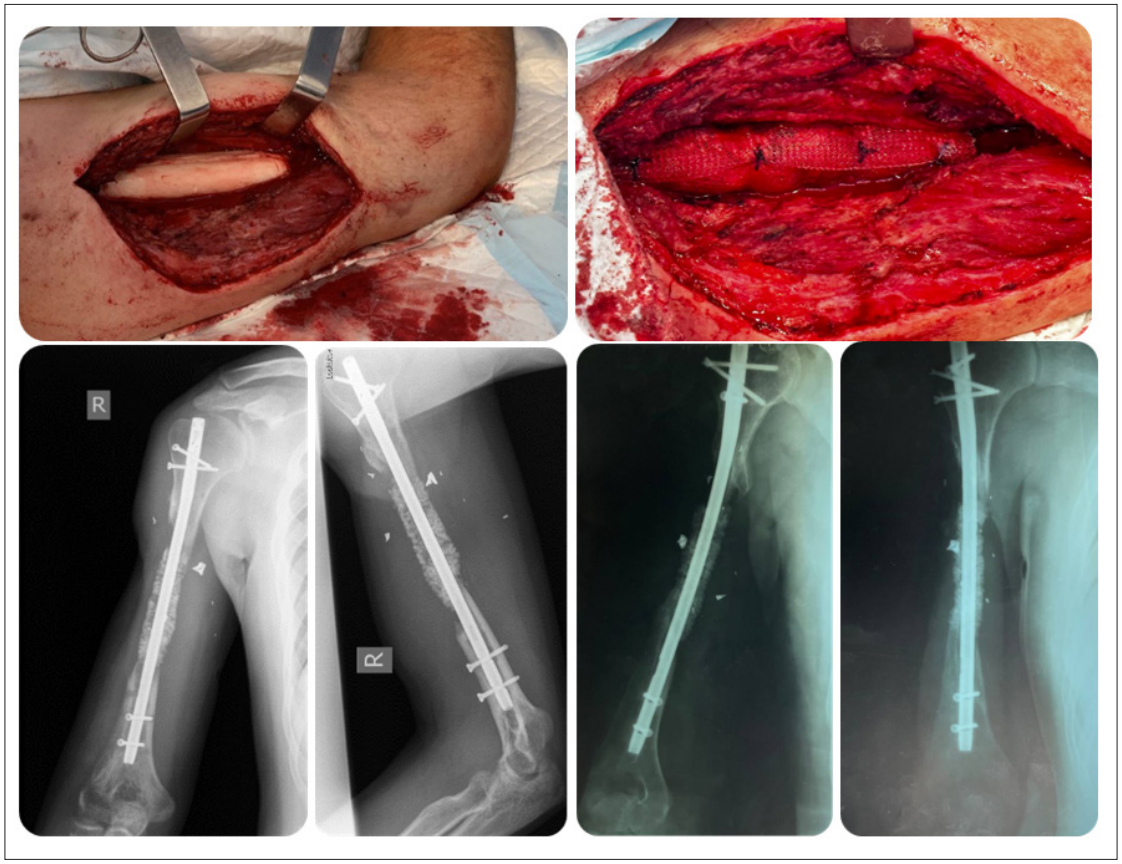
During the first stage of the Masquelet technique, the fixation was converted from external to internal, utilizing the blocking intramedullary nail (BIOS). The bone defect was filled with a polymethylmethacrylate (PMMA) spacer, and neurorrhaphy of the radial nerve was performed simultaneously (images 2).

At the second stage of the Masquelet procedure, the PMMA spacer was replaced with a plastic mixture of graft material, using a surgical mesh as a supporting framework (intraoperative photographs in images 3, postoperative radiograph shown in image 4).

Next two foto intraoperatively, we can see PMMA spacer (images 5) and plastic material and surgical mesh in the wound (images 6)

Follow-up radiographs obtained 6 months after the second surgical stage (images 7 and 8) and after 18 months, demonstrated ongoing bone consolidation in images 9, 10.





Discussion

One of the key challenges in treating patients with critical bone defects is the choice of fracture fragment fixation. In the presence of local soft-tissue septic or trophic complications, preference is given to external fixation methods, and in most such cases, subsequent reconstruction is performed using the bone transport technique with Ilizarov-type external fixators [1,14,23].

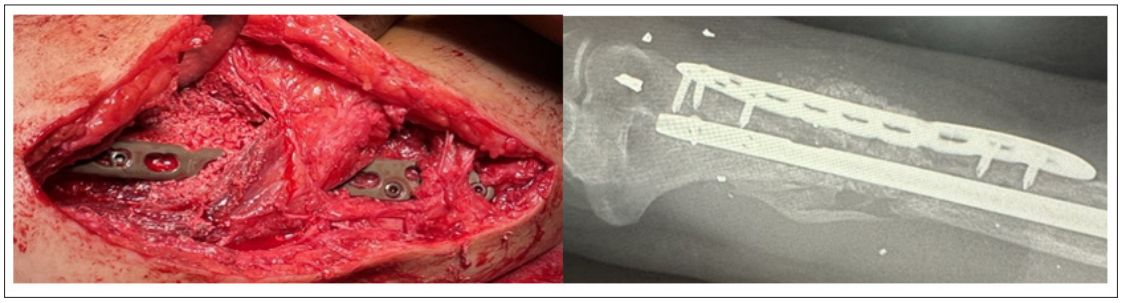
In cases where no septic manifestations are present and local trophic parameters are satisfactory, the choice of fixation method becomes less evident.

According to Ren C. et al. (2022) and other studies, the Masquelet technique demonstrated several advantages compared with external fixation methods: a shorter time to bone consolidation (7.59 vs. 12.22 months), better postoperative quality of life (92.38 vs. 76.20), and a lower complication rate (24.35% vs. 39.23%) [13,16,15,19].

In our clinical practice, we followed a similar algorithm when selecting the treatment method. According to AO principles, in cases of critical humeral bone defects, fixation was approached as stabilization of a comminuted, multifragmentary fracture of the affected segment.

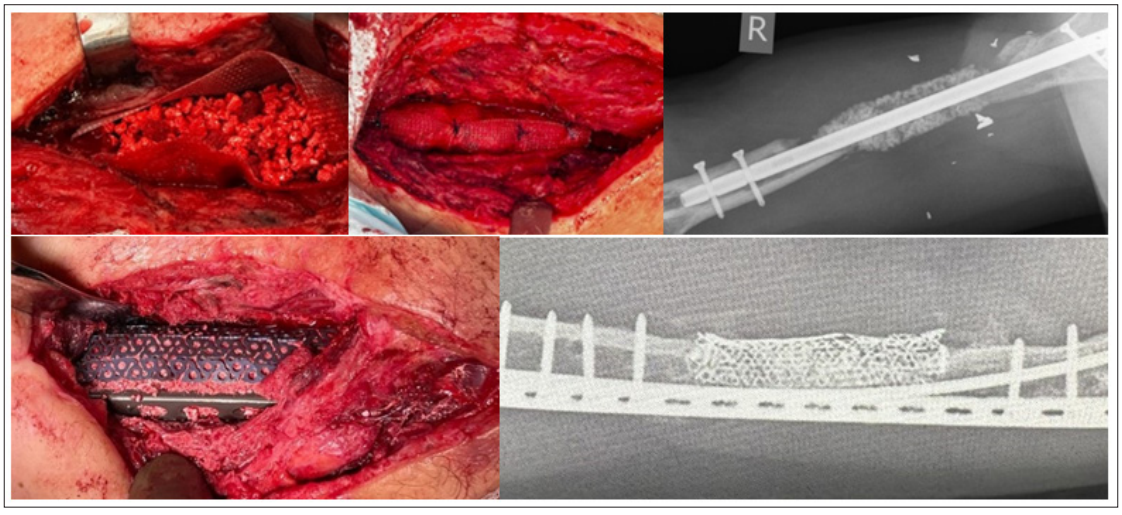
Therefore, to achieve maximum stability, preference was given to locked intramedullary fixation devices (BIOS), which, in addition to providing mechanical stability, offer greater biocompatibility during subsequent bone grafting procedures. This approach helps reduce the required volume of graft material and allows the use of bone tissue obtained during reaming of the intramedullary canal [24,25,20].

When employing a bone grafting mixture of autogenous cancellous bone and bioceramic material in combination with BIOS fixation, certain technical challenges arise concerning the proper filling of the defect cavity. After removal of the cement spacer during the second stage of the Masquelet technique, the induced membrane demonstrates properties similar to the periosteum; however, when impaction techniques are used for defect filling, the membrane alone does not provide sufficient density or resistance to adequately contain the graft material (as demonstrated in the following images).



Accordingly, there arises a need to use mesh structures to maintain the compact form of the plastic graft material, or alternatively, to employ denser forms of bioceramic material for filling cavitary bone defects.

In our practice, we utilized both resorbable polymer meshes and titanium meshes. The advantages of polymer mesh include biocompatibility and radiolucency (images 1, 2, and 3), whereas the advantages of metallic meshes lie in their greater mechanical stability (images 4 and 5).



Following a comparison of bone consolidation times and functional recovery among our patients, depending on the size of the bone defects, we did not observe a clear correlation between these parameters.

Therefore, similar to the conclusions drawn by Masquelet et al, we assume that the healing of a bone defect does not depend on its size; in other words, the length of the bone defect cannot be considered a determining factor that delays bone union [8,18,23].

Conclusions

1. Critical bone defects remain a complex challenge in determining treatment strategies. Currently, there are no clearly defined criteria for their classification, and consequently, no standardized treatment protocols.
2. Therefore, management must be individualized, taking into account all anatomical, biological, and clinical factors.
3. The use of the Masquelet technique with defect reconstruction by a mixture of autogenous cancellous bone graft and bioceramic material is a reliable method in cases of traumatic critical-sized humeral bone defects.

4. To develop a clear and evidence-based algorithm for selecting reconstruction techniques for critical-sized traumatic bone defects, further research and multidisciplinary discussion in this field are necessary.

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