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Early results of shoulder arthrodesis with 3D-titanium implants for treatment of severe gunshot wounds of the shoulder girdle

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As a result of large-scale war in Ukraine, the frequency of gunshot wounds of the upper extremities has increased dramatically, accompanied by massive damage to soft tissue, neurovascular plexuses, and significant bone deficiency, so their treatment with traditional methods is risky. This leads to the development of new treatment methods, in particular, techniques for shoulder arthrodesis. Objective. To investigate the effectiveness of shoulder arthrodesis using an individual 3D-titanium implant and or a locked compression plate (LCP) with bone autoplasty for the treatment of severe combat trauma of the upper extremity. Methods. In 2022–2023, 19 men aged 36.2 (24–52) years with severe combat trauma of the upper extremity underwent shoulder arthrodesis using individual 3D-titanium implants (n = 9) or LCP with bone autoplasty (n = 10). The follow-up period was 18 months. Individual 3D-implants were created in the CAD program Autodesk Fusion 360 and made of Ti_6Al_4V alloy by three- dimensional metal 3D-printing. The functional status of the shoulder joint was assessed by the Oxford Shoulder Score, VAS at 6 and 12 months after surgery. Fusion was checked radiographically at 1, 3, 6 and 12 months. Results. The average follow-up period was 12 months. Ankylosis of the shoulder joint was formed in 18 (95 %) patients, and clinical consolidation without final restructuring with a positive tendency to bone fusion was detected in one patient (5 %). Radiologically confirmed fusion in 8.5 months (6–12). After 12 months, a decrease in pain (VAS: 5 to 1 points; $p < 0.001$) and improvement in the condition of the shoulder (Oxford Shoulder Score: 25 to 40 points, $p < 0.001$) were found compared with 6 months. Conclusions. Treatment of severe combat trauma of the upper extremity by shoulder arthrodesis allows to eliminate pain and restore sufficient function to perform daily tasks one year after surgery. The combination of shoulder arthrodesis with individual 3D-implants resulted in the restoration of upper limb function in all 9 patients with massive bone and muscle defects.

Унаслідок широкомасштабних бойових дій в Україні різко збільшилась частота вогнепальних поранень верхніх кінцівок, які супроводжуються масивними ураженнями м'яких тканин, судинно-нервових сплетень, значним дефіцитом кісткової тканини, тому їхнє лікування традиційними методами є ризикованим. Це обумовлює розробку нових методик лікування, зокрема, технік артродезу плечового суглоба. Мета. Дослідити ефективність застосування артродезу плечового суглоба з використанням індивідуального 3D-титанового імплантата або блокованої компресійної пластини (LCP) із кістковою аутопластикою для лікування важкої бойової травми верхньої кінцівки. Методи. Протягом 2022–2023 рр. 19 чоловікам віком 36,2 (24–52) роки з важкою бойовою травмою верхньої кінцівки виконано артродез плечового суглоба з використанням індивідуальних 3D-титанових імплантатів (n = 9) або LCP із кістковою аутопластикою (n = 10). Термін спостереження склав 18 місяців. Індивідуальні 3D-імплантати створили у CAD-програмі Autodesk Fusion 360 та виготовили зі сплаву Ti_6Al_4V методом тривимірного металевого 3D-друку. Функціональний стан плечового суглоба оцінювали за шкалами Oxford Shoulder Score, ВАШ через 6 та 12 міс. після хірургічного втручання. Рентгенографічно перевіряли зрощення через 1, 3, 6 та 12 міс. Результати. Середній термін спостереження склав 12 міс. У 18 (95 %) пацієнтів сформований анкілоз плечового суглоба, у одного пораненого (5 %) виявлено клінічну консолідацію без кінцевої перебудови з позитивною тенденцією до кісткового зрощення. Рентгенологічно підтверджено зрощення через 8,5 міс. (6–12). Через 12 міс. виявлено зниження больових відчуттів (ВАШ: від 5 до 1 балів; $p < 0,001$) та покращення стану плеча (Oxford Shoulder Score: від 25 до 40 балів, $p < 0,001$) порівняно з 6 міс. Висновки. Лікування важкої бойової травми верхньої кінцівки шляхом артродезу плечового суглоба дозволяє усунути больовий синдром і відновити достатню функцію для виконання повсякденних завдань через рік після хірургічного втручання. Поєднання артродезу плечового суглоба з індивідуальними 3D-імплантатами привело до відновлення функції верхньої кінцівки у всіх 9 пацієнтів із масивними дефектами кісткової тканини та м'язового каркаса. Ключові слова. Артродез плечового суглоба, вогнепальне поранення, 3D-титановий імплантат, кісткова пластика.

Keywords. Shoulder arthrodesis, combat trauma, gunshot wounds, upper extremity, bone defects, 3D-implants

Introduction

A combat injury of a limb is a polystructural lesion of anatomical formations, resulting in massive defects of the skin, muscles, ligaments, bone tissue deficiency, damage to nerves and blood vessels. The majority of extremity injuries (75 %) are caused by explosive weapons, while lower and upper extremity injuries occur with almost equal frequency (52 % and 48 %, respectively). Most often, injuries to the lower extremities are observed in a complex — lower leg (40 %) and thigh (26 %), and for upper extremities — shoulder joint and shoulder (37 %), as well as hands, wrists and fingers (33 %) [1, 2].

Such methods as arthroscopy, endoprosthetic repair, osseous osteosynthesis and intramedullary osteosynthesis significantly expanded the spectrum of surgical interventions in case of injuries of the upper limb. However, in the case of a combat injury, it is not always possible and expedient to use the above methods [3–5]. Unfortunately, modern realities in Ukraine require finding a solution to the problem of treating gunshot wounds of the shoulder joint, which are accompanied by massive soft tissue defects around the shoulder joint, with a massive deficit of bone tissue in the upper third of the humerus. This makes it necessary for doctors to use "unpopular" methods, such as arthrodesis, transposition of muscles and tendons [6–8]. Arthrodesis of the shoulder joint is a surgical intervention in which the articular surfaces of the glenoid and the head of the humerus are resected, the humerus is fixed to the scapula in order to form ankylosis, which subsequently ensures painless functioning of the upper limb in new functional and anatomical conditions [5, 9–12]. According to a recent systematic review of 17 studies (316 patients), arthrodesis of the shoulder joint helps to restore limb function, but has a high risk of complications (33.6 % of patients) — fractures and infections [13].

In order to improve the effectiveness of treatment of severe gunshot wounds of the shoulder joint, we performed arthrodesis of the shoulder joint using a developed and created individual 3D-titanium implant with the formation of a standard, angular ankylosis [6, 14, 15]. In the case of a massive deficiency of soft tissues and bone tissue of the bones forming the shoulder joint, the use of individual 3D-titanium implants is a high-tech option for restoring the function of the upper limb [7, 16].

Purpose: To investigate the effectiveness of shoulder arthrodesis using individual 3D-titanium implants or a locked compression plate (LCP) with bone autoplasty for the treatment of severe combat trauma of the upper extremity.

Material and methods

The design of the study was approved by the local Bioethics Committee of the State Establishment Professor M. I. Sytenko Institute of Pathology of the Spine and Joints of the National Academy of Sciences of Ukraine (Protocol No. 241 dated 19.02.2024). All patients signed an informed consent.

Patients

The study includes treatment outcomes of 19 patients who underwent arthrodesis of the shoulder joint both with the use of individual 3D-titanium implants in 9 patients and LCP with bone autoplasty (10 patients) in the trauma department of the injury clinic of the Military Medical Clinical Center of the Central Region in the period from May 2022 to December 2023 (Table 1).

The inclusion criterion was the presence of severe combat trauma of the upper limb (Fig. 1), defects of the bone tissue of the proximal part of the humerus and glenoid, defects of the soft tissues surrounding the shoulder joint, damage to the axillary and subscapular nerves. For the best functional result after arthrodesis of the shoulder joint, the trapezius, levator scapulae, serratus anterior and rhomboid muscles must be functional.

Exclusion criteria (contraindication to surgical intervention) were: the presence of untreated infectious foci (accompanying injuries); infectious complications of the postoperative wound; severe post-traumatic stress disorder; addiction; alcoholism.

The observation period was 18 months.

3D-titanium implant

Individual 3D-titanium implants were created by computer modeling in the Autodesk Fusion 360 CAD

Table 1

Demographic characteristics of patients

Parameter	Value
Number of patients	19
Men (women)	19 (0)
Right/left upper extremity	11/8
Age (years)	24–52
Weight (kg)	63–110
Height (cm)	165–190
Body mass index (kg/m^2)	20–35

program based on computer tomograms obtained after scanning patients on a Philips Brilliance 64-slice spiral computer tomograph (USA) (Fig. 2).

Spiral computed tomography was performed in compliance with the following criteria:

– obligatory scanning of both humerus with elbow and shoulder joints;

– maximum permissible number of slices;

– thickness of the section no more than 1 mm;

– employment of the artifact suppression mode in the presence of metal in the scanning area.

After modeling, the implants were made of titanium alloy for surgical implantation Ti6AI4V ELI (Grade 23), which met the requirements of the ASTM F136 standard, by the method of three-dimensional metal 3D-printing using DMLM (SLM) technology on Concept Laser M2 Cusing equipment, manufactured in Ukraine.

Technique of surgical intervention

The operation was performed in the patient's position of a "beach chair" with endotracheal anesthesia.

Fig. 1. View of a combat injury of the upper extremity with a massive soft tissue defect, a gunshot fracture of the right humerus, fixed with an external fixation device in a 28-year-old patient

An incision of the skin and subcutaneous fat up to 20 cm long was made from the spine of the scapula to the front edge of the acromion and down the front side of the diaphysis of the humerus, trying to preserve the deltoid muscle as much as possible. The elements of the rotator cuff of the shoulder joint were cut off and the lower surface of the acromion, the articular surfaces of the glenoid and the head of the humerus were decorticated, completely removing the cartilage tissue.

Arthrodesis was performed both between the head of the humerus and the glenoid, and between the head and the acromion (Fig. 3, a). After cutting off the tendon of the long head of the biceps brachii from the place of attachment, it was fixed in the intertuberous groove. After that, the head of the humerus was brought proximal to the acromion and glenoid and fixed in a functionally advantageous position.

A locked compression plate (LCP) of the AO system with cork cancellous and locking screws was used as a metal fixator (Fig. 3, b). It was modeled according to the profile of bone surfaces from the spine of the scapula to the diaphysis of the humerus, reproducing anatomical curves. In all cases reliable compression between the humerus and the scapula was created with the help of two or three cancellous screws. The next cancellous screw was guided from the spine of the scapula to the beak-like process, then the screw was inserted through the acromion into the head of the humerus. The plate was fixed to the diaphysis of the humerus with corkscrews and blocked screws. The following shoulder position was achieved after shoulder arthrodesis: abduction 30°, flexion 30° and its internal rotation 30° in patients without the use of 3D-implants. In the case of using 3D-implants, the bending angle was increased to 44°. In patients without them, autogenous bone grafts were used, which were formed from the crest

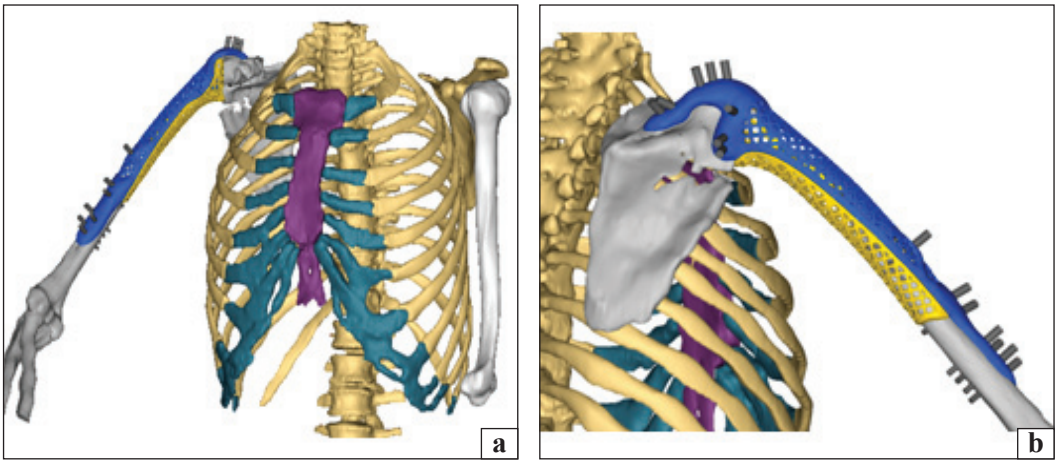

Fig. 2. An example of modeling a 3D-titanium implant in the Autodesk Fusion 360 CAD software: a) front view; b) rear view

of the wings of the iliac bone or areas of the fibula bone. In the presence of massive bone defects (Fig. 4, a), individual 3D-titanium implants were used (Fig. 4, b–d).

The wound was sutured in layers, aspiration drainage was installed for 1 day.

Postoperative care. Rehabilitation

After surgery, all subjects were prescribed an elastic Dezo-type bandage with a wedge-shaped pillow for 8–10 weeks. Movement in the elbow, wrist, and hand joints was allowed immediately after surgery to prevent contractures and loss of function.

X-ray confirmation of bone growth and stability of the 3D-implant was performed 1, 3, 6 and 12 months after surgery in direct and lateral projections. Clinical bone consolidation was defined as the absence of pain syndrome in the area of intervention, the absence of pathological bone and implant mobility. After X-ray confirmation of the fusion, physical therapy was started to improve the function of the shoulder girdle.

Evaluation of treatment results

Functional results were evaluated 1, 3, 6 and 12 months after the intervention and radiographs were taken.

In case of significant progress, the patient was allowed to eat and perform hygiene procedures independently.

Assessment of the functional state of the shoulder joint was carried out according to the Oxford Shoulder Score and VAS scales 6 and 12 months after surgery.

Statistical methods

Oxford Shoulder Score and VAS scores (0 and 100 worst scores, respectively) are given as median Me and first and third quartiles (Q1; Q3). Their comparison between terms was performed using the Wilcoxon signed-rank test for paired samples. The difference between groups was considered significant in $p < 0.05$.

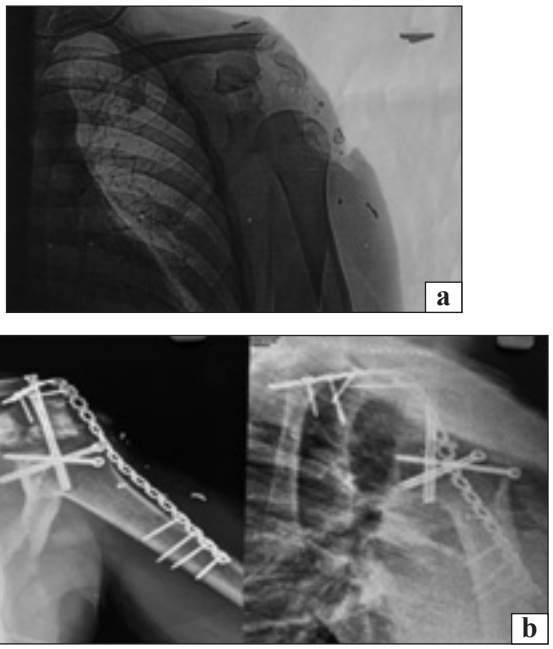

Fig. 3. Radiographs of the patient before (a) and after (b) arthrodesis using the LCP system of the AO with cortical cancellous and blocking screws

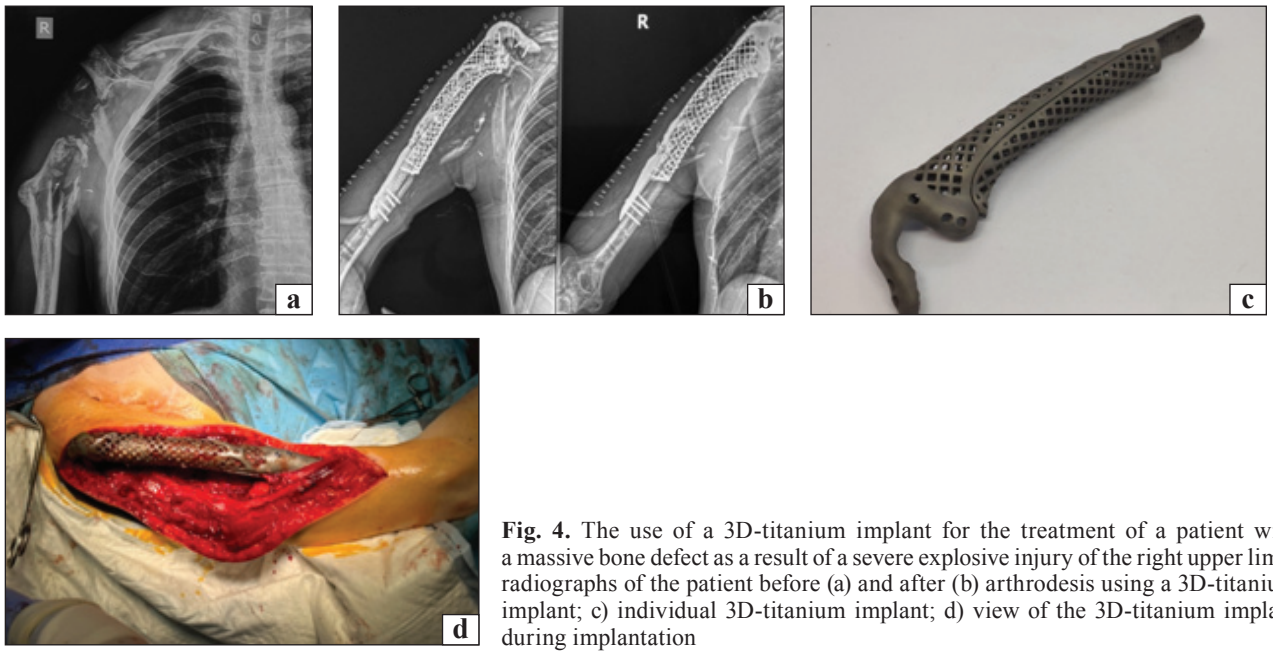

Fig. 4. The use of a 3D-titanium implant for the treatment of a patient with a massive bone defect as a result of a severe explosive injury of the right upper limb: radiographs of the patient before (a) and after (b) arthrodesis using a 3D-titanium implant; c) individual 3D-titanium implant; d) view of the 3D-titanium implant during implantation

Table 2

Results of using arthrodesis combined with 3D-titanium individual implants or locked compression plate (LCP) fixation with bone autoplasty for the treatment of patients with severe upper extremity blast injury

№	Characteristics of the damage	Extremity (right/left)	Age, years	3D-implant (yes/no)	Term before fusion, months	Ankylosis (yes no)
1	GSBW of the soft tissues of the shoulder, GMF of the proximal part of the H	right	24	yes	8	yes
2	Gunshot, bullet through wound of the SJ with GMF of the SJ head	right	25	no	6	yes
3	GSBW of the soft tissues of the upper arm and shoulder with the GMF of the proximal metaepiphysis of the H, GF of the acromial end of the clavicle	left	29	no	9	yes
4	GSBW of the soft tissues of the shoulder with GMF of the proximal metaepiphysis of the H, traumatic amputation of the left upper limb at the level of the lower third of the shoulder	left	24	yes	6	yes
5	GSBW of the soft tissues of the shoulder with GMF of the proximal metaepiphysis of the H	left	39	yes	7	yes
6	GSBW of the soft tissues of the shoulder and forearm with GF of the coracoid and acromial processes of the scapula, acromial end of the clavicle, head of the H and both bones of the forearm	right	43	yes	9	yes
7	GSBW of the soft tissues of the shoulder, GMF of the proximal part of the H	left	47	no	8	yes
8	GSBW of the soft tissues of the shoulder with GMF of the proximal metaepiphysis of the H; GF of the middle third of the ulna	right	45	no	9	yes
9	Gunshot, bullet through wound of the SJ with GMF of the H head	right	27	no	10	yes
10	GSBW of the soft tissues of the upper arm and SJ with GF of the upper third of the H with a bone tissue defect of up to 6 cm	right	48	no	12	yes
11	Gunshot, bullet through wound of the SJ with GMF of the H head	left	27	no	10	yes
12	GSBW of the soft tissues of the SJ and forearm with GMF of the head of the H; GF of the distal epimetaphysis of the radial bone	left	32	no	10	yes
13	Gunshot, bullet wound of the SJ with GF of the acromial end of the clavicle and the upper third of the H	right	52	no	12	yes
14	GSBW of the soft tissues of the SJ with GF of the scapula and the upper third of the H with damage to the brachial artery	right	28	yes	9	yes
15	Gunshot, bullet-blind wound of the SJ with GMF of the H head	left	49	no	8	yes
16	GSBW of the soft tissues of the shoulder with GMF of the upper third of the H with a defect of soft tissues and bone tissue, 8 cm	left	37	yes	8	yes
17	GSBW of the soft tissues of the shoulder with GMF of the upper third of the H with a defect of soft tissues and bone tissue, 8 cm	left	44	yes	6	yes
18	GSBW of the soft tissues of the shoulder with GMF of the upper third of the H with a defect of soft tissues and bone tissue, 6 cm	left	24	yes	6	yes
19	GSBW of the soft tissues of the shoulder with GMF of the upper third of the H with a defect of the soft tissues of the SJ	right	31	yes	9	yes

GSBW — gunshot shrapnel blind wound; GF — gunshot fracture, GMF — gunshot multifragmentary fracture; H — humerus, SJ — shoulder joint

Results

All 19 patients were men with varying degrees of upper extremity damage due to blast trauma, their average age was 36.2 (24–52) years (Table 2). 3D-individual titanium implants were used in 9 patients, 10 patients had LCP of the AO system with cortical cancellous and blocking screws and bone autoplasty depending on the severity of the injury (Table 2).

The average observation period was 12 months. 18 (95 %) men developed ankylosis of the shoulder

joint, one (5 %) showed clinical consolidation without final reconstruction with a positive tendency to bone fusion.

The average period of radiological confirmation of fusion was 8.5 months (6–12). In patients who received a 3D implant, this period was 7.6 months (6–9), and in persons with LCP — 9.4 (6–12) (Table 2).

According to the VAS assessment, the patients' pain sensations decreased after 12 months, compared to the 6-month follow-up ($p < 0.001$) (Table 3). The VAS value was interpreted after 6 months as moderate pain, after 12 months as absence of pain.

According to the results of the Oxford Shoulder Score assessment, an improvement in the condition of the shoulder after 12 months compared to the 6-month follow-up ($p < 0.001$) (Table 3) from 25 to 40 points was also established.

All patients noted a tendency to increase the physical strength of the limb from the 3rd month after surgery (Figs. 5, 6).

Discussion

Gunshot wounds of the shoulder joint are accompanied by massive soft tissue defects, damage to nerves and blood vessels, so the use of shoulder joint endoprosthesis does not allow to restore function. In particular, the use of anatomical endoprostheses requires the presence of a preserved rotator cuff of the shoulder joint. At the same time, the use of reversible endoprostheses of the shoulder joint requires the presence of a capable deltoid muscle and sufficient bone mass of the glenoid.

Table 3

Results of evaluating the effectiveness of treatment according to the Oxford Shoulder Score and VAS (Me (Q1; Q3)) 6 and 12 months after surgery

Scale	Term after surgical intervention, months		P-value
	6	12	
VAS	5 (4–6)	1 (1; 2)	< 0.001
Oxford Shoulder Score	25 (24; 28)	40 (38; 46)	< 0.001

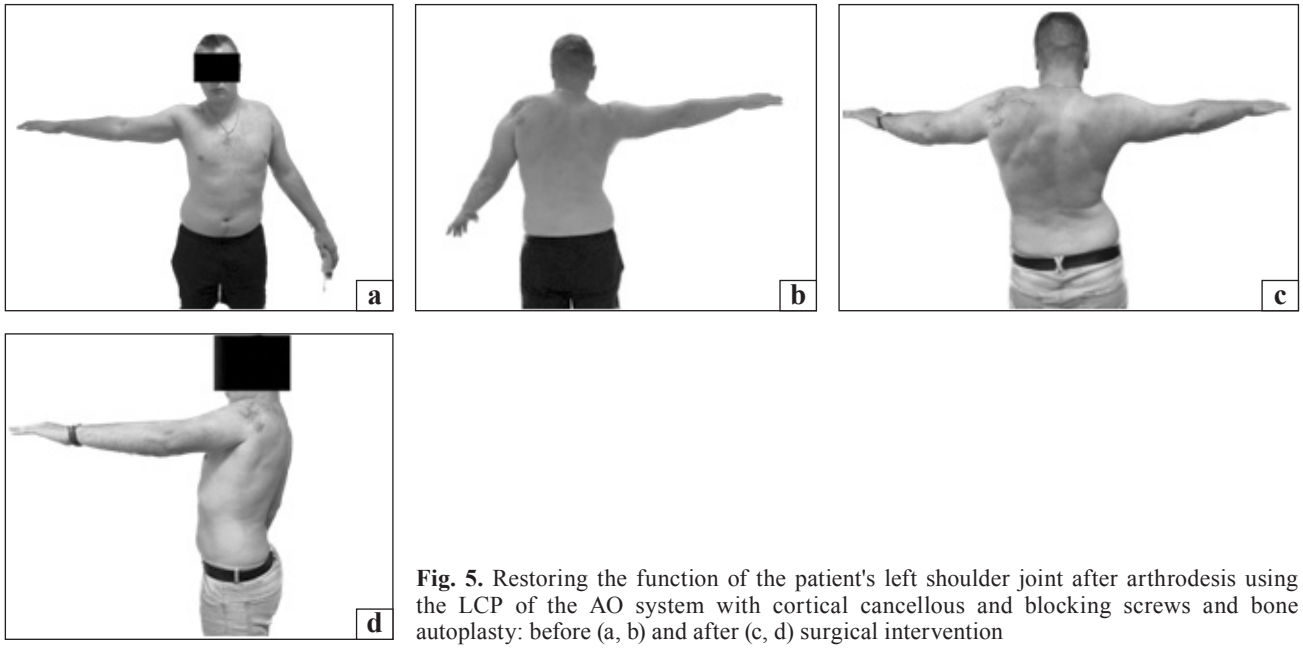

Fig. 5. Restoring the function of the patient's left shoulder joint after arthrodesis using the LCP of the AO system with cortical cancellous and blocking screws and bone autoplasty: before (a, b) and after (c, d) surgical intervention

Fig. 6. Functioning of the patient's shoulder joint after arthrodesis using an individual 3D titanium implant

The use of an individual 3D-titanium implant embodies, firstly, the application of modern technologies in orthopedics to create ankylosis standardized by the angles of the shoulder-scapula ratio, and secondly, a highly effective possibility for the treatment of gunshot wounds of the shoulder joint, which are accompanied by massive bone defects tissue and muscle framework, which sharply limits the possibility of using standard implants. In our study, the use of 3D-titanium implants, created on the basis of the individual results of the tomography of a particular patient, allowed us to achieve maximum perfection and conformity to each bone defect due to precise fit and fixation. This will likely help reduce the time of surgery and create optimal opportunities for reparative processes and restoration of function. According to preliminary results, the time to union in patients with a 3D-titanium implant was shorter compared to those who received a plate (7.6 vs. 9.4 months, respectively).

In the literature available to us, many different positions and positions of the upper limb during arthrodesis in the shoulder joint are described [5, 7]. In our opinion, the most functionally beneficial of them is when the patient can reach his hand to his mouth, bending the upper limb at the elbow joint. From our point of view, the position of the shoulder under the conditions of arthrodesis — abduction 30°, flexion 30° and its internal rotation 30° is optimal, because in this case the patient can independently take food and perform hygienic procedures. However, in the case of using 3D-titanium implants, we can obtain a greater bending angle (up to 44°).

Recommendations for postoperative immobilization after arthrodesis of the shoulder joint, according to the literature, differ. Some sources indicate the need for plaster immobilization for 3–4 months, others achieve good results without any immobilization, except for a wedge-shaped pillow [10, 15]. Most recommend immobilization in a gauze bandage with a wedge-shaped pillow for 8–10 weeks [3]. For more complex cases with massive loss of bone tissue or other complications, an extended period of immobilization should be chosen [5]. In our study, we preferred a Dezo-type elastic bandage with a wedge-shaped cushion for 8–10 weeks.

Early results demonstrate fracture consolidation in severe combat trauma of the upper extremity and are promising. The use of patient-specific, 3D-printed titanium implants offers a new technology that can be applied to address a variety of complex bone defects and upper extremity deformities more effectively and with fewer complications. Despite the large arsenal of metal fixators, there are situations when their presence does not allow replacing massive bone defects. In such cases, the use of standard metal fasteners does not solve the problem of stable fixation of the shoulder-scapular arthrodesis.

In the world literature, there are more and more reports on the use of individual 3D titanium implants, which are designed to restore bone tissue defects when standard structures are not sufficient [17].

Conclusions

The use of shoulder joint arthrodesis for the treatment of severe combat trauma of the upper extremity allowed to achieve functional stability of the shoulder joint in the majority of patients (18 of 19), as a result of which fusion occurred within 12 months of observation. All 19 men were found to have disappearance of the pain syndrome, restoration of sufficient function to perform everyday tasks, and restoration of working capacity in 12 months.

Combining humeral arthrodesis with individual 3D-implants resulted in recovery of upper extremity function in all 9 patients with massive bony and skeletal defects.

Despite the complexity of surgical interventions in patients with gunshot injuries of the shoulder joint, the method of replacing bone defects with individual 3D-implants is justified, as it allows to obtain 95 % of positive results.

Conflict of interest. The authors declare no conflict ofinterest.

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EARLY RESULTS OF SHOULDER ARTHRODESIS WITH 3D-TITANIUM IMPLANTS FOR TREATMENT OF SEVERE GUNSHOT WOUNDS OF THE SHOULDER GIRDLE

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