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Features of surgical treatment of combined gunshot wounds of the hip joint

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A retrospective analysis of surgical treatment is given 7 patients with combined gunshot wounds pelvis and hip joint. Objective. Analyze the results and determine the features of treatment of victims with gunshot wounds to the pelvis and hip joint. Methods. Patients with combined gunshot wounds to the pelvis and hip joint were distributed according to age, the nature of the fracture of the bone, current of the pelvis and proximal thigh, the nature of injuries to the internal organs of the abdominal cavity and pelvis, main nerves, the duration of the total hip arthroplasty (THA), the presence of infectious complications during treatment with the release of pathogen, the period of observation and the assessment on the scale Harris Hip Score (HHS). Analysis of combined firearms wounds of the pelvis and hip joint were carried out comprehensively with the involvement of a multidisciplinary team of specialists (abdominal and vascular surgeons, traumatologist, urologist, proctologist). Results. On the basis of statistical analysis, it was found that among 7 patients with average age 41.1 years, THA was completed in 5/7 (71 %). Medium term to THA (among those who underwent arthroplasty) was 17.0 months. Infectious complications were observed in 57 % of patients: Klebsiella pneumoniae and Klebsiella pneumoniae, Pseudomonas aeruginosa. In case of detected infection or questionable sterility, a two-stage treatment strategy is needed, that has better performance infection control after eradication of infection. Conclusions. In our opinion, the treatment algorithms in the case of gunshot wounds joint injuries of the hip joint will make it possible to reduce the level of infectious complications and improve the reproduction of results of treatment in this category of victims.

Наведено ретроспективний аналіз хірургічного лікування 7 пацієнтів із поєднаними вогнепальними пораненнями таза та кульшового суглоба. Мета. Проаналізувати результати й визначити особливості лікування постраждалих із вогнепальними поєднаними пораненнями таза та кульшового суглоба. Методи. Пацієнти із поєднаним вогнепальними пораненням таза та кульшового суглоба були розподілені згідно з віком, характером перелому кісток таза та проксимального відділу стегна, характером ушкоджень внутрішніх органів черевної порожнини та малого таза, магістральних нервів, терміном проведення ендопротезування кульшового суглоба (ТЕКС), наявністю інфекційних ускладнень протягом лікування з виділенням збудника, терміном спостереження й оцінкою за шкалою Harris Hip Score (HHS). Дослідження поєднаних вогнепальних поранень таза та кульшового суглоба проводилося комплексно зі залученням мультидисциплінарної команди спеціалістів (абдомінальний і судинний хірурги, травматолог, уролог, проктолог). Результати. На основі статистичного аналізу встановлено, що серед 7 пацієнтів із середнім віком 41,1 рік, ТЕКС виконано в 5/7 (71 %). Середній термін до ТЕКС (серед тих, кому виконано ендопротезування) склав 17,0 міс. Інфекційні ускладнення спостерігалися у 57 % випадках, серед яких переважали: Klebsiella pneumoniae та Pseudomonas aeruginosa. У разі виявленої інфекції або сумнівної стерильності необхідна двоетапна стратегія лікування після ерадикації інфекції, яка має кращі показники її контролю. Висновки. На нашу думку, використання наведених алгоритмів лікування в разі вогнепальних поєднаних поранень кульшового суглоба дасть можливість зменшити рівень інфекційних ускладнень і покращити результати лікування в цієї категорії постраждалих. Ключові слова. Вогнепальне поранення, кульшовий суглоб, таз, ендопротезування кульшового суглоба, рівень медичної допомоги

Keywords. Gunshot wound, hip joint, pelvis, hip arthroplasty, level of medical care

Introduction

Gunshot wounds (GSW) to the joints are considered a complex, combined trauma that involves direct mechanical destruction of the cartilage and subchondral bone, massive soft tissue damage, and a high probability of wound contamination. This defines a distinct clinical entity with its own management principles [1, 2].

In particular, gunshot wounds to the pelvis present a unique challenge for orthopedic surgeons due to the high frequency of concomitant injuries to the abdominal organs, urinary system, and hip joints [3, 4].

A clinically significant aspect is that wounds penetrating the joint cavity increase the risk of septic arthritis and subsequent post-traumatic osteoarthritis. Therefore, treatment should aim not only at restoring anatomy but also controlling contamination [5, 6]. Death within the first 24 hours after trauma is mostly due to acute blood loss and associated injuries [7].

Infectious complications (wound infection, septic arthritis, osteomyelitis) are among the main determinants of long-term outcomes for gunshot wounds to the joint. The risk correlates with the level of contamination, the presence of foreign bodies, the time to primary debridement, and the quality of soft tissue coverage [1, 8].

Most patients with transabdominal gunshot wounds to the hip joint (80 %) experienced infectious complications with poor functional outcomes [9].

During military conflicts, multi-drug-resistant gram-negative pathogens such as *Acinetobacter baumannii, Pseudomonas aeruginosa*, and carbapenem-resistant enterobacteria are increasingly dominant. The risk of infection rises with high-energy injuries, the retention of foreign bodies (bullet fragments), delayed surgical debridement, and intestinal injury [10].

Gunshot combined injuries to the hip joint remain a relevant topic today due to the difficulty in diagnosing and treating this pathology, the high percentage of infectious complications, and the significant number of unsatisfactory outcomes, requiring the search for new diagnostic and treatment methods.

Objective: To analyze the results and determine the peculiarities of the treatment of patients with combined gunshot wounds of the pelvis and hip joint in the context of a full-scale war with the Russian Federation.

Materials and Methods:

A retrospective analysis of the surgical treatment of 7 patients with combined gunshot wounds to the hip joint, who were hospitalized in medical facilities of the Ministry of Defense and the Ministry of Health of Ukraine, was conducted.

The work study was performed at the Military Medical Clinical Center of the Northern Region. The study was approved by the local bioethics committee (Protocol No. 4/05, dated 17.09.2025) of the relevant institution in accordance with ICH GCP, the Helsinki Declaration of Human Rights and Biomedicine, as well as the current legislation of Ukraine. All participating patients were informed of the study plan and conditions and provided written informed consent.

Inclusion criteria: combined gunshot penetrating wound of the hip joint with a fracture of the walls of the acetabulum and femoral head, with a follow-up period of 6 months or more.

Exclusion criteria: isolated gunshot non-penetrating soft tissue injury in the hip joint area, as well as patients who died within 72 hours after being admitted to the third-level medical care facility due to the severity of their injuries and the development of complications.

All patients sustained their injuries during the full-scale war between Ukraine and the Russian Federation and underwent surgical treatment in medical institutions of the Ministry of Defense of Ukraine and the Ministry of Health of Ukraine.

The evaluation and analysis of combined gunshot wounds of the pelvis and hip joint were conducted comprehensively with the involvement of a multidisciplinary team of specialists (abdominal and vascular surgeons, traumatologists, urologists, proctologists).

In cases of unstable hemodynamics, the patient was examined in the emergency department, where mobile digital radiography (uDR 370i, China) and ultrasound diagnostics using the FAST protocol (Venue Go, USA) were performed, and hemodynamic parameters were stabilized. After stabilizing the patient's condition, a CT scan of the head, chest, abdominal organs, and pelvis was performed on a Revolution CT scanner (USA) (64 slices with and without contrast).

In suspected injury to major blood vessels, patients underwent CT angiography [11]. In cases of uncontrolled bleeding from major pelvic vessels or gluteal area, with defects in soft tissues or pelvic organs, resuscitative endovascular balloon occlusion of the aorta (REBOA) was used to stabilize hemodynamics. This minimally invasive procedure, which does not require thoracotomy, ensures distal control of hemorrhage, increases afterload on the heart, and thus supports coronary and cerebral perfusion pressure until definitive hemostasis is achieved.

In case of suspected damage to the rectum, an examination by a proctologist was carried out, along with rectosigmoidoscopy. For the kidneys, ureters, bladder, and urethra, ultrasound of the kidneys, triphasic excretory CT-urography, cystography, and cystoscopy were performed.

After stabilizing the patient's condition and completing the examination, priority surgical interventions were performed on the abdominal and pelvic organs, followed by stabilization of the bones and hip joint using external fixation devices (EFD) according to the principles of "*damage control surgery*" [12].

Results and Discussion

The distribution of patients with combined penetrating gunshot wounds to the hip joint was carried out based on the following indicators: age, type of fracture of the pelvic bones and proximal femur, nature of internal organ damage in the abdominal cavity and pelvic region, damage to major nerves, timing of total hip replacement (THR), presence of infectious complications during treatment with identification of the causative agent, observation period, and evaluation according to the Harris Hip Score (HHS) scale (Table 1).

All patients had combined damage to internal organs in the abdominal cavity, pelvic organs, and genitalia in combination with injury to the structures forming the hip joint. Special attention was paid to controlling the time of surgery, as prolonged surgical time in cases of combined trauma worsens treatment outcomes due to the development of coagulopathy and multiple organ failure.

During the installation of the rod EFDs in cases of gunshot fractures of the proximal femur and unstable pelvic fractures, rods with a diameter of 5–6 mm were used, which were screwed into the iliac wings with the formation of rigid compression. Given the presence of bowel paresis and abdominal distension, the transverse bar should be sufficiently high above the skin surface or positioned in a "tent-like" manner. In cases of rectal injury, the placement of a sigmostomy should be slightly higher than the traditional location to prevent infection at the site where the rods are inserted, which should always be emphasized to the surgeons.

In cases of gunshot fractures of the proximal femur with an intact hip socket, it is advisable to use intraacetabular insertion of rods followed by fixation to the distal fragment of the femur. It should be noted that this insertion of rods is recommended to be done under mandatory EOC control. Primary surgical treatment (PST) of gunshot wounds is a critical step in preventing wound infection [3], and the recommended time for its performance is within 6–8 hours after the injury to prevent the transition of the wound from contaminated to infected. Timely and adequate debridement (removal of nonviable tissue with thorough irrigation) is one of the key treatment measures for gunshot wounds. According to the Joint Trauma System War Wounds: Debridement and Irrigation clinical practice guidelines (CPG ID:31), for small wounds, 1–3 liters of saline solution are used, for moderate wounds 4–8 liters, and for large and heavily contaminated wounds, 9 liters or more [13].

For the treatment of gunshot wounds with soft tissue defects, vacuum dressings (NPWT) were used until early wound closure was achieved. These were recommended to be replaced every 2–4 days, depending on the patient's need for serial debridement. Each change of the vacuum dressing should be performed under sterile conditions in the operating room. In our opinion, NPWT should not be used for an extended period as a method for growing granulation tissue. This is a serious mistake that leads to increased treatment duration and the risk of wound infection with anaerobic bacteria. Furthermore, in cases of coagulopathy, the use of NPWT may exacerbate bleeding from the wound, making its application prohibited in these cases.

Currently, in our practice for treating gunshot fractures of the pelvic bones and hip joint in hemodynamically unstable patients, we use the "New Clinical Protocol for the Treatment of Pelvic Bone Fractures (Combat Injuries)" (Figure 1), approved by the Ministry of Health of Ukraine order No. 1237 on 16 July 2024, which is a translation of the JOINT TRAUMA SYSTEM Clinical Practice Guidelines (JTS CPG) for Pelvic Fracture Care (CPG ID: 34).

Implementation of standardized clinical treatment algorithms for patients with pelvic bone fractures has been shown to significantly increase the likelihood of rapid stabilization of the injured patient's condition [10, 15, 16].

The assessment of hip joint function is a key stage in clinical practice in traumatology and orthopedics. The most well-known scales include Harris Hip Score (HHS), Oxford Hip Score (OHS), WOMAC, HOOS, and SF-36 (Figure 2, Table 2).

The Harris Hip Score (HHS) remains the "gold standard" in classical surgical studies due to the combination of objective and subjective indicators. It is simple and comprises 10 items covering four categories: pain, function, absence of deformity, and range of motion in the hip joint. This scale was chosen for analyzing the function of the hip joint in patients

Table 1

Assessment of patient data

№	Date of injury	Type of gunshot injury		Time to DCS after injury, months	Infectious complications and pathogen	Time after injury, months	Harris Hip Score (HHS)
		pelvis and proximal femur	abdominal cavity and pelvic organs, reproductive organs and nerves				
1	04.06.202	Multifragmentary fracture of the neck and head of the right femur; multifragmentary fracture of the right acetabulum with displacement of fragments	Small intestine	21	*Klebsiella pneumoniae Candida krus., A. baumanni*	33	48
2	17.09.2022	Fracture of the acetabular region of the upper third of the right femur with displacement of fragments and marginal fracture of the acetabulum	Rectum with development of phlegmon of the pararectal tissue	25	*Acinetobacter spp., Pseudomonas aeruginosa*	31	80
3	27.12.2022	Multifragmentary fracture of the head and neck of the left femur with fracture of the acetabular floor	Left sciatic nerve	23	"Negative culture" No clinical signs of infection were found	28	36
4	27.04.2023	Fracture of the lef t acetabulum with the presence of a foreign body (metal fragment) in the left sacroiliac joint	Contusion of the extraperitoneal part of the sigmoid colon	9	"Negative culture" No clinical signs of infection were found	24	84
5	24.07.2023	Fracture of the head and upper third of the right femur, right ilium bone	Rectum (with the presence of a metal fragment). Fecal peritonitis. Post-traumatic middle right hemopneumothorax	Not performed	*Pseudomonas aeruginosa, Klebsiella pneumoniae*	21	32
6	08.07.24	Comminuted fracture of the pubic and ischial bones with dislocation fracture of the femoral head, with massive defects of the bone and soft tissues. Adjacent soft tissue injury of the right thigh	Traumatic amputation of the penis. Adjacent injury of the left scrotum with damage to both testicles	7	"Negative culture" No clinical signs of infection were found	"Negative culture" Clinical signs of infection found	34
7	23.09.24	Comminuted fracture of the pelvic basin, ischial bone, pubic bone on the right, and marginal fracture of the femoral head with the presence of a foreign body	Penis and hanging part of the urethra with secondary injury to the right sciatic nerve	Not performed	*Klebsiella pneumoniae Staphylococcus epidermidis*	7	38

with gunshot combined injuries. OHS, WOMAC, and HOOS are more focused on the patient's perception, while SF-36 is used for a general assessment of quality of life.

Clinical Case No. 1

A 45-year-old male patient was admitted for treatment at the trauma clinic with a gunshot wound causing a combined penetrating transabdominal injury to the right hip joint, accompanied by a comminuted fracture of the neck and head of the right femur, a comminuted fracture of the acetabulum, body, and wing of the right ilium with displacement of bone fragments and formation of a bone defect, small intestine injury, and formation of a massive retroperitoneal hematoma in the pelvic region. The patient was in hypovolemic shock, stage III.

Initially, the patient was hospitalized in the emergency medical department, where an abdominal and

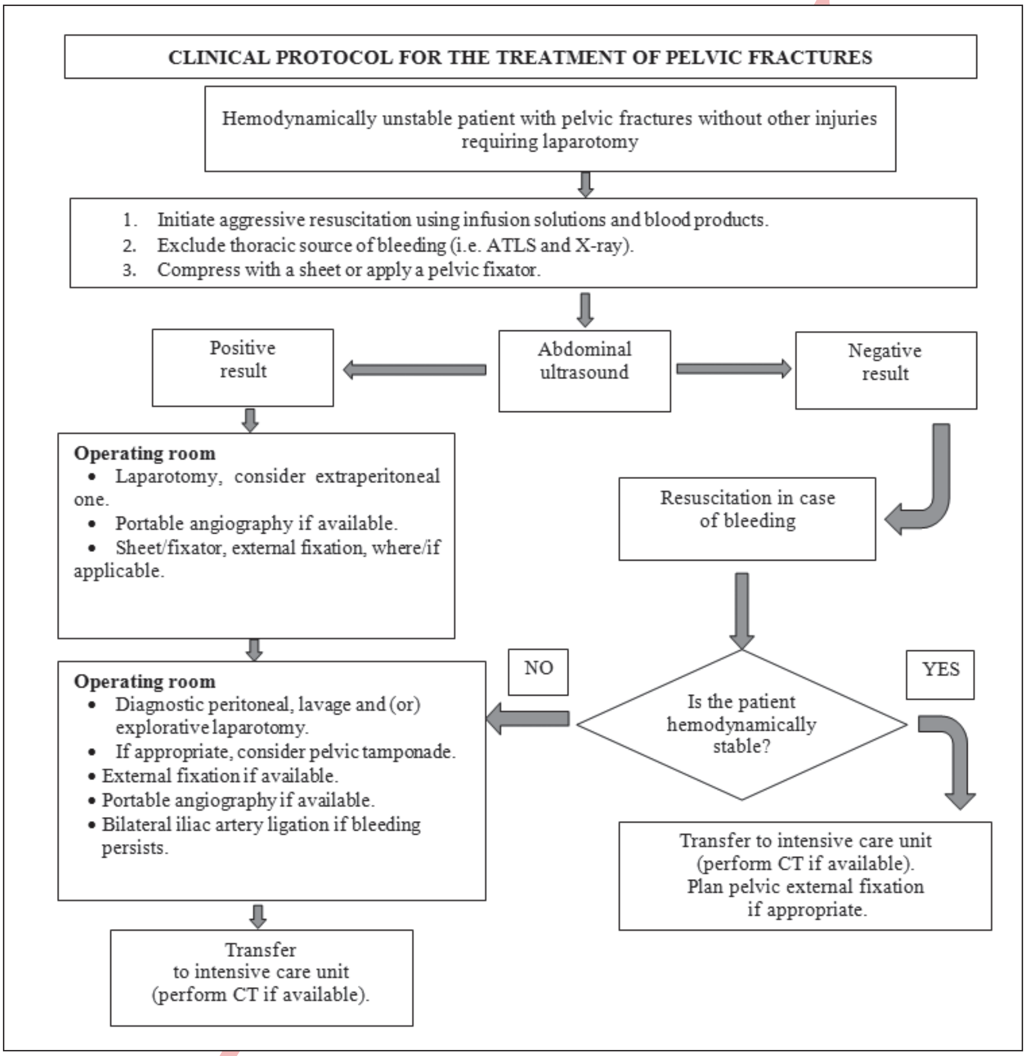

Fig. 1. New clinical protocol for the treatment of pelvic bone fractures (combat injuries)

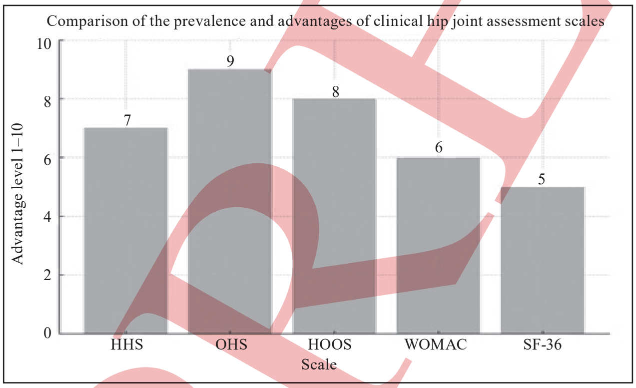

Fig. 2. Prevalence level of hip joint function assessment scales

pelvic ultrasound was performed, revealing free fluid in the abdominal cavity. Radiography of the pelvic bones was carried out, capturing both hip joints, revealing a fracture of the neck and head of the right femur, a comminuted fracture of the acetabulum, body, and wing of the right ilium with displacement of bone fragments (Figure 3, a). After stabilizing the patient's condition and performing PST of the wounds, a laparotomy was performed, along with suturing of the gunshot wounds to the small intestine, revision and drainage of the retroperitoneal hematoma on the right, and sanitation and drainage of the abdominal cavity. The fracture of the pelvic bones and proximal femur was stabilized using a rod EFD for the "pelvis-femur" according to the principles of damage control surgery.

After the surgery, the patient was placed in the anesthesiology, resuscitation, and intensive care unit (ARICU). A CT scan was then performed to clarify the nature of the pelvic bone fractures and the proximal right femur, with 3D modeling (Figure 3, b, c), and follow-up CT scans were performed three months later (Figure 4).

Seven months later, the patient's condition worsened. He presented with pain in the right hip joint and an increase in body temperature. During microbiological examination using PCR, *Klebsiella pneumoniae, Candida krusei*, and *Acinetobacter baumannii* were identified. After further examination, the diagnosis of acute sepsis and septicemia (*Klebsiella pneumoniae, Candida krusei, Acinetobacter baumannii*) was confirmed.

Subsequent repeat surgical treatments were performed with the application of primary delayed sutures. During the treatment phases, no antibacterial cement spacer was installed. One year after the injury, the patient underwent total hip replacement of the right hip joint using a custom-made titanium acetabular implant. A follow-up CT of the pelvis was performed three months after the surgery, and the general appearance of the right hip joint area is shown in Figure 4, a, b.

Post-treatment status after THR. Post-traumatic neuropathy of the right tibial and common fibular nerves with significant paresis of the right foot. The patient was treated with lincomycin 600 mg twice daily intravenously, tazobactam 4.5 g in 100 ml of 0.9% sodium chloride solution, three times a day, transitioning to tigecycline 50 mg twice a day and voriconazole 200 mg twice a day for 21 days. The total duration of antibiotic therapy was 6 weeks. During the treatment, the patient's condition improved. The clinical outcome was assessed 33 months after the injury and 21 months after the final surgery using the HHS. The total score was 48 points, indicating a poor clinical result.

Clinical Case No. 2

A 45-year-old male patient sustained a combined gunshot wound to the proximal right femur and pelvic organs, resulting in a fracture of the acetabulum and penetrating injury to the upper ampullary part of the rectum, along with the presence of a foreign body (bullet) in the left gluteal area. The following procedures were performed: PST of the wounds, a damage control procedure with a Maidle sigmoidostomy and drainage of the perirectal tissue according to McWarter and fixation of the right hip joint and pelvic bones, which was achieved using a rod EFD "pelvis-femur".

The post-operative period was complicated by the development of phlegmon of the perirectal tissue. Microbiological examination revealed *Acinetobacter spp., Pseudomonas aeruginosa*, and the patient received colistin and tigecycline. After eradication of the infection, the sigmoidostomy was closed, and the rectal passage was restored.

31 months after the injury, the patient underwent THR. 6 months after the THR, according to the HHS, the patient achieved 80 points, indicating a good result.

Clinical Case No. 3

A 34-year-old male patient was hospitalized with a gunshot wound to the left hip joint, resulting in

Table 2

Comparative analysis of hip joint function assessment scales

Шкала	Оцінювання/ класифікація	Суб'єк-ть/об'єк-сть	К-ть балів/ запитань	Основне застосування	Переваги	Недоліки
Harris Hip Score (HHS)	Pain, function (walking, stairs, footwear), range of motion, deformity	Combination: doctor + patient	100 points	Clinical examination, joint replacement, injuries	Objective parameters, classic and well-known scale	Less sensitive to patient's subjective feelings, has a "ceiling" in results
Oxford Hip Score (OHS)	Pain and function in daily life	Patient (self-completion)	12 questions (0–48 points)	Quality of life after joint replacement	Simple, convenient, validated	Subjective, without clinical objective component
WOMAC	Pain, function, stiffness	Patient	24 questions	Osteoarthritis, clinical studies	Well adapted for osteoarthritis	Not specific only to the hip joint
HOOS	Pain, symptoms, function, sport/recreation, quality of life	Patient	40 questions	Extended version of WOMAC for the hip joint	Broader domain coverage	Longer questionnaire, more complex to use
SF-36	Quality of life (8 domains, including physical and mental health)	Patient	36 questions	Overall health assessment	Comprehensive assessment, multidisciplinary	Not specific to the hip joint

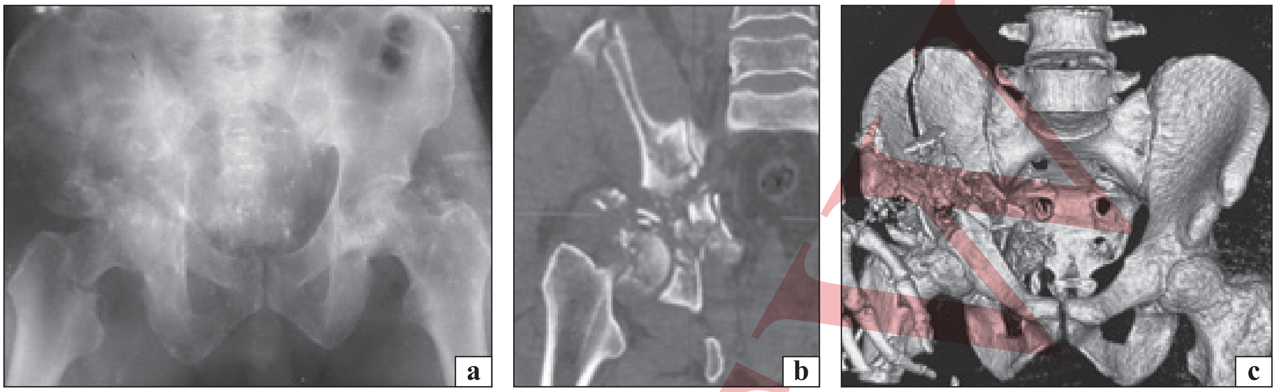

Fig. 3. Photographs of the patient (clinical case No. 1): a — X-ray of the pelvic bones, b and c — CT of the pelvic bones with modeling, comminuted fracture of the neck and head of the right femur, comminuted fracture of the right acetabulum, body and wing of the right iliac bone with displacement of bone fragments and formation of a bone defect

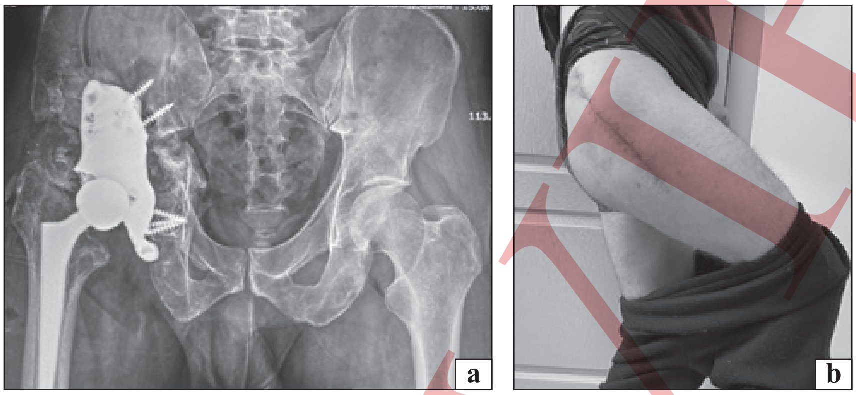

Fig. 4. Photographs of the X-ray image and the right hip joint of the patient (clinical case No. 1): a — control CT of the pelvic bones with hip joints 3 months after surgery, hip joint endoprosthesis and titanium acetabular; b — general view of the proximal femur after surgery with active flexion in the hip joint.

a fracture of the femoral head and neck and a comminuted fracture of the acetabulum floor with displacement, along with damage to the sciatic nerve.

After PST of the wound, the left hip joint was stabilized with a rod EFD “pelvis-femur” according to the damage control principles. After wound healing, the EFD was removed, and the left hip joint was fixed with a circular hip brace. Because of the infection risk, THR was postponed initially, but the procedure was performed 23 months after the injury.

27 months after the injury, the patient still had sciatic neuropathy and contracture of the left knee, significantly impairing the support function of the lower limb. 6 months after the THR, the patient had 36 points on the HHS, indicating a poor treatment outcome.

Clinical Case No. 4

A 47-year-old patient with a combined gunshot shrapnel penetrating injury to the abdomen and contusion of the extraperitoneal portion of the sigmoid colon, fracture of the left ilium and acetabulum with the presence of a foreign body (metallic shrapnel) in the left sacroiliac joint. The following procedures were performed: PST of the wounds, laparocentesis with subsequent myoplasty of the left lateral abdominal wall according to the damage control principle. Nine months after the injury, THR was performed. According to the HHS, 24 months after the THR, the patient received 84 points, indicating a good treatment outcome.

Clinical Case No. 5

A 46-year-old male soldier sustained a combined gunshot shrapnel injury to the pelvis with a gunshot fracture of the femoral head and upper third of the right femur, a fracture of the right ilium with rectal injury, formation of a retroperitoneal hematoma on the right side, and fecal peritonitis. An urgent laparotomy was performed, including obturative resection of the colon, rectal repair, tamponade of the abdominal cavity, and fixation of the hip joint and pelvic bones with a rod EFD “pelvis-femur” according to the damage control principle. The patient was later transferred to medical institutions in western Ukraine. Three weeks later, the EFD was removed. Four months later, an antibacterial cement spacer was installed due to the development of an infection in the hip joint (*Pseudomonas aeruginosa, Klebsiella*). Due to prolonged bed rest (10 months), the patient developed pressure sores in the sacral area. Reconstruction was performed only in 2 years — restoring the connection between the sigmoid and rectum with the formation of an ileostomy. Final reconstruction of the small intestine is planned. During the surgical interventions, the patient developed adhesion disease and, due to prolonged bed rest and inadequate rehabilitation, developed an extensor contracture of the knee joint. Two years after the injury, the patient received 32 points on the Harris Hip Score (HHS), indicating a poor treatment outcome. THR was not performed.

Clinical Case No. 6

A 30-year-old male patient with a combined gunshot shrapnel injury to the pelvis and extremities, with a comminuted fracture of the pubic and ischial bones, a dislocation of the femoral head, massive bone and soft tissue defects, traumatic amputation of the penis, left scrotal injury, and damage to both testicles. The following procedures were performed: PST of the left inguinal and gluteal wounds, resection of the hanging part of the penis, bilateral orchiectomy, placement of an epi-cystostomy; fixation of the upper third of the femur fragments using a rod EFD "pelvis-femur" according to the damage control principle. Nine months after the injury, the patient underwent THR. The patient continued to have urinary issues due to chronic prostatitis, along with the absence of part of the penis and testicles. According to the HHS, 7 months after the THR, the patient received 34 points, indicating a poor treatment outcome.

Clinical Case No. 7

A 37-year-old male soldier was hospitalized with a combined gunshot wound to the pelvis and extremities, with a complete rupture of the pendulous part of the urethra, comminuted fracture of the acetabulum, ischial and pubic bones on the right side, and marginal fracture of the femoral head along with the presence of a foreign body. The following procedures were performed: PST of the wounds, laparotomy, cystostomy, bladder revision, suturing of the wound in the pendulous part of the urethra on the catheter, epi-cystostomy with drainage of the paravesical space and pelvis, fixation of the pelvic bone fragments and the right femoral head with a rod EFD "pelvis-femur" according to the damage control principle. Later, the patient developed chronic post-traumatic osteomyelitis of the femoral head, complicated by phlegmon of the right hip joint and perineum. Three months after the injury, drainage of the phlegmon in the right hip joint and perineum was performed. After revision of the hip joint area, debridement, and placement of an antibacterial cement spacer with gentamicin and vancomycin, the patient developed complications in the right hip joint area (*Klebsiella pneumoniae and Staphylococcus epidermidis*). Only after removal of the spacer, repeated surgical treatments, and administration of a combination of linezolid 600 mg and co-trimoxazole (Biseptol 480 mg) for 6 weeks, the infectious process was controlled. According to the HHS, 12 months after the injury, the patient received 38 points, which indicates a poor treatment outcome. THR was not performed.

Statistical analysis showed that among 7 patients with an average age of 41.1 years, THR was performed in 5/7 (71 %). The average time to THR was approximately 17.0 months. Infectious complications were found in 4 out of 7 (57 %). The most common pathogens were *Klebsiella pneumoniae* (3), *Pseudomonas aeruginosa* (2); other pathogens included *Acinetobacter / A. baumannii, Staphylococcus epidermidis*, and *Candida krusei*. The average HHS for all patients was 50.3, for those with infections it was 49.5, and for those without infections it was 51.3. Based on the data, it was revealed that the high percentage of infections (57 %) and the dominance of Gram-negative flora (*Klebsiella, Pseudomonas, Acinetobacter*) requires a change in the treatment strategy, including early microbiological diagnostics, aggressive wound debridement, and targeted antibiotic therapy. Due to contamination (fecal, urogenital, or foreign bodies such as bullets, shrapnel) and massive defects, in some cases, delayed reconstruction or THR with a staged approach is advisable, which corresponds to current recommendations for post-traumatic and contaminated cases.

According to the literature, in the case of established infection or suspected sterility, a two-stage strategy (removal with intensive debridement using an antibacterial cement spacer, followed by reconstruction or THR after infection eradication) shows better results in controlling infection in several studies.

In all 4 patients studied, the presence of Gram-negative pathogens was found. In two of them, antibiotic spacers were used. Despite the use of antibiotic spacers, complete eradication of the infection was not achieved, and therefore THR was postponed due to the persistence of the microflora.

Given the high percentage of unsatisfactory treatment outcomes, there was a need to form a preliminary treatment algorithm for gunshot combined injuries of the hip joint based on our own research and the data from literature sources [17–21].

I. Initial measures (acute period):

1. ABC (resuscitation), hemostasis, shock control — damage control principles. Embolization or vascular reconstruction in pelvic hemorrhage;

2. Rapid multidisciplinary assessment (traumatologist, abdominal surgeon, urologist, infectious disease specialist);

3. Early and documented microbiological diagnosis, initiation of antibiotic therapy considering the risk of Gram-negative multi-resistant bacteria in combat injuries.

II. Surgical tactics in the acute period:

1. Radical surgical treatment, necrectomy, removal of foreign bodies;

2. Control of contamination sources (small and large intestine, rectum, urethra/urogenital tract);

3. Primary stabilization of the pelvis (external fixation according to damage control orthopedics);

4. Use of antibacterial spacers or VAC therapy for soft tissue and bone defects.

III. Planning of reconstruction or THR:

1. In the absence of infection and with stable soft tissues — delayed THR (after ≥ 6 months);

2. In the presence of infection or high risk — two-stage approach (sanitation, antibiotic spacer → THR);

3. In case of Gram-negative flora (Klebsiella, Pseudomonas, Acinetobacter) and multi-resistant flora, mandatory consultation with an infectious disease specialist and immunologist with the use of reserve antibiotics based on sensitivity, considering the potential presence of biofilm on implants.

IV. Orthopedic technical recommendations for THR after gunshot injury to the hip joint:

1. Preparedness for large bone defects: use modules for restoring acetabular defects (anti-protrusion rings, structural autografts/allografts, and in case of a large defect — additive technologies);

2. In case of neurological damage (sciatic nerve) — realistic expectations regarding function; consider special prostheses/limiting devices to reduce dislocations in conditions of weak muscles;

3. Planning for implantation with the involvement of a rehabilitation specialist — individual recovery program.

V. Postoperative control:

1. Regular clinical and laboratory monitoring: C-reactive protein, ESR, procalcitonin;

2. Aspiration if infection is suspected and mandatory microbiological testing;

3. Targeted antibiotic therapy based on culture results with mandatory consultation with an infectious disease specialist and immunologist;

4. Individual rehabilitation program.

Discussion

Gunshot combined injuries of the pelvis and hip joint are severe polystructural trauma, and the treatment outcome depends on timely, consistent, and adequate medical assistance at all levels; the degree of damage to the internal organs of the abdominal cavity and pelvic region, especially the small and large intestines; and the nature of the fracture of the bone structures involved in the formation of the hip joint.

Patients with pelvic bone fractures and hemodynamic instability present a complex challenge for the trauma team, as acute bone fragments resulting from pelvic ring injuries can tear surrounding soft tissues and cause severe bleeding. The most common sources of bleeding are the fracture surfaces and the retroperitoneal venous plexus; less frequently, damage occurs to the sciatic artery [22].

The group at risk also includes the hollow visceral organs of the abdominal cavity and pelvis, as well as the LV nerve root and lumbar plexus.

Pelvic bone fractures are often associated with other life-threatening injuries. The mortality rates among the civilian population range from 6 % to 35 %, with higher rates associated with open fractures [7, 23, 24].

High-velocity gunshot wounds (> 2000 ft/s) are characterized by more destructive effects on the musculoskeletal system, requiring more aggressive surgical intervention strategies, similar to open fractures resulting from blunt trauma [25–28].

Although hip and pelvic joint injuries are rare, their diagnosis and treatment remain complex, particularly in cases of blind combined injuries, where the entry wound is located not over the damaged joint but in another anatomical region [10].

The most challenging to treat are transabdominal gunshot wounds to the hip joint and pelvis, as they are accompanied by contamination (soiling) of these areas with bowel contents. This requires urgent surgical intervention for vascular, visceral, and urogenital injuries after achieving hemodynamic stability [11, 29–31].

There is a consensus in the literature regarding the removal of intra-articular bullets, which are in contact with synovial fluid, to avoid mechanical joint destruction, lead arthropathy, plumbism (systemic lead toxicity), and infection [20].

Bullets and metal fragments located within the bone without contact with synovial fluid do not require removal, but the risk of infection in this category of gunshot wounds is higher compared to gunshot fractures of the limbs [32–34].

In gunshot wounds to the abdomen, buttocks, or thighs, there should be a high suspicion of a transpelvic trajectory. It is important to note that the bullet's path can be nonlinear with unpredictable trajectories due to its instability, ricochets, and fragments [20, 35].

P.H. Navsaria et al. defined the indications for laparotomy as: peritoneal signs, hemodynamic instability, rectal bleeding, or the inability to perform a reliable clinical examination. They suggested routine CT scans only for macroscopic hematuria. The percentage of non-operative treatment for transpelvic injuries was 26.4 %, with a minimum of 24 hours of careful monitoring. The frequency of therapeutic laparotomies in their study was 97.7 % [16].

According to foreign sources, the main recommendations for gunshot transpelvic injuries of the hip joint should include mandatory repeated intra- and postoperative sampling for microbial cultures and sensitivity testing, early removal of foreign fragments (if possible), and radical wound sanitation. Molecular methods (mNGS) can be helpful in cases of negative cultures or polymicrobial infections. Empirical therapy based on local resistance data should be conducted. In military cases, it is necessary to account for the high frequency of multidrug-resistant gram-negative strains [6, 32, 39, 40–43].

Such injuries are associated with a high percentage of unsatisfactory treatment outcomes due to the development of infectious complications, lack of adequate surgical intervention, and, given the deep location of the hip joint, the development of contractures in adjacent joints due to the absence of timely and appropriate rehabilitation. Other complications may include adhesive disease, formation of bowel and bladder fistulas in case of damage to these organs, pressure ulcers, and deep vein thrombosis of the lower extremities due to prolonged bed rest and lack of preventive measures, as well as cosmetic and functional changes in the genital organs.

The use of damage control surgery in patients with gunshot wounds to the hip joint should be strictly individualized, as the high risk of infectious complications does not allow for a predictable good outcome. Emphasis should be placed on wound sanitation, controlled stabilization, a staged approach, and delayed reconstruction.

This category of patients should be treated in multidisciplinary healthcare institutions of the Ministry of Defense and the Ministry of Health of Ukraine, where all diagnostic and therapeutic equipment is available, and surgeons with a high level of expertise and experience in treating severe combined combat trauma are present. These institutions should also ensure timely medical and social rehabilitation.

Conclusions

Combined gunshot wounds of the hip joint with concomitant damage to the internal organs of the abdominal cavity and pelvic region are complex both diagnostically and therapeutically, characterized by a high risk of complications and significant deterioration in the quality of life in the future.

Based on statistical analysis, it was established that, among 7 patients with an average age of 41.1 years, damage control surgery was performed in 5 out of 7 (71 %). The average time to damage control surgery was 17 months. Infectious complications were observed in 5% of the patients, with *Klebsiella pneumoniae* and *Pseudomonas aeruginosa* being the predominant contaminants.

The implementation of damage control surgery in this category of patients requires an extremely cautious approach. The obtained results indicate the need for further clinical studies to determine the optimal criteria for indications for damage control surgery after combat-related injuries of the hip joint.

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

Prospects for Further Research. It can be expected that the use of the proposed preliminary treatment algorithm for gunshot combined injuries of the hip joint could potentially reduce the incidence of infectious complications, but this needs to be confirmed by further clinical studies.

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References

1. Becker, V. V., Brien, W. W., M., P., & J., W. (1990). Gunshot injuries to the hip and abdomen. *The journal of trauma: injury, infection, and critical care, 30*(11), 1324–1329. https://doi.org/10.1097/00005373-199011000-00003
2. Gunshot injuries resulting in arthroplasty: A literature review and case report resulting in a Megaprosthesis. (2024). *Annals of Case Reports, 9*(3). https://doi.org/10.29011/2574-7754.101855
3. Atlas of combat surgical trauma (experience of anti-terrorist operation / joint forces operation). (2021). Kharkiv: Collegium.
4. Almirah, A., Mahyoub, A., Al-Gabaly, W., Haidar, H., Alhamadi, W., Mothanna, Z., & Ahmed, F. (2024). Treatment outcomes of total hip arthroplasty following hip joint gunshot and shell fragment injuries: Insights from a single-center retrospective study in Yemen. *Cureus*. https://doi.org/10.7759/cureus.71648
5. Antoni, A., & Maqungo, S. (2023). Current concepts review: Management of civilian transpelvic gunshot fractures. *Injury, 54*(12), 111086. https://doi.org/10.1016/j.injury.2023.111086
6. Taheriazam, A., & Saeidinia, A. (2023). Two-stage revision of infected hip prosthesis after post-operative antibiotic therapy: An observational study. *Medicine, 102*(6), e32878. https://doi.org/10.1097/md.0000000000032878

7. Dheenadhayalan, J., Nagashree, V., Devendra, A., Velmurugesan, P. S., & Rajasekaran, S. (2023). Management of open fractures: A narrative review. *Journal of clinical orthopaedics and trauma*, 44, 102246. https://doi.org/10.1016/j.jcot.2023.102246
8. Kalairajah, Y., Azurza, K., Hulme, C., Molloy, S., & Drabu, K. J. (2005). Health outcome measures in the evaluation of total hip Arthroplasties — A comparison between the Harris hip score and the Oxford hip score. *The journal of arthroplasty, 20*(8), 1037–1041. https://doi.org/10.1016/j.arth.2005.04.017
9. Pohleman, T., Bosch, U., Haas, N., & Tscherne, H. (1992). Standardized techniques for internal stabilization of the pelvic ring. *Journal of orthopaedic trauma, 6*(4), 484. https://doi.org/10.1097/00005131-199212000-00030
10. Hanna, T. N., Shuaib, W., Han, T., Mehta, A., & Khosa, F. (2015). Firearms, bullets, and wound ballistics: An imaging primer. *Injury, 46*(7), 1186–1196. https://doi.org/10.1016/j.injury.2015.01.034
11. Atlas of radiological diagnostics of gunshot wounds: atlas. (2024). Vinnytsia: TVORY.
12. Fischer, M., Nonnenmacher, L., Reichert, J. C., Bohnert, J. A., Idelevich, E. A., Doğan, E., Becker, K., & Wassilew, G. I. (2024). Case report: Hip arthroplasty after fracture-related joint infection caused by extensively drug-resistant klebsiella pneumoniae. *Frontiers in surgery*, 11. https://doi.org/10.3389/fsurg.2024.1363298
13. Clinical practice guidelines joint trauma system war wounds: debridment and irrigation (CPG ID:31). (2024).
14. Joint Trauma System Pelvic Fracture Care Clinical Practice Guidelines (CPG ID: 34). (2024).
15. Davis, J. M., Stinner, D. J., Bailey, J. R., Aden, J. K., & Hsu, J. R. (2012). Factors associated with mortality in combat-related pelvic fractures. *Journal of the American academy of orthopaedic surgeons*, 20, S7–S12. https://doi.org/10.5435/jaaos-20-08-s7
16. Navsaria, P. H., Edu, S., & Nicol, A. J. (2011). Nonoperative management of pelvic gunshot wounds. *The American journal of surgery, 201*(6), 784–788. https://doi.org/10.1016/j.amjsurg.2010.03.014
17. Alqazzaz, A., Bush, A. N., Zhuang, T., Dehghani, B., Gibon, E., & Nelson, C. L. (2024). Acute total hip arthroplasty following acetabular fracture is associated with a high risk of revision, dislocation, and Periprosthetic fracture. *The journal of arthroplasty, 39*(9), S270–S274.e1. https://doi.org/10.1016/j.arth.2024.04.046
18. Poole, G. V., Ward, E. F., Muakkassa, F. F., Hsu, H. S., Griswold, J. A., & Rhodes, R. S. (1991). Pelvic fracture from major blunt trauma outcome is determined by associated injuries. *Annals of surgery, 213*(6), 532–539. https://doi.org/10.1097/00000658-199106000-00002
19. Das, A., Tripathy, S. K., Mohapatra, I., Poddar, N., Pattnaik, D., S, S., & Panigrahi, K. (2025). Microbiological profile and outcome of surgical site infections following orthopedic surgeries in a tertiary care hospital. *Cureus*. https://doi.org/10.7759/cureus.76874
20. Qin, Y., Liu, Z., Li, L., Yang, Y., Huang, X., Liang, W., & Lin, L. (2024). Comparative reinfection rate of one-stage versus two-stage revision in the management of periprosthetic joint infection following total hip arthroplasty: A meta-analysis. *BMC Musculoskeletal Disorders, 25*(1). https://doi.org/10.1186/s12891-024-08199-y
21. Sop, J. L., Sop, A. Open Fracture Management. (2025).. Treasure Island (FL): StatPearls Publishing.
22. McLean, J. M., Cappelletto, J., Clarnette, J., Hill, C. L., Gill, T., Mandziak, D., & Leith, J. (2016). Normal population reference values for the Oxford and Harris hip scores — Electronic data collection and its implications for clinical practice. *HIP International, 27*(4), 389–396. https://doi.org/10.5301/hipint.5000465.
23. Croce, M. A., Magnotti, L. J., Savage, S. A., Wood, G. W., & Fabian, T. C. (2007). Emergent pelvic fixation in patients with exsanguinating pelvic fractures. *Journal of the American college of surgeons, 204*(5), 935–939. https://doi.org/10.1016/j.jamcollsurg.2007.01.059
24. Sodagari, F., Katz, D. S., Menias, C. O., Moshiri, M., Pellerito, J. S., Mustafa, A., & Revzin, M. V. (2020). Imaging evaluation of Abdominopelvic gunshot trauma. *RadioGraphics, 40*(6), 1766–1788. https://doi.org/10.1148/rg.2020200018
25. Pathomorphosis of gunshot wounds of soft tissues. (2018). Under the general editorship of Tsymbalyuk, V. I., Khomenko, I. P., Lurin, I. A., Usenko, O.Yu., Boyka, V. V. Kharkiv: Kolegium.
26. Bartlett, C. S. (2003). Clinical update: Gunshot wound ballistics. *Clinical orthopaedics and related research*, 408, 28–57. https://doi.org/10.1097/00003086-200303000-00005
27. Barach, E., Tomlanovich, M., & Nowak, R. (1986). Ballistics: A Pathophysiologic examination of the wounding mechanisms of firearms: Part I. *The journal of trauma: injury, infection, and critical care, 26*(3), 225–235. https://doi.org/10.1097/00005373-198603000-00003
28. Bartkiw, M. J., Sethi, A., Coniglione, F., Holland, D., Hoard, D., Colen, R., Tyburski, J. G., & Vaidya, R. (2010). Civilian gunshot wounds of the hip and pelvis. *Journal of orthopaedic trauma, 24*(10), 645–652. https://doi.org/10.1097/bot.0b013e3181cf03ea
29. Treatment of the wounded with combat injuries of the abdomen (based on the experience of the ATO/JFO): monograph. (2022). Kherson: Oldi+.
30. Guidelines for military field surgery. (2024). Kyiv: «Lyudmila Publishing House».
31. Lopez, P. P. (2007). Unstable pelvic fractures: The use of angiography in controlling arterial hemorrhage. *Journal of trauma: injury, infection & critical care, 62*(6), S30–S31. https://doi.org/10.1097/ta.0b013e3180654086
32. Bartlett, C. S., Helfet, D. L., Hausman, M. R., & Strauss, E. (2000). Ballistics and gunshot wounds: Effects on musculoskeletal tissues. *Journal of the American academy of orthopaedic surgeons, 8*(1), 21–36. https://doi.org/10.5435/00124635-200001000-00003
33. Baum, G. R., Baum, J. T., Hayward, D., & MacKay, B. J. (2022). Gunshot wounds: Ballistics, pathology, and treatment recommendations, with a focus on retained bullets. *Orthopedic research and reviews*, 14, 293–317. https://doi.org/10.2147/orr.s378278
34. Miller, P. R., Moore, P. S., Mansell, E., Meredith, J. W., & Chang, M. C. (2003). External fixation or Arteriogram in bleeding pelvic fracture: Initial therapy guided by markers of arterial hemorrhage. *The journal of trauma: injury, infection, and critical care, 54*(3), 437–443. https://doi.org/10.1097/01.ta.0000053397.33827.dd
35. Hanson, T. M., Nierenberg, D. W., LaRoche, H. B., Mead, K. C., & Ames, J. B. (2021). Symptomatic lead toxicity and joint pain because of migration of shotgun pellets into the hip 12 years after injury. *JBJS case connector, 11*(2). https://doi.org/10.2106/jbjs.cc.20.00751
36. Tisnovsky, I., Katz, S. D., Pincay, J. I., Garcia Reinoso, L., Redfern, J. A., Pascal, S. C., Wham, B. C., Naziri, Q., & Suneja, N. (2021). Management of gunshot wound-related hip injuries: A systematic review of the current literature. *Journal of orthopaedics*, 23, 100–106. https://doi.org/10.1016/j.jor.2020.12.029
37. Smith, W., Williams, A., Agudelo, J., Shannon, M., Morgan, S., Stahel, P., & Moore, E. (2007). Early predictors of mortality in Hemodynamically unstable pelvis fractures. *Journal of orthopaedic trauma, 21*(1), 31–37. https://doi.org/10.1097/bot.0b013e31802ea951
38. Hoogeboom, T. J., De Bie, R. A., Den Broeder, A. A., & Van den Ende, C. H. (2012). The Dutch lower extremity functional scale was highly reliable, valid and responsive in individuals with hip/knee osteoarthritis: A validation study. *BMC musculoskeletal disorders, 13*(1). https://doi.org/10.1186/1471-2474-13-117
39. Agolini, S. F., Shah, K., Jaffe, J., Newcomb, J., Rhodes, M., & Reed, J. F. (1997). Arterial Embolization is a rapid and effective technique for controlling pelvic fracture hemorrhage. *The journal of trauma: injury, infection, and critical care, 43*(3), 395–399. https://doi.org/10.1097/00005373-199709000-00001
40. Ghali, A. N., Venugopal, V., Montgomery, N., Cornaghie, M., Ghilzai, U., Batiste, A., Mitchell, S., & Dawson, J. (2023).

Infectious profiles in civilian gunshot associated long bone fractures. *International orthopaedics, 48*(1), 31–36. https://doi.org/10.1007/s00264-023-05870-2

41. Ibrahim, Y., Jamal, S., & Akhtar, K. (2021). The evidence base for 2017 BOAST-4 guidance on open fracture management: Are we due an update? *Journal of clinical orthopaedics and trauma*, 17, 233–238. https://doi.org/10.1016/j.jcot.2021.03.020
42. Miley, E. N., Casanova, M. P., Pickering, M. A., Cheatham, S. W., Larkins, L. W., Cady, A. C., & Baker, R. T. (2024). Psychometric analysis of the hip disability and osteoarthritis outcome score (HOOS). *Healthcare, 12*(17), 1789. https://doi.org/10.3390/healthcare12171789
43. Ramasamy, B., Abrahams, J. M., Bunting, A. C., Costi, K., Clothier, R. J., Solomon, L. B., & Callary, S. A. (2025). Total hip arthroplasty for acute acetabular fractures through the replace-in-situ philosophy. *The bone & joint journal, 107-B*(8), 784–792. https://doi.org/10.1302/0301-620x.107b8.bjj-2024-1232.r1

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FEATURES OF SURGICAL TREATMENT OF COMBINED GUNSHOT WOUNDS OF THE HIP JOINT

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Destruction of bone and surrounding tissues in case of gunshot fractures of long bones of the extremities (clinical and radiological classification). *First report*

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Objective. To determine the nature of the destruction of the bone and surrounding tissues in gunshot fractures of the long bones of the extremities and to create their clinical and radiological classification. Material and methods. 123 cases with gunshot fractures of the long bones of the extremities (127 fractures) were studied. The number of intermediate fragments, the magnitude of their transverse displacement, the length of the bone destruction zone, the shape and size of the soft tissue wound were studied. During the operation, the state of the anatomical connection of the fragments with the periosteum and muscles was assessed. Based on known data on the mass and speed of traumatic agents, calculations of their energy that occur during the action of a bullet and a hit by a moving car were made. Results. 97 % of the victims had multifragment fractures, among them 50 % had 2–3 intermediate fragments, 30 % — 4–6 and 22 % — 7 or more, or a primary bone defect was formed. Based on the number of formed intermediate fragments, the magnitude of their transverse displacement and the presence (or absence) of anatomical connection with living tissues, we distinguished three types of gunshot fracture: 1 — with slight or moderate transverse displacement of the intermediate and main fragments (within the diameter of the bone and with preservation of the longitudinal orientation); 2 — with significant transverse displacement of one or more intermediate fragments (in the direction of the projectile movement) with loss of anatomical connection with the periosteum and formation of a parietal defect of the bone and a wound of medium or large size; 3 — with excessive transverse displacement of all intermediate fragments (in the direction of the projectile movement) with loss of their anatomical connection with the periosteum and formation of a complete transverse defect of the bone. It was found that in the majority (66%) of gunshot fractures, despite the presence of a soft tissue wound, the intermediate and main fragments retain an anatomical connection with the periosteum and muscles, and this is of great importance in choosing treatment tactics.

Мета. З'ясувати характер руйнування кістки й оточуючих її тканин за вогнепальних переломів довгих кісток кінцівок і створити їх клініко-рентгенологічну класифікацію. Методи. Досліджено 123 особи з вогнепальними переломами довгих кісток кінцівок (127 переломів). Вивчали кількість проміжних уламків, величину їхнього поперечного зміщення, протяжність зони руйнування кістки, форму та розміри рани м'яких тканин. Під час операції оцінювали стан анатомічного зв'язку уламків з окістям і м'язами. На підставі відомих даних про масу і швидкість травмуючих агентів проведено розрахунки їхньої енергії за умов дії кулі чи удару автомобілем, який рухається. Результати. У 97 % постраждалих були багатоуламкові переломи, серед них 50 % мали 2–3 проміжні уламки, 30 — 4–6 і 22 % — 7 і більше проміжних уламків, або утворився первинний дефект кістки. На підставі кількості утворених проміжних уламків, величини їх поперечного переміщення та наявності (або відсутності) анатомічного зв'язку з живими тканинами нами виділено три типи вогнепальних переломів: 1 — із незначним або помірним поперечним переміщенням проміжних і основних уламків (у межах поперечника кістки і зі збереженням повздовжньої орієнтації); 2 — зі значним поперечним переміщенням одного або декількох проміжних уламків (за напрямом руху снаряда) зі втратою анатомічного зв'язку з окістно-м'язовим футляром та утворенням пристінкового дефекту кістки і рани середніх або великих розмірів; 3 — із надмірним поперечним переміщенням усіх проміжних уламків (за напрямком руху снаряда) з втратою ними анатомічного зв'язку з окістно-м'язовим футляром та утворенням повного поперечного дефекту кістки. Висновки. Виявлено, що за більшості (66 %) вогнепальних переломів, не дивлячись на наявність рани м'яких тканин, проміжні й основні уламки зберігають анатомічний зв'язок з окістям і м'язами, це має важливе значення вибору тактики лікування. Ключові слова. Вогнепальні переломи, морфологія, класифікація.

Keywords. Gunshot fractures, morphology, classification

Introduction

Fractures caused by projectiles with a reserve of kinetic energy are different from those we are used to seeing in peacetime, as they are associated with the action of a high-energy carrier. From the experience of recent years, it is evident that fractures of long bones caused by bullets or shrapnel occur in the following forms: comminuted (26 %), shattered (69 %), and with the formation of a primary bone defect (5 %) [1]. Our previous analysis of gunshot fractures showed that they approached types B (40 %) and C (47 %) in terms of the fracture plane and the number of fragments, according to the AO classification (Fracture and Dislocation Classification Compendium) [3]. However, some types of gunshot bone destruction were not accounted for, such as fractures that involve the presence of a bone defect.

In scientific articles on the treatment of gunshot fractures, the Gustilo-Anderson classification for open fractures is used, which was proposed in 1976 [4] and later refined in 1984 [5]. Regarding the relationship between the nature of the fracture plane and the extent of soft tissue damage, the authors of the classification note that for types I and II of open fractures, there is one transverse or oblique plane, while for type III, there are several planes and the formation of intermediate fragments. It should be noted that this classification is based on the experience of treating open fractures in peacetime, among which fractures with a single fracture plane are most common.

The morphology of a gunshot fracture is inextricably linked to the destruction of the surrounding soft tissues, and all of this must be considered and evaluated as a whole. From our point of view, having a uniform mechanism of injury and similar patterns of destruction, gunshot fractures require a separate classification that would divide them by severity, healing prognosis, and would also serve as a basis for choosing the treatment method.

Objective: To investigate the nature of bone destruction and the surrounding tissues in gunshot fractures of long bones in the limbs and create a clinical-radiological classification for them.

Materials and Methods

The study was conducted in compliance with the requirements and provisions of the Helsinki Declaration on human rights, the Constitution and basic health protection laws of Ukraine, and all ethical standards regarding clinical research (Protocol No. 256 dated 17.11.2025, State Institution Professor M. I. Sytenko Institute of Spinal Pathology and Joint Diseases of the National Academy of Medical Sciences of Ukraine). All patients signed informed consent.

The study is based on the experience of treating 123 patients with gunshot fractures of long bones in the limbs at the State Institution Professor M. I. Sytenko Institute of Spinal Pathology and Joint Diseases of the National Academy of Medical Sciences of Ukraine (93 cases) and the Communal Non-profit Enterprise M.I. Kononenko Chuhuiv Central Hospital (30 cases). By the localization of the affected segment, the distribution was as follows: lower leg 38 (34 %), thigh 30 (24 %), shoulder 30 (24 %), forearm 25 (18 %). Among them, in 4 cases, two segments were affected in different combinations (a total of 127). These patients were admitted urgently either directly from the trauma site (36 cases) or within 3-12 days after the injury for continued treatment with an external fixation device.

Clinical evaluation of the shape and size of the wound channel or defect

Among the variety of gunshot wounds, we consider it rational to distinguish three variants. The *tunnel form* of the wound channel has the following characteristics:

– the length of the channel exceeds or corresponds to the size of the skin wound;

– the volume of soft tissue defect is not large, disappearing into the depth due to the adhesion of the walls, and the edges of the skin wound can be approximated with sutures;

– it can be either a blind or a through wound.

Sectoral form of the defect, which extends either to the soft tissues only or to both the soft tissues and the destroyed bone. The characteristics of this form are:

– the possibility of visual control over almost the entire wound surface;

– tissue deficiency and difficulty in approximating the wound edges.

A combination of both variants is possible when the entry tunnel part of the wound channel transitions into a sectoral form (*tunnel-sectoral form*).

During the initial examination of a gunshot fracture, it is not always possible to measure and assess the extent of soft tissue destruction, especially when the channel has a tunnel form. The main objective parameter is the size of the skin wound, which we propose to classify as small (up to 3 cm), medium (4–10 cm), and large (over 10 cm), taking its largest longitudinal dimension as the basis.

Characteristics of bone destruction and fragment displacement based on radiographic data

Since most fractures were comminuted and could be classified as types B and C, we focused on the following signs:

1. The number of intermediate fragments, their shape, and size;

2. The extent of the maximum transverse displacement of the main fragments (Fig. 3) relative to each other. This was measured with the fragments fixed by an external device and expressed as a percentage of the transverse size of the bone;

3. The extent of the maximum transverse displacement of intermediate fragments (Fig. 3) relative to the surface of the main fragments, also expressed in relative units. Special attention was given to the presence of rotational displacement of fragments, which could indicate their detachment from soft tissues. If there was a transverse displacement of the intermediate or main fragment relative to the bone's transverse diameter, it was considered insignificant or moderate; if it exceeded the full transverse diameter, it was considered significant; and if it went beyond the surface of the segment, it was considered excessive.

4. The extent of the bone destruction zone (Fig. 1) was also determined as a percentage relative to the length of the segment.

Additional information about the extent of internal soft tissue destruction and the state of the anatomical connection between intermediate fragments, the periosteum, and muscles was obtained during the primary surgical treatment of the wound. During the procedures to remove metal projectiles, an attempt was made to visually and palpably assess the size of muscle destruction, as well as the condition of intermediate fragments that were found far from their natural position. It is worth noting that the ability to inspect destruction in the case of a tunnel wound channel is limited, so palpatory examination was relied upon. When necessary, in cases where metal objects needed to be removed, the wound channel was rationally expanded, and the condition of the tissues was visually assessed.

The study materials were statistically processed using both parametric and non-parametric analysis methods in Microsoft Office Excel 2016 electronic spreadsheets. The statistical analysis was carried out using the STATISTICA 10.0 software. For describing quantitative indicators, the measurement results were calculated using descriptive statistics methods: mean (M) and its standard deviation (SD), minimum and maximum values. To compare independent groups in cases of small sample sizes and absence of normal distribution of data, the Mann–Whitney U test was used. To study the relationship between phenomena, where the quantitative data distribution deviated from normal, the non-parametric method of Spearman's rank correlation coefficient was applied [6].

Results and Discussion

The analysis revealed the following distribution of gunshot fractures by the number of fragments:

- No intermediate fragments (single plane fracture) — 4 (3 %);
- 1–3 intermediate fragments — 63 (49.6 %);
- 4–6 intermediate fragments — 38 (30 %);
- 7 or more intermediate fragments — 11 (8.7 %);
- Presence of a primary bone defect — 11 (8.7 %).

Most of the fractures were comminuted fractures (97 %). Among these, 49.6 % had 1–3 intermediate fragments, and as the number of fragments increased, the frequency of such fractures decreased. It is also important to note that in 8.7 % of fractures, a bone defect was formed, preceded by a condition with a large number of intermediate fragments displaced in the direction of the projectile's motion, accompanied by soft tissue destruction. In 2 of the injured patients, the intermediate fragments were lost during the previous stages, while in the remaining 9, they were removed during repeated surgical wound debridements.

A characteristic feature of comminuted gunshot fractures of long bones was that the destruction occurred through the formation of cracks and splits, mainly oriented in the longitudinal direction, resulting in intermediate fragments with an elongated shape. This can be explained by the fact that cracks form along the interosteonal substance [7], and osteons in long bones, as known, are oriented in the longitudinal direction. As for the extent of bone destruction, the fractures were distributed as follows: 54 % of gunshot fractures affected 25% of the segment length, 43 % were in the range of 26–50 %, and 3 % had a length greater than 50 % of the segment length. Thus, we can see that significant bone destruction is associated with the formation of mainly longitudinal splits.

Displacement of main fragments

After the main fragments were joined by the external fixation system, in most fractures (76 %), a transverse displacement occurred that did not exceed the transverse diameter of the bone at this level. In the remaining 24 %, the displacement exceeded the transverse diameter. This was the position achieved during the primary surgical treatment of the wounds and fixation of the fragments with the external pin apparatus. As a rule, the fragments were aligned by traction of the segment, restoring its anatomical axis. This position of the main fragments was considered acceptable.

Magnitude and direction of intermediate fragment displacement and the nature of soft tissue destruction

The displacement of the intermediate fragments varied, and thus, we identified three clinical groups of gunshot fractures.

The *first group* consists of fractures where both intermediate and main fragments retain moderate displacement in width, creating an expansion of the damaged part of the bone, up to about 50 % (Fig. 1). In this case, the intermediate fragments maintain their longitudinal orientation and show no significant rotational displacement. Most of these fractures were combined with a blind or through-and-through tunnel-shaped soft tissue wound of small or medium size — 80 cases (63 %). This group also includes gunshot fractures with a single fracture plane (4 cases, or 3 %), with minor or moderate transverse displacement of the fragments.

The *second group* is characterized by intermediate fragments (or one of them) being displaced transversely to a significant or excessive extent, exceeding the full transverse diameter of the bone and extending beyond its boundaries. These fragments lost their longitudinal orientation or rotated around their longitudinal and transverse axes. The radiological signs indicated possible periosteum detachment from the intermediate fragments displaced in this manner (Fig. 2). Based on the characteristics and size of the wounds (medium or large), it was observed that the direction of fragment displacement corresponded to the trajectory of the projectile. The viability of the intermediate fragments was evaluated during the surgical wound treatment. If a fragment was detached from the soft tissues and surrounding necrosis had developed, it was removed, leading to the formation of a wall defect. However, another portion of the intermediate fragments remained connected to the periosteum and muscles by their outer surface, forming a kind of bridging structure between the main fragments. This variant of bone destruction was recorded in 32 cases (25 %).

The *third group* consisted of 11 cases (8.7 %) where all or most of the intermediate fragments were displaced beyond the segment, detached from the soft tissues, leading to the formation of a total bone defect (Fig. 3). In the case of the last two variants, the fracture was accompanied by a soft tissue wound, which had a tunnel-sectoral or sectoral shape of medium or large size. For a general representation of these types of gunshot fractures, a schematic illustration is provided (Fig. 4).

The numerical values of the transverse displacement of intermediate fragments in the first and second groups of patients were calculated using the non-parametric Mann-Whitney U-test. In the first group (n = 80), the average displacement was (27.1 ± 14.6) % (range 1–56), while in the second group (n = 32) it was (78.2 ± 14.0) % (range 57–100). A statistically significant difference was observed between the groups for this parameter ($U = 0$, $Z = -6.32$; $p = 0$, $p < 0.05$), which is an expected result, as a prior biased distribution by groups was made.

The number of intermediate fragments in group 1 (n = 80) averaged (2.9 ± 2.2) pieces (range 0–9), while in group 2 (n = 32) it was (4.4 ± 2.5) pieces (range 0–9). A statistically significant difference was found between the groups for this parameter, calculated using the Mann-Whitney U-test ($U = 286.5$; $Z = -2.26$; $p = 0.02$; $p < 0.05$).

A moderate direct correlation was observed between the magnitude of the maximum transverse displacement of intermediate fragments and the total size of the wound in both groups ($r = 0.44$; $p < 0.05$).

The extent of bone destruction in group 1 (n = 80) averaged (24.2 ± 9.5) % (range 6–44), in group 2 (n = 32) it was (30.2 ± 9.6) % (range 13–48), and in group 3, it was (20.5 ± 7.6) % (range 6–32). There was no statistically significant difference between the groups for this parameter (Mann-Whitney U-test: $U = 248.00$; $Z = -1.92$; $p = 0.05$; $p > 0.05$). This value is not a criterion for group classification, but in all cases, it influences the choice of method for connecting the main fragments.

A moderate direct correlation was found between the extent of bone destruction and the number of intermediate bone fragments in all groups ($r = 0.37$; $p < 0.05$).

It was observed that the nature of bone destruction in gunshot fractures significantly differs from fractures occurring in peacetime, particularly those caused by high-energy projectiles (such as vehicles moving at high speeds). For the latter, the characteristic fracture pattern is a transverse single-plane fracture or a fracture that forms one intermediate triangular-shaped fragment (so-called “bumper fracture”).

Building on known facts, let us explore the specific features of the mechanogenesis of bone destruction in gunshot fractures. First, we will calculate and compare the kinetic energy carried by bullets from common types of firearms [8] and a passenger car in motion using the well-known formula $E = mv/2$ (see Table).

The calculations show that a passenger car weighing 1300 kg moving at a speed of 60 km/h carries 7 to 12 times more kinetic energy than a bullet from a firearm with an initial velocity of 800–954 m/s.

Fig. 1. Photographic prints of the injured limb and X-ray of a 45-year-old patient Ts. who sustained a gunshot fracture of the middle third of the left tibia with moderate transverse displacement of the intermediate fragments and a blind tunnel wound of medium size. First clinical group.

Fig. 2. Photographic prints of the limb and X-ray of a 25-year-old injured patient H. who had several displaced, non-viable intermediate fragments removed during the primary surgical treatment, in the direction of the entry wound, which was closed after cleaning by suturing the edges. After 2 months, periosteal bone regeneration (indicated by the arrow) had formed over the remaining intermediate fragments. Second clinical group.

This fact leads us to assume that the magnitude of kinetic energy itself is not the cause of fragmentation during bone destruction. As we can see, a bullet or metal shrapnel primarily destroys bone by creating numerous longitudinal cracks, which, as they expand, lead to the fragmentation of the bone. According to fracture mechanics theory [9], this is the most common form of brittle failure: "the result of the avalanche-like growth of microcracks (at speeds up to 1/3 of the speed of sound), when elastic deformation reaches a magnitude that atomic bonds break...". There is also quasi-brittle failure, which is characterized by a certain zone of plastic deformation before cracks appear. According to [7, 10], compact human bone fails in a brittle manner. The authors note that the nature of this process depends on the deformation rate: at low deformation speeds, the failure process can be considered viscous, while at high deformation rates, it is distinctly brittle. Thus, we can hypothesize that in the case of a gunshot fracture, under the influence of high projectile speed, high-speed stress and deformation occur in the bone, leading to brittle failure and the formation of many fragments. Interestingly, the authors of this theory note a direct correlation between the amount of energy expended and the number of cracks (fractures) formed [9].

From a mechanical standpoint, it is crucial to differentiate between the processes of bone destruction and the subsequent damage to soft tissues. J. J. Amato et al. [11] and G. R. Baum et al. [12] experimentally and clinically demonstrated that when a projectile with high velocity strikes bone, the resulting fragments gain kinetic energy and act as secondary projectiles that damage soft tissues. However, this is only possible if the fragments accumulate enough energy to damage the periosteum, muscles with their fascial sheaths, aponeuroses, and skin. These structures, in contrast to bone, have distinct physical and

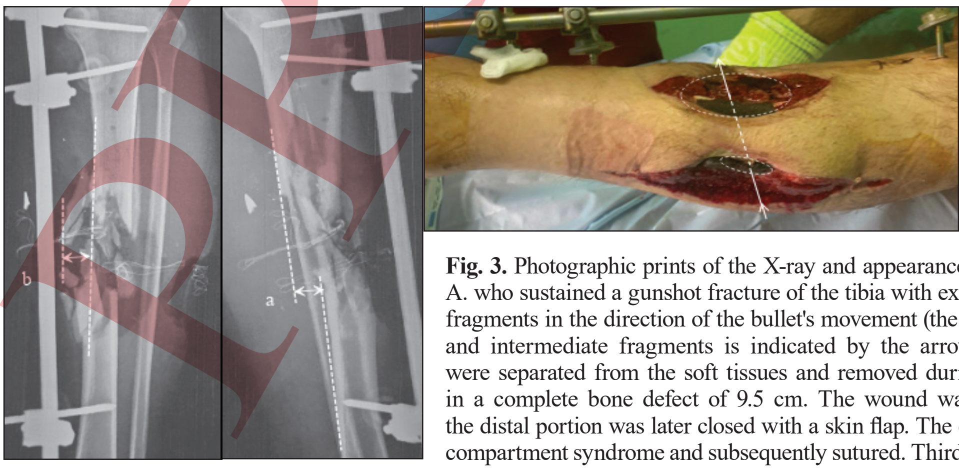

Fig. 3. Photographic prints of the X-ray and appearance of the tibia of a 45-year-old patient A. who sustained a gunshot fracture of the tibia with excessive displacement of intermediate fragments in the direction of the bullet's movement (the transverse displacement of the main and intermediate fragments is indicated by the arrows). Seven intermediate fragments were separated from the soft tissues and removed during the primary treatment, resulting in a complete bone defect of 9.5 cm. The wound was classified as tunnel-sectoral, and the distal portion was later closed with a skin flap. The entrance wound was enlarged due to compartment syndrome and subsequently sutured. Third clinical group.

Table

The kinetic energy of a moving car and bullets from different types of firearms

Source of kinetic energy	Weapon caliber (mm)	Mass of kinetic energy carrier (g)	Speed (m/s)	Amount of energy (J)
Car	—	1 300 000	16.6 (60 km/h)	17 911 400
AK 47	7.62	7.9	800	2 528 000
AK 74	5.45	3.4	914	1 420 173
M 193	5.56	3.6	954	1 638 208

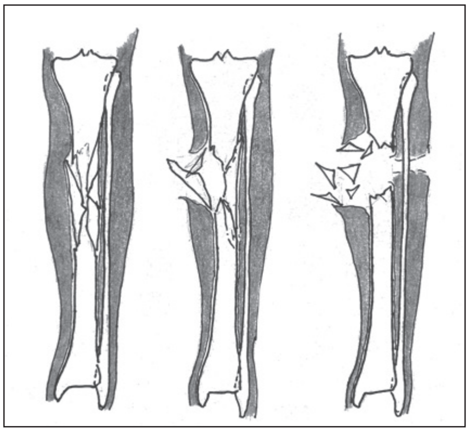

Fig. 4. Schematic representation of types of gunshot fractures.

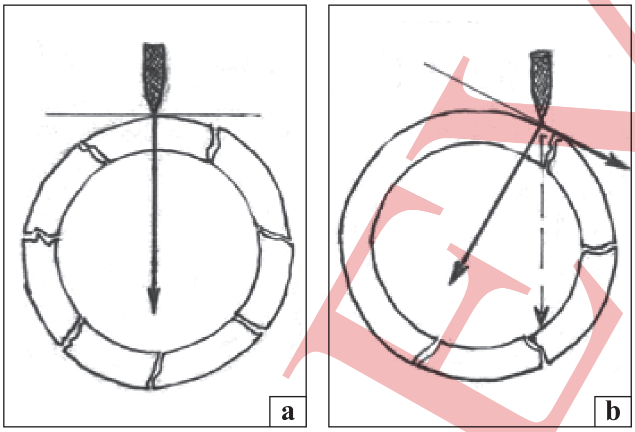

Fig. 5. Schematic representation of the distribution of the bullet's force impulse under central impact (a) and when acting at an angle (b).

mechanical properties and can withstand similar forces, but with different outcomes. For example, the periosteum, which contains a strong fibrous layer with longitudinally arranged collagen and elastin, demonstrates viscoelastic behavior and can endure tensile stress up to 26.67 MPa [13], unlike the brittle nature of bone. This means that the periosteum can deform plastically and elastically to some extent, absorbing the energy carried by the fragments without sustaining significant damage.

It is important to note that in 63 % of cases (the first clinical group), the intermediate fragments formed during a gunshot fracture did not undergo significant displacement. This may indicate that the periosteal-muscular sheath around the fractured bone was preserved, possibly with some tears. We can hypothesize that this portion of fractures occurred under conditions where the kinetic energy of the projectile was not maximized due to several factors, such as the projectile passing through the segment with minimal contact with the bone or its relatively low velocity. Therefore, in these cases of gunshot fractures, the soft tissue damage was relatively less, primarily caused by the projectile itself.

The second and third types of gunshot fractures showed signs of significant destruction of the periosteal-muscular sheath, leading to partial or complete defects in the diaphyseal walls. This was the result of the action of greater kinetic energy, enough to crush the bone, detach the fragments from the periosteum, and displace them a considerable distance. It is essential to understand that only part of the projectile's energy may be used to destroy the bone, particularly in through-and-through wounds. We propose that the effect of energy transfer from the projectile to the bone depends on the angle of the applied force relative to the bone's surface. It is known from mechanics that when a force is applied to an inclined surface, the force is distributed according to the parallelogram law — part of the force acts perpendicular to the surface, and the other part acts parallel to the inclined surface. Since long bones have a circular or triangular cross-section, there is a high likelihood that the projectile's forces act at an angle, producing a tangential vector that displaces the epicenter of bone destruction and the adjacent tissues in the corresponding direction. This can explain the asymmetrical destruction, leading to the formation of a partial defect. In cases where the projectile's force is large and directed perpendicularly to the surface of the bone (toward the bone's center), total destruction may occur, creating a full transverse defect (Figure 5).

In our view, there are significant differences between the clinical types of gunshot fractures that must be considered for predicting the healing process and determining the appropriate treatment strategy for these fractures.

In the case of the first type, the axial alignment of the fragments remains satisfactory after closed reduction and fixation of the main fragments with an external apparatus. The preservation of the anatomical connection of most of the periosteal-muscular sheath with the main and intermediate fragments is a key factor for the formation of periosteal bone regeneration, which can cover the entire area of bone destruction during further apparatus-based treatment.

The second type differs from the previous one by a significantly larger volume of damaged soft tissues and a partial (periosteal) bone defect. This type requires additional treatment measures for wound cleaning and closure, as well as various actions aimed at achieving bone union of the main fragments.

The third type of gunshot fracture differs from the previous types in that it results in a complete bone defect of varying size, requiring a different treatment approach, such as reconstructive and restorative surgeries or amputation.

Conclusions

Gunshot fractures caused by bullets or shrapnel are characterized by the presence of a destruction zone in the bone with the formation of intermediate fragments. Depending on the amount of kinetic energy transferred, these fragments may move, causing detachment from the surrounding soft tissues.

Diaphyseal gunshot fractures of long bones in the extremities, depending on the degree of displacement of the intermediate fragments and whether or not they maintain their anatomical connection with soft tissues, can be divided into three types:

– Type I – With slight or moderate transverse displacement of the intermediate and main fragments (within the bone's transverse diameter and maintaining longitudinal orientation), which preserve anatomical connection with the periosteal-muscular sheath and do not extend beyond it. In this case, the soft tissue wounds require minimal treatment (can be closed with secondary sutures).

– Type II – With significant transverse displacement of one or more intermediate fragments (in the direction of the projectile's movement), losing their anatomical connection with the periosteal-muscular sheath, and resulting in a periosteal bone defect and a medium or large wound.

– Type III – With excessive transverse displacement of all intermediate fragments (in the direction of the projectile's movement), losing their anatomical connection with the periosteal-muscular sheath, and forming a complete transverse bone defect.

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

Prospects for Further Research. A second report is planned, in which an analysis of treatment outcomes based on the proposed classification will be conducted.

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References

1. Classification of gunshot wounds of skull and cerebrum. Chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://redcross.org.ua/wp-content/uploads/2024/04/Classification-of-gunshot-wounds-of-skull-and-cerebrum.pdf
2. Korzh, M., Popsuishapka, O., Lytvyshko, V., Shevchenko, I., Doluda, Y., Gubskyi, S., Hrytsenko, A., Mikhanovskiy, D., Marushchak, O., Tokhtamyshev, M., & Arutunan, Z. (2024). Problematic issues of the treatment of diaphyseal gunshot fractures of long bones of extremities. *Orthopaedics traumatology and prosthetics,* (4), 109–120. https://doi.org/10.15674/0030-598720234109-120
3. Meinberg, E., Agel, J., Roberts, C., Karam, M., & Kellam, J. (2018). Fracture and dislocation classification compendium—2018. *Journal of orthopaedic trauma, 32*(1), S1–S10. https://doi.org/10.1097/bot.0000000000001063
4. Gustilo, R., & Anderson, J. (1976). Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones. *The journal of bone & joint surgery, 58*(4), 453–458. https://doi.org/10.2106/00004623-197658040-00004
5. Gustilo, R. B., Mendoza, R. M., & Williams, D. N. (1984). Problems in the management of type III (Severe) open fractures. *The journal of trauma: injury, infection, and critical care, 24*(8), 742-746. https://doi.org/10.1097/00005373-198408000-00009
6. Peacock, J., & Peacock, P. (2011). Oxford handbook of medical statistics. Oxford University Press.
7. Knets, G. O., Pfafrod, Y. Zh., & Saulgosis, I. V. (1980). Deformation and destruction of hard biological tissues. Riga: «Zinatne». [in russian]
8. Mahoney, P. F., Ryan, J. M., Brooks, A. J., & Schwab, C. W. (2005). Ballistik Trauma. A Pracical Guide. Springer, 2nd ed.
9. Dolgov, O. M. (2019). Fracture Mechanics: Textbook. Ministry of Education and Science of Ukraine, National Technical University «Dnipro Polytechnic». Dnipro: NTU «Dnipro Polytechnic». [in Ukrainian]
10. Strength problems in biomechanics. (1988). Ed. by I. F. Obraztsov. Moscow: «Higher School». [in russian]
11. Amato, J. J., Syracuse, D., Seaver, P. R., & Rich, N. (1989). Bone as a secondary missile. *The journal of trauma: injury, infection, and critical care, 29*(5), 609–612. https://doi.org/10.1097/00005373-198905000-00013
12. Baum, G. R., Baum, J. T., Hayward, D., & MacKay, B. J. (2022). Gunshot wounds: Ballistics, pathology, and treatment recommendations, with a focus on retained bullets. *Orthopedic research and reviews*, 14, 293–317. https://doi.org/10.2147/orr.s378278
13. Evans, S. F. (2012). Top down bottom up approaches to elucidating multiscale periosteal mechanobiology: Tissue level and cell scale studies. Department of biomedical enjineering case western reserve university.

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DESTRUCTION OF BONE AND SURROUNDING TISSUES IN CASE OF GUNSHOT FRACTURES OF LONG BONES OF THE EXTREMITIES (CLINICAL AND RADIOLOGICAL CLASSIFICATION). *FIRST REPORT*

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Application of surgical technologies for the treatment of victims with long bone defects due to modern combat trauma

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Modern combat operations cause severe injuries to humans due to the impact of new, more intense means of destruction. Objective. To determine the general structure of the application of medical technologies for the surgical treatment of victims with defects of long bones due to modern combat trauma. Materials and methods. The study is of a cohort nature, conducted in accordance with the requirements and criteria of evidence-based medicine with the level of evidence II b Oxford. The study array consisted of 115 cases of long bone defects in victims with combat trauma. This study was conducted in compliance with the requirements of the Declaration of Helsinki, approved by the Bioethics Commission of the State Research Institute «Ukrainian Scientific and Practical Center of Emergency Medical Care and Disaster Medicine of the Ministry of Health of Ukraine». Results. The study found that in the general population of victims with long bone defects due to combat trauma, the following technologies were most often used: retrograde bone transport 29.35 %, Masquelet technology 27.17 %, antegrade bone transport 21.74 %. It was also found that only Masquelet technology is used in the surgical treatment of long bone defects of all limb segments. The choice of technology for the treatment of long bone defects probably depends on the limb segment. All of the listed technologies were used on the distal segment of the lower limb, but to varying degrees. Conclusions. In the treatment of long bone defects due to modern combat trauma, technologies are diverse, including both the latest and classic approaches. Masquelet technology is the method of choice for surgical treatment of victims of modern combat trauma with bone defects of the long bones of the upper limb and the proximal segment of the lower limb. Antegrade transport technology is the method of choice for the distal segment of the lower limb. The use of a specific technology for surgical treatment of bone defects due to modern combat trauma evidently depends on the characteristics of the affected segment. Further careful research is needed to reliably explain this fact.

Особливістю сучасних бойових дій є застосування новітніх інтенсивніших засобів ураження і, як наслідок — тяжкіші ушкодження людини. Мета. Визначити загальну структуру застосування медичних технологій хірургічного лікування постраждалих із дефектами довгих кісток унаслідок бойової травми. Методи. Робота має когортний характер, проведена відповідно до вимог і критеріїв доказової медицини зі забезпеченням рівня доказовості IIb Oxford. Масив дослідження склав 115 випадків дефектів довгих кісток у постраждалих із бойовою травмою. Результати. Виявлено, що в пацієнтів із дефектами довгих кісток унаслідок бойової травми в загальному масиві найчастіше застосовувались такі технології: антеградний кістковий транспорт — 29,35 %, Masquelet — 27,17 %, ретроградний кістковий транспорт — 21,74 %. Доведено, що лише технологія Masquelet застосовується для хірургічного лікування дефектів довгих кісток усіх сегментів кінцівок. Вибір методики лікування таких дефектів вірогідно залежить від сегмента кінцівок. На дистальному сегменті нижньої кінцівки застосовувалися в різній мірі всі перелічені способи. Висновки. Існують різноманітні методики лікування дефектів довгих кісток унаслідок сучасної бойової травми — як новітні, так і класичні. Технологія Masquelet є методом вибору хірургічного втручання постраждалих унаслідок сучасної бойової травми з дефектами довгих кісток верхньої кінцівки та проксимального сегмента нижньої кінцівки. Спосіб антеградного транспорту використовується в разі ураження дистального сегмента нижньої кінцівки. Застосування конкретної методики оперативного втручання в разі кісткових дефектів здебільшого залежить від зони ураження. Для достовірного пояснення цього факту потрібні подальші ретельні дослідження. Ключові слова. Довгі кістки, дефекти, розміри, хірургічне лікування, технології.

Keywords. Long bones, defects, sizes, surgical treatment, technologies

Introduction

The ongoing modern combat operations on Ukrainian territory result in severe injuries to individuals due to the impact of newer, more intensive means of destruction. Today, the analysis of these injuries shows that 50–65 % of them affect the extremities [1, 2], often accompanied by significant damage to both bones and soft tissues. This leads to an increased risk of defects in long bones, both primary and secondary in nature [3, 4].

Unfortunately, the effectiveness of treatment for patients with long bone defects caused by combat injuries in Ukraine, as in the rest of the world, cannot be considered satisfactory due to the absence of a unified system for surgical treatment methods. The variety of defect characteristics and their extent demands a certain level of standardization in the use of these treatment methods. To develop such a system, it is critically important to study and analyze the surgical intervention techniques applied to patients with long bone defects [5-8].

All of the above emphasizes the necessity, relevance, and nature of this study. This publication is the first report of our observations and focuses solely on the general characteristics of surgical technologies used to treat patients with long bone defects resulting from combat trauma.

Objective: to determine the overall structure of the application of medical surgical technologies in the treatment of patients with long bone defects resulting from combat trauma.

Materials and Methods

This study is of a cohort nature, conducted according to the requirements and criteria of evidence-based medicine with a level of evidence IIb, as per Oxford classification. It includes 115 cases of long bone defects in patients with combat trauma, selected through irreversible randomization from a total pool of 5,000 cases.

We performed an analysis of the medical records of the patients with respect to the use of surgical treatment methods for bone defects. Under these conditions, evaluating the correctness and appropriateness of a particular method was deemed adequate by default.

Upon primary examination of the actual data, we found that the following surgical treatment technologies were applied: Masquelet technique, antegrade bone transport, retrograde bone transport, “antegrade + retrograde bone transport”, bifocal limb lengthening, trifocal limb lengthening, bone plastic surgery, length correction, and acute shortening.

A parametric (rank) and non-parametric (polychoric) analysis of the study material was conducted using elements of fractal analysis. Data processing was performed using computer technologies.

The study was carried out in accordance with the requirements and criteria of evidence-based medicine, adhering to the principles of the Helsinki Declaration and the laws of Ukraine, approved by the Bioethics Commission of the State Enterprise “Ukrainian Scientific-Practical Center for Emergency Medical Care and Disaster Medicine of the Ministry of Health of Ukraine”, protocol No. 4 dated 12.11.2025. All patients provided informed consent.

Results

The aim of our study implied a general analysis of the application of surgical treatment technologies for large bone defects in the total sample (Table 1).

It was found that, among patients with long bone defects, anterograde bone transport was the most commonly used technique (29.35 %), ranking first, followed by Masquelet in second place (27.17 %), and retrograde bone transport in third (21.74 %). The smallest proportion (the last, seventh rank) was occupied by bifocal lengthening and acute shortening, both at 1.09 %. The ratio of the maximum to minimum values is 26.93, indicating high dissipation of the distribution and indirectly pointing to the reliability of these results.

For a more detailed study of the issue of the use of surgical intervention technologies, the sample of patients with long bone defects was divided into groups by the location of the injured area of the limbs and treatment methods (Table 2).

Data analysis, presented in Table 2, showed the following: first, there is no overlap in the ranking positions of surgical treatment technologies across the anatomical segments of the limbs; second, for defects of the proximal limb segments, Masquelet is used most often. It is applied twice as often on the proximal part of the upper limb as it is on the lower limb.

In the distal parts of the limb segments, there is a significant difference between the upper and lower limbs. In the first case (forearm), Masquelet was used, and in volumes similar to those in the proximal limb part. Bone plastic surgery was also applied in cases of defects in the proximal part of the upper limb.

During the surgical treatment of bone defects in the distal part of the upper limb, in addition to Masquelet, technologies such as anterograde bone transport and length correction were used (both 14.29 %).

Table 1

Analysis of the application of various surgical approaches for treating long bone defects

Technology	Percentage (%)	Rank
Masquelet	27.17	2
Anterograde bone transport	29.35	1
Retrograde bone transport	21.74	3
Anterograde + retrograde bone transport	3.26	6
Bifocal limb lengthening	1.09	8
Trifocal limb lengthening	2.17	7
Bone grafting	4.35	5
Length correction	9.78	4
Acute shortening	1.09	8

Table 2

Study of the cohort of patients in groups based on injury segment and intervention

Technology	Shoulder	Rank	Forearm	Rank	Hip	Rank	Tibia	Rank	Total
	percentage (%)		percentage (%)		percentage (%)		percentage (%)		percentage (%)
Masquelet	80.00	1	71.42	1	38.89	1	14.52	3	27.17
Anterograde bone transport	0	3	14.29	2	16.67	3	37.09	1	29.35
Retrograde bone transport	0	3	0	3	27.77	2	25.80	2	21.74
Anterograde + retrograde bone transport	0	3	0	3	0	4	4.84	5	3.26
Bifocal limb lengthening	0	3	0	3	0	4	1.61	7	1.09
Trifocal limb lengthening	0	3	0	3	0	4	3.22	6	2.17
Bone grafting	20.00	2	0	3	0	4	3.22	6	4.35
Length correction	0	3	14.29	2	16.67	3	8.06	4	9.78
Acute shortening	0	3	0	3	0	4	1.61	7	1.09

When treating bone defects in the proximal segment of the lower limb, two key observations stand out: Masquelet is used half as often, and there is a wider range of other techniques employed, including retrograde and anterograde bone transport, as well as length correction.

For defects in the distal part of the lower limb, bone transport is predominantly used (anterograde — 37.09 % and retrograde — 25.80 %). Masquelet was used much less, in only 14.52 % of cases, and length correction in 8.06 %. Other methods used included bifocal and trifocal limb lengthening, and, interestingly, acute shortening of the limb.

In summary, it can be noted that during the surgical treatment of bone defects in both the upper and lower limbs, technologies were applied to varying extents.

To further examine the frequency of use of different surgical treatment technologies in patients with long bone defects, we divided the patients into groups based on the injured segment of the limb (Table 3).

It was found that only Masquelet was used during surgeries for long bone defects in all segments of the limbs. This method is most frequently used for defects in the distal part of the lower limb (36.00 %), and least frequently on the humerus (16.00 %). For the femur, the proportion is 28.00 %, and for the forearm, it is 20.00 %.

The treatment technology of anterograde bone transport was most commonly used for defects of the tibia — in 85.19 % of cases, and least frequently for fractures of the radius — 3.70 %. This method was not statistically significant in the treatment of patients with humeral bone defects.

Retrograde bone transport was only applied for long bone defects of the lower limb: in 75.00 % of cases for the tibia and in 25.00 % for the femur. It was not performed in statistically significant volumes in the upper limb segments.

Surgical treatment technologies such as bifocal or trifocal lengthening of the limb, anterograde + retrograde bone transport, and acute shortening were only used for tibial bone defects (100 % in terms of proportion).

Length correction was most commonly applied for distal bone defects of the lower limb — 55.56 %, for the femur — 33.33 %, and only 11.11 % for the radius. Thus, this technique was used in 88.89 % of cases for lower limb segments.

Bone plastic surgery was used in 25.00 % of cases for humeral defects and in 75.00 % for large tibial defects.

Therefore, the Masquelet technique is more universal and can be used for large defects of various limb segments, whereas most other methods have much narrower applicability, limited to specific areas.

After conducting a polychoric analysis of the data in Table 3, a positive (φ^2 = 0.3381), very strong (C = 0.5027), and statistically significant (χ^2 = 31.11) correlation was found between the types of surgical treatment and the segment of the limb affected by the defect. These data fall within the confidence field.

Thus, it can be concluded that the application of surgical treatment technologies for long bone defects is significantly dependent on both the "upper-lower" limb and "distal-proximal" segment classification.

Discussion

The results of this study indicate a variety of technologies used during surgical interventions for patients with long bone defects caused by modern combat injuries. Both modern techniques like Masquelet and traditional methods like bone transport are employed.

Comparisons with global literature suggest that Masquelet is more commonly used abroad for combat injuries [9, 10]. However, this comparison cannot be considered entirely accurate due to the unique scope and nature of limb injuries in modern combat operations in Ukraine, particularly in terms of the medical assistance provided.

A significant advantage of our study is the detailed investigation of the application of technologies based on the localization of bone defects in different segments of the limbs. While such studies have been conducted abroad, they have been limited to specific methods of surgical treatment [11, 12].

In open and accessible sources of scientific information, we did not find data on the use of surgical treatment technologies for long bone defects due to modern combat injuries based on limb segments in statistically significant volumes [13–15]. Our research has proven that the choice of a particular intervention for bone defects caused by combat trauma is significantly dependent on the affected segment. At the same time, it should be noted that only Masquelet was used to treat defects in all limb segments. Additionally, we established the predominant use of the Masquelet technique for upper limb defects. It was found that this method was mostly used for proximal segments of both the upper and lower limbs.

Bone transport was virtually not applied to the proximal upper limb, and retrograde bone transport was not used for the upper limbs. Furthermore, techniques such as bifocal and trifocal lengthening and acute shortening of bones were not used, but bone plastic surgery was relatively widely applied to the proximal upper limb segment. On the other hand, the preferred method for surgical treatment

Table 3

Distribution of the cohort of patients in groups by treatment method based on the injured segment

Technology	Shoulder	Forearm	Hip	Tibia	Total
	percentage (%)				
Masquelet	16.00	20.00	28.00	36.00	100
Anterograde bone transport	0	3.70	11.11	85.19	100
Retrograde bone transport	0	0	25.00	75.00	100
Anterograde + retrograde bone transport	0	0	0	100.00	100
Bifocal limb lengthening	0	0	0	100.00	100
Trifocal limb lengthening	0	0	0	100.00	100
Bone grafting	25.00	0	0	75.00	100
Length correction	0	11.11	33.33	55.56	100
Acute shortening	0	0	0	100.00	100

of upper limb defects and proximal lower limb defects is Masquelet, while for distal lower limb defects, the preferred method is anterograde bone transport. It is important to note that all surgical intervention technologies were used exclusively for treating bone defects in the distal lower limb segment. The analysis of open sources did not allow us to explain these facts with certainty. This requires detailed and thorough investigation, the results of which will be shared in our future scientific publications.

Conclusions

The technologies for treating long bone defects due to modern combat trauma are diverse and include both innovative and classical approaches. The Masquelet technique is the most commonly applied method for surgical treatment of patients with long bone defects of the upper limb and proximal segment of the lower limb caused by modern combat trauma, while anterograde bone transport is used for the distal segment of the lower limb.

The use of a specific surgical technology for treating bone defects due to modern combat trauma is likely dependent on the segment of the injury. Further thorough studies are required to reliably explain this fact.

Conflict of Interest. The authors declare that there is no conflict of interest.

Prospects for Further Research. Future studies will aim to analyze the use of specific surgical technologies for treating bone defects caused by modern combat trauma, depending on the size of the defect.

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References

1. Trutyak, I., Los, D., Medzyn, V., Trunkvalter, V., & Zukovsky, V. (2022). Treatment of combat surgical trauma of the limbs in the conditions of modern war. Proceeding of the Shevchenko Scientific Society. *Medical sciences, 69*(2). https://doi.org/10.25040/ntsh2022.02.16
2. Khomenko, I. P., Korol, S. O., Khalik, S. V., Shapovalov, V. Y., Yenin, R. V., Herasimenko, O. S., & Tertyshnyi, S. V. (2021). Clinical and epidemiological analysis of the structure of combat surgical injury during antiterrorist operation / Joint forces operation. *Ukrainian journal of military medicine, 2*(2), 5–13. https://doi.org/10.46847/ujmm.2021.2(2)-005
3. Finco, M. G., Kim, S., Ngo, W., & Menegaz, R. A. (2022). A review of musculoskeletal adaptations in individuals following major lower-limb amputation. *Journal musculoskelet neuronal interact. 22*(2):269–283.
4. Janak, J., Kotwal, R. S., Howard, J. T., Gurney, J., Eastridge, B. J., Holcomb, J. B., Shackelford, S. A., De Lorenzo, R. A., Stewart, I. J., & Mazuchowski, E. L. (2024). Advancing combat casualty care statistics and other battlefield care metrics. *Journal of special operations medicine, 24*(2), 11. https://doi.org/10.55460/xbjf-aqpx
5. Wang, C., Ma, T., Li, Z., Wang, Q., Li, Z., Zhang, K., & Huang, Q. (2023). A modified hybrid transport technique combined with a retrograde tibiotalocalcaneal arthrodesis nail for the management of distal tibial periarticular osteomyelitis and associated defects. *Journal of orthopaedic surgery and research, 18*(1). https://doi.org/10.1186/s13018-023-03744-2
6. Fu, J., Wang, X., Wang, S., Chen, Z., Shen, J., Li, Z., & Xie, Z. (2023). Induced membrane technique combined with a retrograde intramedullary nail for the treatment of infected bone defects of the ankle. *Scientific reports, 13*(1). https://doi.org/10.1038/s41598-023-34014-0
7. Yang, N., Ma, T., Liu, L., Xu, Y., Li, Z., Zhang, K., Wang, Q., & Huang, Q. (2023). Shortening/re-lengthening and nailing versus bone transport for the treatment of segmental femoral bone defects. *Scientific reports, 13*(1). https://doi.org/10.1038/s41598-023-40588-6
8. Buryanov, O., Kvasha, V., Kuprii, V., Sobolevskiy, Y., Chornyi, V., Hliba, H., & Rohozynskyi, V. (2024). Modern technologies for bone defect replacement (Literature review). *Orthopaedics, traumatology and prosthetics*, (1), 79–88. https://doi.org/10.15674/0030-59872024179-88.
9. Gindraux, F., Rondot, T., De Billy, B., Zwetyenga, N., Fricain, J., Pagnon, A., & Obert, L. (2017). Similarities between induced membrane and amniotic membrane: Novelty for bone repair. *Placenta*, 59, 116–123. https://doi.org/10.1016/j.placenta.2017.06.340
10. Villarreal-Villarreal, G. A., Simental-Mendía, M., Alonso, A. A., Vilchez-Cavazos, F., Acosta-Olivo, C. A., & Peña-Martínez, V. M. (2023). Comparison of anterior iliac crest versus proximal tibia autologous bone Graft harvesting: A systematic review and meta-analysis. *The journal of foot and ankle surgery, 62*(2), 388–397. https://doi.org/10.1053/j.jfas.2022.10.004
11. Shi, L. L., Garg, R., Jawa, A., Wang, Q., Chai, Y., Zeng, B., & Jupiter, J. B. (2020). BONY hypertrophy in vascularized fibular grafts. *HAND, 17*(1), 106–113. https://doi.org/10.1177/1558944719895784
12. Hamiti, Y., Abudureyimu, P., Lyu, G., Yusufu, A., & Yushan, M. (2024). Trifocal versus Pentafocal bone transport in segmental tibial defects: A matched comparative analysis for posttraumatic osteomyelitis treatment. *BMC musculoskeletal disorders, 25*(1). https://doi.org/10.1186/s12891-024-07507-w
13. Wallace, S. J., & Rozbruch, S. R. (2023). Trifocal tandem tibial bone transport and knee stabilization using the Ilizarov method. Limb lengthening and reconstruction surgery case atlas, 1–7. https://doi.org/10.1007/978-3-319-02767-8_458-1
14. Carter, J. T., Craft, M., Dabash, S., Thabet, A. M., & Abdelgawad, A. (2021). Bifocal femoral lengthening with intramedullary magnetic lengthening nail following osteotomy propagation. *Journal of limb lengthening & reconstruction, 7*(2), 139–141. https://doi.org/10.4103/jllr.jllr_9_21
15. Yushan, M., Hamiti, Y., Yalikun, A., Lu, C., & Yusufu, A. (2022). Bifocal femoral lengthening assisted by preoperative 3-dimensional design in the restoration of posttraumatic limb length discrepancy. *BMC Surgery, 22*(1). https://doi.org/10.1186/s12893-022-01697-7

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APPLICATION OF SURGICAL TECHNOLOGIES FOR THE TREATMENT OF VICTIMS WITH LONG BONE DEFECTS DUE TO MODERN COMBAT TRAUMA

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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].

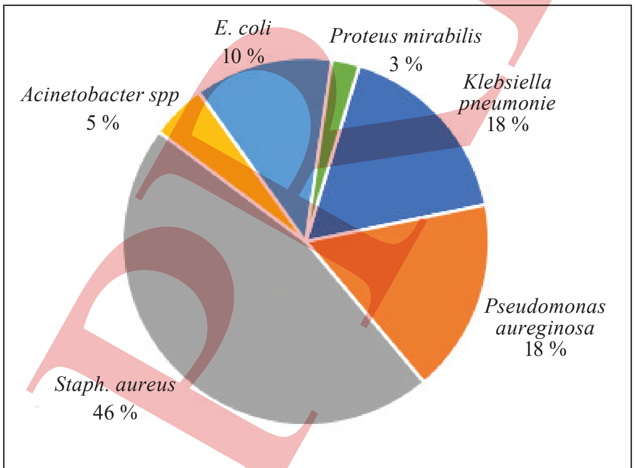

Fig. 1. Distribution of the patient group by pathogens of the pathological process

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 (ρ = –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 (ρ = 0.39) and muscle tissue defects (ρ = 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 (ρ = 0.38), damage to major arteries (ρ = 0.25), muscles (ρ = 0.55), and nerves of the lower leg (ρ = 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* (ρ = 0.26) and *Pseudomonas aeruginosa* (ρ = 0.25) — consolidation occurred more slowly; while a moderate inverse correlation (ρ = –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 (ρ = 0.36), skin defects (ρ = 0.26), and muscle tissue defects (ρ = 0.42). A moderate direct correlation (ρ = 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.

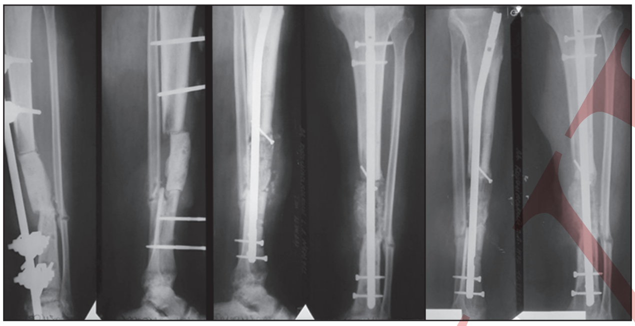

Fig. 2. Clinical case No. 1. Patient K, 35 years old, treated using the Masquelet technique, with a 9 cm defect in the tibia

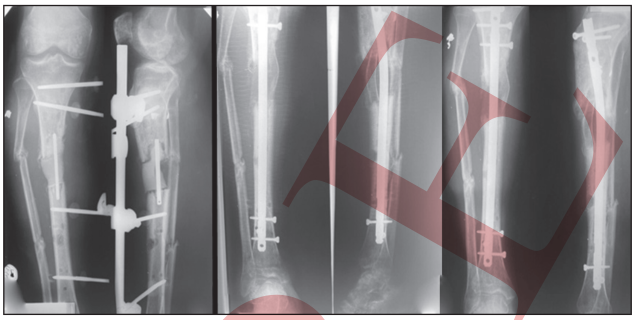

Fig. 3. Clinical case No. 2. Patient B, 42 years old, treated using the Masquelet technique, with a 5 cm defect in the tibia

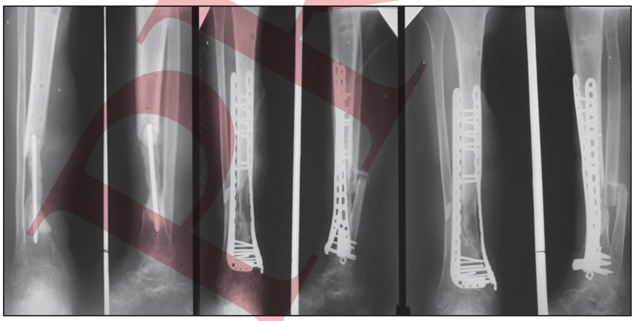

Fig. 4. Clinical case No. 3. Patient H, 29 years old, treated using the Masquelet technique, with a 7 cm defect in the tibia

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.

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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.

References

1. Zhang, H., Zhao, X., Yang, X., Zhang, X., Chen, X., Zhou, T., Xu, X., Song, M., Luo, S., Xie, Z., Xu, Y., & Shi, J. (2023). Comparison of internal and external fixation after debridement in the Masquelet technique for Cierny-Mader type IV tibial post-traumatic osteomyelitis. *Injury, 54*(2), 422–428. https://doi.org/10.1016/j.injury.2022.11.030
2. Kazmirchuk, A., Yarmoliuk, Y., Lurin, I., Gybalo, R., Burianov, O., Derkach, S., & Karpenko, K. (2022). Ukraine's Experience with Management of Combat Casualties Using NATO's Four-Tier "Changing as Needed" Healthcare System. *World journal of surgery, 46*(12), 2858–2862. https://doi.org/10.1007/s00268-022-06718-3
3. Burianov, O. ., Yarmoliuk, Y., Derkach, S., Gritsai, M., Klapchuk, Y., Los, D. ., Omelchenko, T. ., & Kolov, G. (2023). Criteria for predicting risks in the case of replacing an external fixator with an internal fixator during the treatment of gunshot fractures of the extremities. *Orthopaedics, traumatology and prosthetics*, (1), 5–9. https://doi.org/10.15674/0030-5987202315-9
4. Lurin, I., Burianov, O., Yarmolyuk, Y., Klapchuk, Y., Derkach, S., Gorobeiko, M., & Dinets, A. (2024). Management of severe defects of humerus in combat patients injured in Russo-Ukrainian war. *Injury, 55*(2), 111280. https://doi.org/10.1016/j.injury.2023.111280
5. Xie, J., Wang, W., Fan, X., Li, H., Wang, H., Liao, R., Hu, Y., & Zeng, M. (2022). Masquelet technique: Effects of vancomycin concentration on quality of the induced membrane. *Injury, 53*(3), 868–877. https://doi.org/10.1016/j.injury.2021.11.003
6. Gouron R. (2016). Surgical technique and indications of the induced membrane procedure in children. *Orthopaedics & traumatology, surgery & research : OTSR, 102*(1 Suppl), S133–S139. https://doi.org/10.1016/j.otsr.2015.06.027
7. Ahmed, H., Shakshak, M., & Trompeter, A. (2025). A review of the Masquelet technique in the treatment of lower limb critical-size bone defects. *Annals of the Royal College of Surgeons of England, 107*(6), 383–389. https://doi.org/10.1308/rcsann.2023.0022
8. Wang, P., Wu, Y., Rui, Y., Wang, J., Liu, J., & Ma, Y. (2021). Masquelet technique for reconstructing bone defects in open lower limb fracture: Analysis of the relationship between bone defect and bone graft. *Injury, 52*(4), 988–995. https://doi.org/10.1016/j.injury.2020.12.009
9. Alford, A. I., Nicolaou, D., Hake, M., & McBride-Gagyi, S. (2021). Masquelet's induced membrane technique: Review of current concepts and future directions. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society, 39*(4), 707–718. https://doi.org/10.1002/jor.24978
10. Tetsworth, K. D., Burnand, H. G., Hohmann, E., & Glatt, V. (2021). Classification of Bone Defects: An Extension of the Orthopaedic Trauma Association Open Fracture Classification. *Journal of orthopaedic trauma, 35*(2), 71–76. https://doi.org/10.1097/BOT.0000000000001896
11. Tennyson, M., Krzak, A. M., Krkovic, M., & Abdulkarim, A. (2021). Cambridge Protocol for Management of Segmental Bone Loss. *Journal of orthopaedic case reports, 11*(1), 45–50. https://doi.org/10.13107/jocr.2021.v11.i01.1958
12. Chloros, G. D., Kanakaris, N. K., Harwood, P. J., & Giannoudis, P. V. (2022). Induced membrane technique for acute bone loss and nonunion management of the tibia. *OTA international : the open access journal of orthopaedic trauma, 5*(2 Suppl), e170. https://doi.org/10.1097/OI9.0000000000000170
13. Wang, Z., Zou, C., Zhan, X., Li, X., Ghen, G., & Gao, J. (2024). Application of double plate fixation combined with Masquelet technique for large segmental bone defects of distal tibia: a retrospective study and literature review. *BMC surgery, 24*(1), 103. https://doi.org/10.1186/s12893-024-02396-1
14. Dugan, T. R., Hubert, M. G., Siska, P. A., Pape, H. C., & Tarkin, I. S. (2013). Open supracondylar femur fractures with bone loss in the polytraumatized patient — Timing is everything!. *Injury, 44*(12), 1826–1831. https://doi.org/10.1016/j.injury.2013.03.018

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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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Biomechanical study of a combined fixation system for gunshot femoral fractures

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Gunshot injuries of the femur in combat settings are associated with high-energy trauma and unstable diaphyseal fractures (81.4 %), which require fixation methods with increased demands for mechanical rigidity. Objective. To investigate the stress-strain state of a computer model of the femur with a comminuted fracture fixed with an intramedullary spacer and an external fixation device using pins of 5 mm and 6 mm in diameter. Methods. A three-dimensional model of a diaphyseal comminuted femoral fracture and two models of combined fixation («external fixator + intramedullary spacer») with four pins of 5 mm and 6 mm diameter were created. Biomechanical analysis was performed using the finite element method. The evaluated parameters included displacement, stress, and strain under a static load of 400 N. Results. Numerical analysis of the stress-strain state demonstrated that both studied constructs with 5-mm and 6-mm pins provide sufficient fixation stiffness. Increasing the pin diameter to 6 mm resulted in reduced maximal displacements and peak stresses, indicating a biomechanical advantage of the «bone – intramedullary spacer + external fixator with 6-mm pins» system. Conclusions. The conducted numerical stress-strain analysis showed that despite adequate stability provided by both fixation systems, the «bone + intramedullary spacer + external fixator with 6-mm pins» construct has a biomechanical advantage over the construct with 5-mm pins in terms of maximal displacement, stress, and strain values.

Вогнепальні ушкодження стегнової кістки в умовах бойових дій характеризуються високоенергетичними травмами та нестабільними діафізарними переломами (81,4 %), які потребують методів фіксації з підвищеними вимогами до механічної жорсткості. Мета. Дослідити напружено-деформований стан комп'ютерної моделі стегнової кістки з багатоуламковим переломом, фіксованої інтрамедулярним спейсером і апаратом зовнішньої фіксації зі стрижнями діаметрами 5 та 6 мм. Методи. Створено тривимірну модель діафізарного багатоуламкового перелому стегнової кістки та дві моделі комбінованої фіксації «АЗФ + інтрамедулярний спейсер» із використанням чотирьох стрижнів діаметрами 5 та 6 мм. Біомеханічний аналіз виконано методом скінченних елементів. Оцінювали показники напружено-деформованого стану — переміщення, напруження та деформація — за умов прикладання статичної сили 400 Н. Результати. Чисельний аналіз напружено-деформованого стану показав, що обидві досліджувані конструкції зі стрижнями параметрами 5 і 6 мм забезпечують достатню жорсткість фіксації. Збільшення діаметрів стрижнів до 6 мм супроводжується зниженням максимальних переміщень і пікових напружень, що свідчить про біомеханічну перевагу системи «кістка + інтрамедулярний спейсер + АЗФ зі стрижнями діаметром 6 мм». Висновки. Проведений чисельний аналіз напружено-деформованого стану продемонстрував, що попри достатню стабільність обох систем фіксації стегнової кістки, «кістка + інтрамедулярний спейсер + АЗФ зі стрижнями діаметром 6 мм» має біомеханічну перевагу над системою «кістка + інтрамедулярний спейсер + АЗФ зі стрижнями 5 мм» за показниками максимальних переміщень, напружень і деформацій. Ключові слова. Вогнепальний перелом, стегнова кістка, апарат зовнішньої фіксації, інтрамедулярний спейсер, метод скінченних елементів, біомеханічне моделювання.

Keywords. Gunshot fracture, femur, external fixation device, intramedullary spacer, finite element method, biomechanical modeling

Introduction

Gunshot wounds to the limbs account for 62.6–70.0 % of the structure of modern combat surgical trauma, with a significant portion affecting the lower limbs [1, 2]. The share of gunshot injuries to the thigh reaches 13.6–28.3 %, and femoral fractures make up 7.0–22.3 % of all injuries [2, 3]. Their severe nature, caused by the high kinetic energy of the projectile, leads to the formation of large bone defects, numerous fragments, and significant soft tissue destruction [3, 4]. Diaphyseal lesions account for 81.4 % of injuries [5]. In 79.5 % of patients, bone tissue defects are detected [1, 6], and in 84.5 %, traumatic shock develops, which further complicates treatment tactics and increases the risk of early complications [2, 7].

Traditional fixation methods do not always provide the necessary stability in cases of large bone defects and multi-fragment injuries. In such situations, there is a need for combined consolidation techniques, including the use of external fixation devices (EFD) combined with intramedullary constructs and antibiotic cement spacers [8, 9]. The optimal configurations of these systems, their rigidity, load resistance, and ability to maintain controlled fracture alignment remain undefined, and existing clinical data are fragmented and limited.

For this reason, biomechanical studies are becoming increasingly important, as they allow the creation of models of severe gunshot injuries, evaluation of various combined fixation options, and analysis of their behavior under load. The results of such experiments are crucial for practical medicine, as they help reduce the risks of secondary displacements, instability of the constructs, local overloading, and the development of infectious complications, as well as contribute to optimizing surgical tactics in the case of gunshot fractures.

In the publication [8], the authors demonstrated the biomechanical superiority of an EFD system with six 5-mm diameter rods and an intramedullary spacer (IMS) over a construct with exclusive EFD fixation for gunshot fractures of the femur (GSFF). However, the question of determining the optimal number and diameter of the rods in the EFD system combined with IMS to ensure sufficient fracture stability remains relevant.

One way to enhance the stability of bone fragment fixation is by increasing the diameter of the EFD rods. Biomechanical studies suggest that this approach helps reduce fragment displacement and increases the rigidity of the fixation system. In works [10, 11], it was shown that the optimal fixation for GSFF is an EFD system consisting of a beam and four 6-mm diameter rods placed in different planes. However, the use of larger diameter rods is associated with greater trauma to bone and soft tissues, is technically more complex, and may prolong the duration of the surgical procedure.

Currently, the number of publications studying the biomechanical properties of the femur in combined fixation options remains limited, emphasizing the need for further research to develop individualized approaches to choosing surgical treatment tactics for patients with GSFF.

Thus, the scientific problem of optimizing combined fixation in GSFF is highly relevant both for fundamental biomechanical research and for modern traumatology and military surgery. This study is a continuation of the authors' own research aimed at investigating the behavior of the "bone + EFD + IMS" system in this category of injured patients.

Objective: to investigate the stress–strain state of a computer model of the femur with a comminuted fracture fixed with an intramedullary spacer and an external fixation device using rods with diameters of 5 and 6 mm.

Material and Methods

In collaboration with specialists from the Biomedical Engineering Laboratory of the State Institution "Institute of Traumatology and Orthopedics of the National Academy of Medical Sciences of Ukraine", a finite element model of the femur with a gunshot comminuted fracture in the middle third was constructed (7 intermediate fragments with partial contact between them). In the diaphyseal region, the minimum bone diameter was 33.0 mm, and the width of the medullary canal was 15.0 mm. In the transition zones from the diaphysis to the metaphysis, the diameters increased in accordance with the anatomical features of the femur. Soft tissue structures of the thigh were not considered in the created model.

Fixation of the femur using a combination of an IMS and a rod-based EFD was analyzed. The following models were studied: 1 — two 5.0-mm diameter rods proximally and two distally, fixed to a single bar; 2 — an analogous configuration with 6.0-mm diameter rods. The distance from the femur to the supporting EFD bar with a diameter of 10 mm was 100 mm.

The IMS consists of a 5-mm-thick frame made of surgical steel (AISI 316) and coated with bone cement (polymethyl methacrylate). The total thickness of the spacer was 10 mm. A metal loop is located at the proximal end, allowing implantation and removal of the fixator [8, 9].

The proximal end of the spacer was positioned in the region of the greater trochanter of the femur, and the distal end was located 20 mm above the articular surface. EFD rods with diameters of 5.0 and 6.0 mm were inserted bicortically in the areas of medullary canal widening, alongside the trajectory of the spacer.

During modeling, the material was considered homogeneous and isotropic. The mechanical properties of the materials were selected according to data from the technical literature [12–15]. The following physical and mechanical parameters were used for the analysis: E — Young's modulus, v — Poisson's ratio (Table 1).

An anatomical femur model was obtained by converting a computed tomography scan into a solid model using the IntelliSpace Portal software environment and imported into SolidWorks 23. Calculations of the stress–strain state of the models were performed using the SimSolid software environment.

To analyze the stress–strain state of the biomechanical models, the finite element method was used. The following boundary conditions were defined: the distal articular surface of the femur was rigidly fixed; a static force of 400 N, corresponding to 40 kg (half the body weight of a male serviceman), was applied to the femoral head; and a triangular mesh with Gauss points was created. The investigated effects included displacement, stress, and strain. In the SimSolid software, a system of linear equilibrium equations of the finite element model was solved, with determination of displacement at each node.

Stress values were compared at control points, namely: the upper third of the femur, the gunshot fracture zone, the lower third, the areas where the EFD rods entered the bone, three points on the IMS, and the middle of the bar for both variants of femoral fixation (Fig. 1). The maximum stress values in these anatomical regions and structural elements were analyzed.

Results

At the first stage of the study, the stress–strain state of the femoral model with a gunshot fracture fixed using an IMS and an EFD with 5.0-mm diameter rods was examined. Analysis of the "displacement" parameter showed that the maximum displacement reached 4.5 mm in the region of the proximal epimetaphysis of the femur, where displacement of the proximal fragment was observed, while the distal fragment remained stable. In the gunshot fracture zone, the maximum displacement was 1.9 mm. The distal fragment demonstrated rigid fixation with displacement values up to 0.3 mm. In the area of the upper part of the bar and on the proximal EFD rod, the corresponding displacement value was 3.7 mm (Fig. 2a).

Examination of the "deformation" parameter showed that the peak value reached 0.052 % in the gunshot fracture zone. In the upper and lower thirds of the femur, the deformation ranged from 0.011 % to 0.052 %. The highest values were localized in the middle third of the IMS, at 0.117 %. On the EFD rods, the deformation was 0.032 % at the bone entry sites (Fig. 3a).

Assessment of the "stress" parameter showed that the highest value occurred in the middle section of the IMS in the gunshot fracture zone, amounting to 50.3 MPa. On the lower rod and the two upper rods at the bone entry points, the stress ranged from 44.6–48.7 MPa. In the femur, the maximum stress level in the fracture zone was up to 22.6 MPa (Fig. 4a, c).

In the second stage, the stress–strain state of the femoral model fixed with an IMS and EFD using 6.0-mm diameter rods was investigated.

The "displacement" parameter was analyzed, and it was found that the maximum displacement reached 3.0 mm in the upper part of the model. In the gunshot fracture zone, the displacement of the fragments was up to 1.5 mm. The displacement of the bar and upper rod in the upper part of the EFD structure was 2.5 mm (Fig. 2b).

In the "deformation" analysis, it was determined that the maximum values reached 0.018 % and were observed in the middle parts of the three lower EFD

Table 1

Physical and mechanical properties of the materials used

Material	Young's Modulus, E, MPa	Poisson's ratio, v	Yield strength, RHa, MPa
Cortical bone layer	183 50	0.30	170
Trabecular bone layer	500	0.28	10
Surgical steel AISI 316	200 000	0.30	505
Bone cement	1.82	0.18	70

rods, the bar, and the upper part of the IMS frame. In the gunshot fracture zone and at the bone entry points, the deformation was 0.014 %, with no peak values detected (Fig. 3b).

The "stress" values were then analyzed. On the three lower EFD rods, the maximum stress was 44.2 MPa, at 43.4 MPa in the upper part of the IMS, and 35.4 MPa in the central section of the bar (Fig. 4b, d). No critical peak values were detected. The stress in the femur at the gunshot fracture zone, as well as in the upper and lower fragments, was up to 4.4 MPa.

Based on the obtained data, a comparative analysis of the stress values at control points for the two femoral fixation options — IMS and EFD with four rods of diameters 5.0 and 6.0 mm — was conducted (Fig. 5).

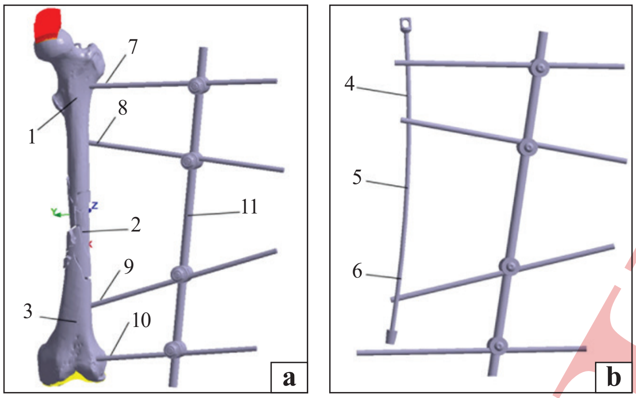

Fig. 1. Investigated models: a — femur with a fixation system, where the red zone represents the force application area, and the yellow zone represents the fixation surface; b — bone fixation systems. 1–11 — control points for measuring stresses.

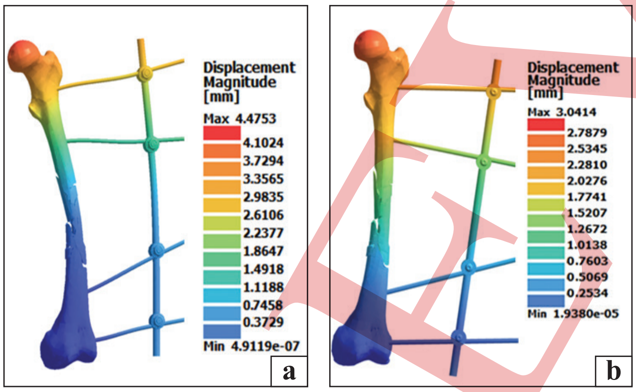

Fig. 2. Distribution of displacements in the femur model with pins of the following diameters: a — 5 mm; b — 6 mm.

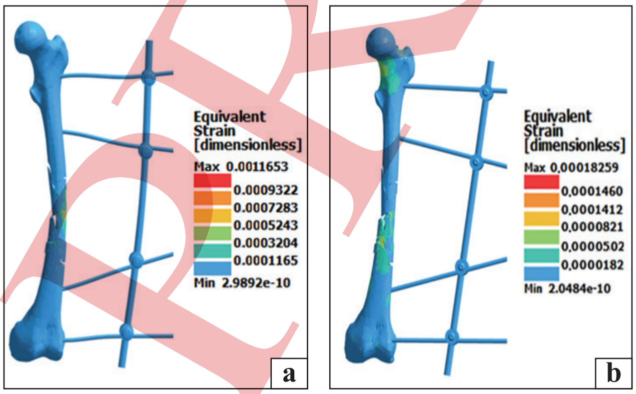

Fig. 3. Distribution of deformation in the model with pins of the following diameters: a — 5 mm; b — 6 mm.

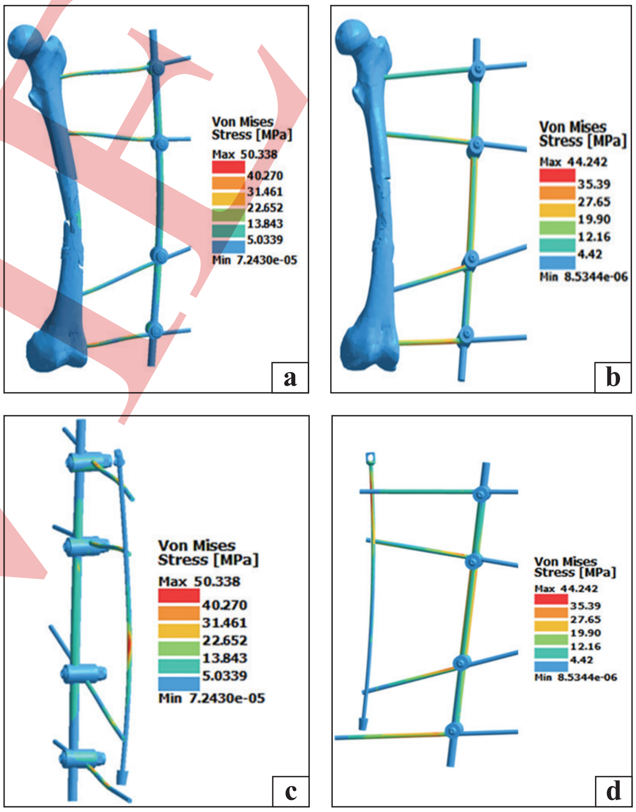

Fig. 4. Distribution of stresses in the model with pins of the following diameters: a, c — 5 mm; b, d — 6 mm (in b and d — fixation elements are placed outside the femur).

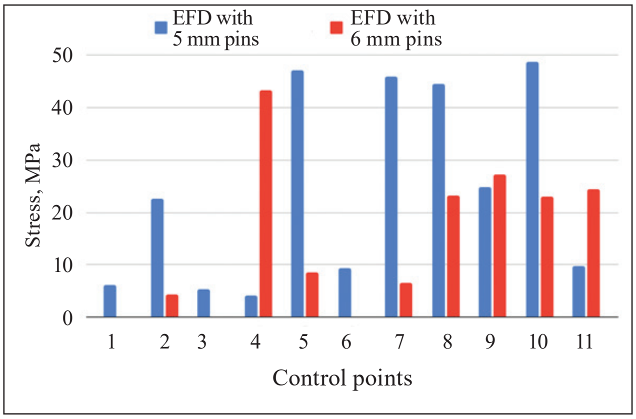

Fig. 5. Comparison of stresses in control points of the system “femur + IMS + EFD" with pins of diameters 5 and 6 mm.

The maximum values of the studied parameters for the different configurations of the combined femoral fixation system are presented in Table 3. The strength limits and the maximum allowable deformation for bone and steel are provided according to the technical literature [12–15].

Discussion

The results of the stress–strain analysis of the femur for gunshot diaphyseal fractures showed that combined fixation using IMS and EFD provides sufficient stability in both of the studied variants.

Based on the analysis conducted, it was determined that under the conditions of bone fragment fixation using both investigated designs, the stress and deformation values remain within normal ranges and do not exceed the material strength limit or the maximum allowable deformation (Table 3). The comparison of the models demonstrated that increasing the rod diameter from 5.0 to 6.0 mm resulted in a moderate decrease in peak stress at the control points and a reduction in relative deformation. However, both systems maintained sufficient overall rigidity.

In the model with 5 mm diameter rods, the displacement of the bone fragments in the fracture zone was 1.9 mm, for the EFD rods it was 3.0 mm, and for the intramedullary spacer it was 1.9 mm. In the second model (6 mm diameter rods), these values were slightly lower — 1.5, 2.3, and 1.5 mm, respectively. The difference in displacement was 0.4–0.7 mm, which, in the authors' opinion, is not clinically significant.

The stress distribution revealed a biomechanical advantage for the system "bone + IMS + EFD with 6 mm diameter rods". For the bone fragments in the fracture zone, the stress with 5 mm diameter rods was 22.6 MPa, whereas with 6 mm rods, it was 4.4 MPa. On the rods, the stresses were 45.9 MPa and 27.3 MPa, respectively. The peak stresses in the spacer were virtually the same between the models — 47.2 MPa and 43.4 MPa. These values are far from the critical limits for the materials (505 MPa for the EFD and 170 MPa for bone), indicating no risk of further deformation or failure of the structure.

A similar trend was observed during the deformation analysis. In the first model, the deformation of the bone was 0.052 %, of the rods 0.032 %, and of the IMS 0.117 %. In the second model, the respective values were 0.014 %, 0.018 %, and 0.018 %. Despite the differences in these values, the deformations for all elements remained within the elastic limits of the materials, indicating no threat of loss of stability for the construct (the maximum allowable deformation for bone tissue is 0.25 %, and for steel, it is 0.2 % —Table 3).

A comparison of the obtained results with the data from previous modeling [8], during which the systems "bone + EFD with 6 rods of 5 mm diameter" and "bone + IMS + EFD with 6 rods of 5 mm diameter" were compared, was also carried out.

It was found that in the model with 6 rods, the displacement of the bone fragments and IMS was 1.4 mm, while the displacement of the rods was 0.3 mm, indicating a high stability of the construct due to the increased number of fixation points. Despite this, the stresses in the system elements remained comparable to those obtained in the models with 4 rods. In the bone and rods, the stress was 13.1 MPa, while in the spacer it reached 26.5 MPa — values lower than in the 4-rod variants. This suggests a more uniform load distribution in the EFD system with 6 rods, but it does not result in a significant reduction in displacement.

In publications [16–19], the method for placing an intramedullary implant covered with a cement mantle in case of infection in the fracture area of long bones was investigated. The metal frames most used for covering were intramedullary blocked, non-blocked,

Table 3

Comparison of physicomechanical properties in femur fixation with rod-type EFD and IMS

Configuration of EFD in combination with IMS		Displacement in the fracture zone, mm	Stress, MPa	Deformation, %
4 pins with a diameter of 5 mm	Bone	1.9	22.6	0.052
	EFD pins	3.0	45.9	0.032
	IMS	1.9	47.2	0.117
4 pins with a diameter of 6 mm	Bone	1.5	4.4	0.014
	EFD pins	2.3	27.3	0.018
	IMS	1.5	43.4	0.018
Critical values	Bone	—	170.0	0.250
	Steel (EFD pins, IMS)	—	505.0	0.200

and elastic rods, as well as 2–4 Ilizarov wires. This method ensured infection eradication and fracture stabilization. However, complications such as the destruction of the cement mantle, breakage of the metal implant, deformation and migration of the construct, and damage to the intramedullary canal of the bone were noted.

The use of an intramedullary spacer without an EFD is not recommended, as it does not provide axial or rotational stability for the fragments. The spacer material cannot maintain the length of the bone or resist twisting, so without the EFD, such a construct is mechanically unstable.

Positioning the IMS with a 10 mm diameter in the center of the bone marrow canal complicates the technique for placing EFD rods, which should be conducted in a bicortical manner, bypassing the trajectory of the spacer. Therefore, using rods with smaller diameters has advantages: it is technically simpler, reduces the duration, and minimizes the trauma of the surgical procedure.

Our study has certain limitations, considering that the finite element method models the idealized behavior of bone fragments and the fixation system elements and does not fully account for the influence of soft tissues on the parameters considered. Therefore, clinical validation of the results is important, as it lays the groundwork for using the combined fixation method with an intramedullary spacer as an effective treatment for diaphyseal fractures.

The obtained data can be used to optimize fixation schemes for gunshot fractures of the femur and improve clinical treatment protocols.

Conclusions

The numerical analysis of the stress–strain state demonstrated that the system "bone + intramedullary spacer + EFD with 6 mm diameter rods" has a biomechanical advantage over the system "bone + intramedullary spacer + EFD with 5 mm diameter rods" in terms of maximum displacement, stress, and deformation. At the same time, the obtained values of the studied parameters did not reach the critical limits for bone tissue and fixation elements, indicating sufficient stability for both combined fixation options, allowing their use depending on the specific clinical situation.

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

Future Research Prospects. Future research should focus on studying the clinical effectiveness of the proposed combined fixation technique for bone fragments of the femur through prospective analysis of treatment outcomes in patients with gunshot fractures. A comparison of complication rates, consolidation times, and functional treatment outcomes using rods of different diameters is necessary.

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Authors' Contributions. Luryn I. A. — critical review of the article, final approval; Buryanov O. A. — analysis of results, final approval of the article; Yarmolyuk Yu. O. — design and modeling, statistical analysis, critical review of the article; Matviychuk B. V. — review and analysis of related works, design and modeling, drafting the article.

References

1. Khomenko, I. P., Korol, S. O., Matviichuk, B. V., & Ustinova, L. A. (2019). Surgical tactics of treatment of the wounded persons with the gun-shot injuries of the hip on all levels of medical support. *Klinicheskaia khirurgiia, 86*(5), 22–26. https://doi.org/10.26779/2522-1396.2019.05.22 (in Ukrainian)
2. Kazmirchuk, A. P., Buryanov, O. A., Yarmolyuk, Y. O., & Matviichuk, B. V. (2025). Tactics of surgical treatment of gunshot diaphysis fractures of the femur: review of literature sources. *Current aspects of military medicine, 32*(1), 47–59. https://doi.org/10.32751/2310-4910-2025-32-1-04 (in Ukrainian).
3. Khomenko, I. P., Lurin, I. A., Korol, S. O., Shapovalov, V. Yu., & Matviichuk, B. V. (2020). Conceptual principles of the wounded combatants' evacuation, suffering military surgical trauma on the medical support levels. *Clinical surgery, 87*(5–6), 60–65. https://doi.org/10.26779/2522-1396.2020.5-6.60 (in Ukrainian)
4. Johnson, D. J., Versteeg, G. H., & Middleton, J. A. (2021). Epidemiology and risk factors for loss to follow-up following operatively treated femur ballistic fractures. *Injury, 52*(8), 2403–2406. https://doi.org/10.1016/j.injury.2021.06.012
5. Makhubalo, O., Burger, M., & Jakoet, S. (2023). Early outcomes of surgically managed civilian gunshot femur fractures at a level one trauma unit in Cape Town, South Africa: A retrospective review. *European journal of trauma and emergency surgery,* 49, 859–865. https://doi.org/10.1007/s00068-022-02138-z
6. Tisnovsky, I., Katz, S. D., & Pincay, J. I. (2021). Management of gunshot wound-related hip injuries: A systematic review of the current literature. *Journal of orthopaedics,* 23, 100–106. https://doi.org/10.1016/j.jor.2020.12.029
7. Maqungo, S., Fegredo, D., Brkljac, M., & Laubscher, M. (2020). Gunshot wounds to the hip. *Journal of orthopaedics,* 22, 530–534. https://doi.org/10.1016/j.jor.2020.09.018
8. Lurin, I., Burianov, O., Yarmolyuk, Y., & Matviichuk, B. (2025). Analysis of the stress-deformed state of the femur with gunshot fracture with various methods of its fixation. *Orthopaedics, traumatology and prosthetics*, (3), 5–11. https://doi.org/10.15674/0030-5987202535-11
9. Kazmirchuk, A. P., Buryanov, O. A., Yarmolyuk, Y. O., Yalovenko, V. A., & Matviichuk, B. V. (2025). The use of intramedullary spacers for the prevention and treatment of infectious complications in victims with gunshot-related femoral fractures. *Current Aspects of Military Medicine, 32*(2), 10-22. https://doi.org/10.32751/2310-4910-2025-32-2-01 (in Ukrainian).
10. Korzh, M. O., Popsuishapka, O. K., Lytvyshko, V. O., Shevchenko, I. V., Doluda, Y. A. (2023). Problematic issues of the treatment of diaphyseal gunshot fractures of long bones of extremities. *Orthopedics, traumatology and prosthetics,* (4), 109–120. https://doi.org/10.15674/0030-598720234109-120
11. Popsuishapka, O. K., Subbota, I. A. (2025). Features of deformation of the "debris — external core apparatus" model in case of using structures with different structural geometry.

Orthopedics, traumatology and prosthetics, (1), 65–74. http://doi.org/10.15674/0030-59872025165-74
12. Maganaris, C. N., & Paul, J. P. (1999). In vivo human tendon mechanical properties. *The journal of physiology, 521*(1), 307–313. https://doi.org/10.1111/j.1469-7793.1999.00307.x
13. Hvid, I., Christensen, P., Søndergaard, J., Christensen, P. B., & Larsen, C. G. (1983). Compressive strength of tibial cancellous Bone:Instron® and Osteopenetrometer measurements in an autopsy material. *Acta orthopaedica scandinavica, 54*(6), 819–825. https://doi.org/10.3109/17453678308992915
14. Cowin, S. C. (2001). *Bone mechanics handbook*. CRC Press.
15. Scherer, J., Hure, J., Madec, R., Bourdais, F. L., Van Brutzel, L., Sao-Joao, S., Kermouche, G., Besson, J., & Tanguy, B. (2024). Tensile and micro-compression behaviour of AISI 316L austenitic stainless steel single crystals at 20 °C and 300 °C: Experiments, modelling and simulations. *Materials science and engineering: A*, 900, 146471. https://doi.org/10.1016/j.msea.2024.146471.
16. Powell, K. P., Hammouda, A. I., Hlukha, L. P., Rivera, J. C., & Patel, M. (2022). Motorized intramedullary nail lengthening in the older population. *Journal of clinical medicine, 11*(17), 5248. https://doi.org/10.3390/jcm11175242
17. Conway, J. D., Elhessy, A. H., Galiboglu, S., Patel, N., & Geshef, M. G. (2022). Efficacy of infection eradication in antibiotic cement-coated intramedullary nails for fracture-related infections, nonunions, and fusions. *Antibiotics, 11*(6), 709. https://doi.org/10.3390/antibiotics11060709
18. Tanasienko, P., & Kolov, H. (2023). Analysis of the treatment of patients with infectious complications after osteosynthesis. *Experimental and Clinical Medicine, 92*(2), 14–21. https://doi.org/10.35339/ekm.2023.92.2.tak
19. Ismat, A., Walter, N., Baertl, S., Mika, J., Lang, S., Kerschbaum, M., Alt, V., & Rupp, M. (2021). Antibiotic cement coating in orthopedic surgery: a systematic review of reported clinical techniques. *Journal of orthopaedics and traumatology, 22*(1), 56. https://doi.org/10.1186/s10195-021-00614-7

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BIOMECHANICAL STUDY OF A COMBINED FIXATION SYSTEM FOR GUNSHOT FEMORAL FRACTURES

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Analysis of the prevalence and risk factors for venous thromboembolic complications in patients with proximal femoral fractures

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Due to the increasing incidence of PFA fractures and the associated morbidity and disability, the treatment and rehabilitation of patients with this pathology is a global problem of modern traumatology and orthopedics. Objective. To determine the incidence of venous thromboembolic complications in the setting of proximal femoral fractures, the presence of additional risk factors, and the possibility of using the Caprini score to identify surgical patients at "extremely high risk" of venous thromboembolism (VTE). Methods. The examination and treatment results of 153 (58 men, 95 women) patients aged 23 to 94 years (average 69.95±15.83 years) with proximal femoral fracture were studied. Results. The incidence of acute venous thromboembolic complications among patients with proximal femoral fractures is 13.7 %. The vast majority (98 %) of patients in this category have additional risk factors for VTE development, in addition to femoral fracture. A Caprini score of 10 points is associated with an increase in the risk of VTE development in patients with proximal femoral fractures by 11.7 times (95 % CI [1.25–109.3]), 11 points — by 23.7 times (95 % CI [2.25–250.2]), 12 points — by 45.1 times (95 % CI [4.42–461.0]), 13 and more points — by 79 times (95 % CI [8.95–697.4]) compared with the presence of 5–8 points. Conclusions. The Caprini score was found to identify patients at "extremely high risk" of developing VTE. The cut–off level of the Caprini score > 10 points allowed identifying patients at "extremely high risk" of thrombosis (AUROC 0.845; 95 % CI 0.769–0.922).

Через зростання частоти переломів ПВС й асоційованої з цим захворюваності й інвалідності, лікування та реабілітація пацієнтів із цією патологією є глобальною проблемою сучасної травматології та ортопедії. Мета. Визначити частоту розвитку венозних тромбоемболічних ускладнень у пацієнтів із переломами проксимального відділу стегна (ПВС), наявність додаткових факторів ризику та можливості використання шкали Caprini для ідентифікації хірургічних хворих із «вкрай високим ризиком» розвитку венозної тромбоемболії (ВТЕ). Методи. Досліджено результати обстеження та лікування 153 (58 чоловіків, 95 жінок) пацієнтів віком від 23 до 94 років (у середньому 69,95±15,83) із переломом ПВС. Результати. Частота гострих венозних тромбоемболічних ускладнень серед хворих із переломами ПВС становить 13,7 %. Переважна більшість (98 %) пацієнти цієї категорії мають додаткові фактори ризику розвитку ВТЕ, крім перелому стегнової кістки. Оцінка за шкалою Caprini 10 балів асоціюється із збільшенням ризику розвитку ВТЕ у хворих із переломами проксимального відділу стегна в 11,7 разів (95 % ДІ [1,25–109,3]), 11 балів — у 23,7 рази (95 % ДІ [2,25–250,2]), 12 балів — у 45,1 рази (95 % ДІ [4,42–461,0]), 13 і більше балів — у 79 разів (95 % ДІ [8,95-697,4]) порівняно з наявністю 5–8 балів. Висновки. Виявлено, що оцінка за шкалою Caprini дозволяє виявити пацієнтів «украй високого ризику» (extremely high risk) розвитку ВТЕ. Граничний рівень (cut-off) кількісної оцінки ризику за шкалою Caprini > 10 балів дозволяє виявити хворих «украй високого ризику» тромбозів (AUROC 0,845; 95 % ДІ 0,769–0,922). Ключові слова. Перелом проксимального відділу стегна, венозний тромбоз, фактори ризику, шкала Caprini.

Keywords. Proximal femoral fracture, venous thrombosis, risk factors, Caprini score

Introduction

According to the predictive data from the Danish National Register, the number of patients with proximal femur fractures (PFF) will increase by 2.5 times during the period from 2010 to 2040. Additionally, the number of affected individuals in the age groups over 60, 70, and especially 80 and 90 years old will rise significantly. This trend is largely related to the aging population [1]. Other reports have also identified an increase in the overall number of PFFs [2, 3], even though some indicated stable or decreasing age-adjusted incidence rates [4]. Due to the growing frequency of PFFs and the associated morbidity and disability, treatment and rehabilitation of patients with this condition have become a global problem in modern traumatology and orthopedics. Furthermore, the annual high number of new fractures (over 10 million) creates a significant physical, psychological, and financial burden on patients, their families, and significantly strains the healthcare system as a whole [5, 6].

Venous thromboembolism (VTE) is a serious complication of PFF due to a combination of factors related both to the trauma itself and the patient's immobilization. On the one hand, traumatic injury, especially in the case of complex fractures, is often accompanied by damage to blood vessels around the fracture site. This creates conditions for the formation of blood clots at the injury site. It is also important to remember that any traumatic stress to the body can trigger activation of the blood coagulation processes, which increases the risk of developing VTE, especially when combined with blood vessel damage and disrupted blood flow. On the other hand, post-trauma immobilization, particularly for the proximal parts of the limbs, leads to slowed blood flow in the veins, which also increases the likelihood of clot formation [7, 8]. At present, the issue is particularly serious when patients have to remain in the hospital for over three days while waiting for postponed surgery for a PFF, due to various objective reasons. Prolonging the time from the moment of injury to surgical intervention significantly increases the risk of thrombosis, multiplying the likelihood of its occurrence several times [9].

According to a systematic review and meta-analysis by Y. Hu et al. [8], the overall combined prevalence of preoperative deep vein thrombosis (DVT) in the thigh was 24.1 % (95 % CI: [19.3–28.8]). One study reported a two-fold higher prevalence of preoperative DVT, 52.5 %, in patients with PFF [10], while in another publication, the prevalence was only 5.3 % after hip fracture in elderly patients. On this basis, the authors concluded that routine venous thromboprophylaxis is not warranted for this patient population [11].

The development of DVT in the limbs increases the duration of hospitalization and healthcare costs [12]. Moreover, it can lead to pulmonary artery thromboembolism and subsequent post-thrombotic syndrome, which negatively affect the quality of life and are causes of hospital mortality [8]. According to existing data [12], about 50 % of patients with proximal venous thrombosis have asymptomatic pulmonary artery thromboembolism, and 80 % of cases with thromboembolism have asymptomatic DVT in the lower limbs. It is important to understand that the development of venous thromboembolism (VTE) in the preoperative period can result in delays in surgical intervention, shifting it from the optimal timing, which negatively affects the final treatment outcomes [8]. The use of anticoagulant therapy in patients with femoral fractures helps reduce the frequency of preoperative VTE and fatal complications [13].

A critical assessment of the existing literature reveals notable limitations and inconsistencies in the information related to preoperative VTE among individuals with PFFs. In response to these findings, this study was designed and implemented.

Objective: To reduce the incidence of deep vein thrombosis in patients with proximal femur fractures by determining the effectiveness of using the Caprini scale to identify individuals with a trauma surgery profile who belong to the "very high risk" group for developing venous thromboembolism.

We set the following main tasks:

1. To determine the frequency of preoperative deep vein thrombosis (DVT) in the lower limbs in patients with proximal femur fractures (PFF);
2. To identify additional risk factors for the development of venous thromboembolism (VTE) in this group of patients;
3. To investigate individual risk factors and the cumulative effect of these factors, and to determine whether the standard approach to thromboprophylaxis (e. g., using the Caprini scale to assess the risk of VTE) is appropriate.

Materials and Methods

The study was conducted in accordance with the principles of the Helsinki Declaration and the Council of Europe Convention on Human Rights and Biomedicine. The article materials were reviewed and approved by the Bioethics Committee of Shupyk National University of Health of Ukraine (protocol

No. 9, dated 22.11.2023). All patients gave informed consent to participate in the study.

The study was based on the results of examinations and treatment of 153 individuals aged 23 to 94 years (mean (M ± σ) — 69.95 ± 15.83) with PFF, who were hospitalized in the Trauma and Orthopedic Department of Kyiv City Clinical Hospital No. 8 during 2023. Among them, 58 (37.9 %) were men and 95 (62.1 %) were women.

Inclusion criteria: Age 18 years or older, presence of a proximal femur fracture, informed consent from the patient to participate in the study.

Exclusion criteria: Age under 18 years, the need for therapeutic doses of direct anticoagulants, thrombocytopenia, coagulopathy, hemorrhagic syndrome (unrelated to disseminated intravascular coagulation), blood disorders, decompensated cardiovascular and respiratory diseases (heart failure NYHA III or higher, significant arrhythmias, grade III respiratory failure), acute and chronic hepatitis B or C, severe renal or liver failure, malignancies, pregnancy, refusal to participate in the study.

Falls were the most common cause of PFF in the analyzed sample — 145 out of 153 patients (94.8 %). Less frequently, trauma was caused by combat actions — 6 cases (3.9 %) and road traffic accidents — 2 (1.3 %).

Surgical intervention was performed in 76 patients (49.7 %) of the 153 participants in the study. Among them: 41 cases involved hip joint replacement, 33 cases involved metal osteosynthesis (MOS), and 2 cases involved external fixation devices with simultaneous use of a Vacuum-Assisted Closure (VAC) system. The remaining 77 individuals, who refused surgical intervention, were treated conservatively (skeletal traction).

Standard examination included taking disease and medical history, physical examination, palpation, assessment of the range of motion in the joints, evaluation of the condition of the venous system in the lower limbs according to the classification of chronic venous diseases: pain syndrome, if present — character and degree of pain, presence of peripheral edema, condition of the skin, functional tests, and the patient's level of physical activity. Prior to surgery, all patients underwent ultrasound examination of the veins in the lower limbs with the use of a compression test and color Doppler.

The risk of developing venous thromboembolism (VTE) was assessed using the validated Ukrainian-language Caprini scale (Caprini Risk Assessment Model), which includes a list of risk factors for venous thromboembolic complications in surgical patients. Each risk factor is assigned a score from 1 to 5. According to the total score, the risk of thrombosis development is classified as follows:

– Very low (less than 0.5 %) — 0;
– Low (around 1.5 %) — 1–2;
– Moderate (around 3 %) — 3–4;
– High (around 6 %) — 5 or more.

Statistical analysis of the data was performed using Microsoft Excel and the licensed IBM "Statistical Package for Social Science (SPSS) Statistics" software, version 20.0.0 for Windows. Descriptive statistics are presented as the mean value with the corresponding standard deviation (M ± σ). The statistical significance of differences in frequencies was analyzed using the Pearson χ^2 test. Additionally, odds ratios (OR) were calculated to assess the strength of the association between the factors studied.

The odds ratio (OR) was calculated as the ratio of the event frequency in the compared groups. For each indicator, a 95 % confidence interval (CI) was determined. A result was considered statistically significant if the confidence interval did not include the value 1.

The relationship between the variables studied was examined using correlation analysis and the Pearson correlation coefficient (r), whose significance was tested using the t-test. For multivariate analysis, the binomial logistic regression method was used. The predictive capacity of the model for assessing the risk of VTE was studied using ROC analysis. A result was considered statistically significant if the p-value was less than 0.05 (confidence level — 95 %).

Results

In the analyzed cohort of patients, the frequency of acute venous thromboembolic complications in cases of PFF was 13.7 % (21 out of 153 cases), with the vast majority (95.2 %) being lower limb deep vein thrombosis (DVT). At the same time, half of the patients (50.0 %) were found to have thrombotic occlusion of the calf vein.

Patients with PFF are classified into a high-risk group for the development of VTE, as according to the Caprini scale, a femoral fracture is assigned 5 points, and a score of ≥ 5 points stratifies the risk of thrombosis as high.

In addition to the fracture itself, which is assigned 5 points on the Caprini scale, the vast majority of patients with PFF (98 %) were shown to have numerous and varied additional risk factors for VTE (on average (2.66 ± 1.48) factors per person). Information regarding these factors is provided in Table 1.

Analysis of Additional Risk Factors

Table 1

Prevalence of individual risk factors for venous thromboembolism development

Age (years)	Patient number (n = 153)	
	abs.	%
Proximal femur fracture	153	100.0
Age ≥ 40 years	143	93.5
Previous major surgery in the medical history	41	26.8
Swelling of the lower limbs	35	22.9
Family history of VTE	29	19.0
Severe pulmonary disease, including pneumonia (< 1 month), impaired lung function	27	17.7
Varicose veins of the lower limbs	24	15.7
Obesity (BMI > 30 kg/m²)	23	15.0
History of VTE	21	13.7
Bed rest for > 72 hours	21	13.7
Inflammatory bowel diseases in the medical history	11	7.2
Thrombophilia	10	6.5
Acute cerebrovascular accident (< 1 month)	9	5.9
Malignant neoplasms in the medical history	4	2.6
History of VTE	3	2.0
Central venous catheterization	2	2.1
For women (n = 95): ≥ 3 spontaneous miscarriages Stillbirths / fetal death Premature delivery with toxemia during pregnancy or fetal growth restriction Hormone Replacement Therapy (HRT)	 6 4 7 9	 6.3 4.2 7.4 9.5

The analysis of the additional risk factors on the Caprini scale revealed a direct correlation between their number and the frequency of acute venous thrombosis (r = 0.504; p < 0.001). The data in Figure 1 show that the risk of developing acute venous thrombosis increases with the number of additional risk factors. Specifically, with 3 additional risk factors, the frequency of venous thromboembolism (VTE) in the studied cohort was 10.3 %, with 4 factors it increased to 28.6 %, with 5 factors it reached 50 %, with 6 factors it was 85.7 %, and with 7 factors, it was 100 %.

For the analysis of the frequency of verified acute venous thrombosis based on the Caprini score, the patients were divided into the following groups:

– Group I: 80 individuals with a score of 5–9 points;
– Group II: 31 cases with a score of 10 points;
– Group III: 13 cases with a score of 11 points;
– Group IV: 11 cases with a score of 12 points;
– Group V: 18 cases with a score of 13 or more points.

It was found that in Group I, acute VTE developed in 1 out of 80 cases; in Group II, in 4 out of 31 cases; in Group III, in 3 out of 13 cases; in Group IV, in 4 out of 11 cases; and in Group V, in 9 out of 18 cases. These frequencies were 1.3 %, 12.9 %, 23.1 %, 36.4 %, and 50.0 %, respectively (p < 0.001) (Figure 2).

It was established that an increase in the Caprini score was significantly associated with an increased risk of developing VTE in patients with proximal femur fractures. Specifically, a score of 10 points increases the risk of venous thromboembolism by 11.7 times (95 % CI: [1.25–109.3]; p = 0.008), 11 points increases the risk by 23.7 times (95 % CI: [2.25–250.2]; p < 0.001), 12 points increases the risk by 45.1 times (95 % CI: [4.42–461.0]; p = 0.008), and 13 or more points increases the risk by 79 times (95 % CI: [8.95–697.4]; p < 0.001), compared to patients with a score of 5–8 points.

The results of the ROC analysis confirmed the high predictive ability of the Caprini scale for the development of VTE: the area under the curve (AUC) was 0.845 (95% CI: [0.769–0.922]; p < 0.001).

During the ROC curve coordinate analysis, the cutoff point that significantly predicts the development of VTE in patients with proximal femur fractures in the high-risk group was determined to be

10.5 points on the Caprini scale (sensitivity 76.2 %, specificity 80.3 %) (Table 2).

Therefore, the criterion that significantly increases the risk of VTE in patients with PFF in the high-risk group while receiving pharmacological thromboprophylaxis at the standard prophylactic dose is the presence of 11 or more points on the Caprini scale. Specifically, in patients with fewer than 11 points on the Caprini scale, the frequency of VTE in our study was 5/111 cases (4.5%) compared to 16/42 cases (38.1%) in patients with 11 or more points on this scale (OR 13.1; 95% CI [4.38–38.9], p < 0.001).

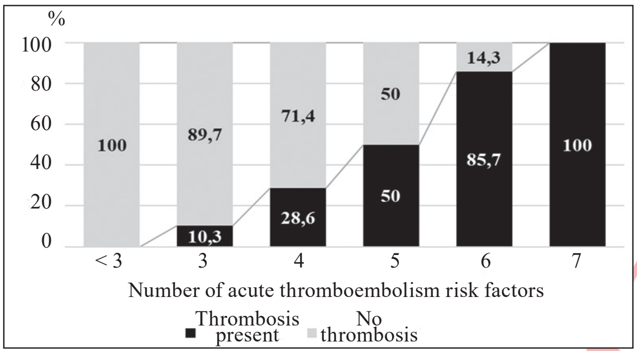

Fig. 1. Frequency of verified acute venous thromboembolism in patients (n = 153) with additional risk factors

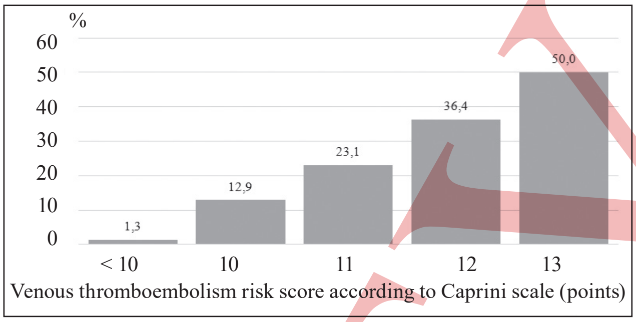

Fig. 2. Frequency of verified acute venous thromboembolism in patients (n = 153) with varying scores on the Caprini Risk Assessment Scale

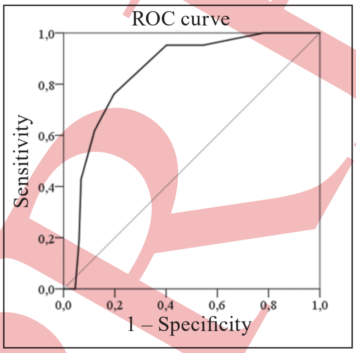

Fig. 3. ROC curve showing the correlation between the probability of VTE development in patients with proximal femoral shaft fractures and their risk score according to the Caprini scale

Discussion

VTE, specifically DVT, is a common complication in patients with proximal femur fractures (PFF) [8]. The majority of scientific publications report on the prevalence of postoperative DVT in patients in this category [7, 14]. However, there is insufficient data on the frequency and localization of preoperative DVT in patients with fractures of long tubular bones (including femur, tibia, and fibula) of the lower limbs. It should also be acknowledged that existing clinical guidelines do not distinguish between preoperative and postoperative thrombosis in terms of screening and diagnostic strategies. In fact, much more attention is given to the prevention and treatment of postoperative VTE than to preoperative thrombosis [8].

Our data indicate that the prevalence of this complication in patients with PFF was 13.7 %, with the vast majority (95.2 %) being lower limb DVT. This rate is twice as low as the overall pooled prevalence of preoperative DVT, which was 24.1 % (95 % CI 19.3–28.8 %) in a systematic review and meta-analysis published in 2023 [8]. This discrepancy likely reflects population characteristics, particularly differences in baseline risk. At the same time, there are studies showing a DVT rate (16.3 %) similar to the one we found [15].

As noted by other authors, we believe that the relatively high prevalence of preoperative DVT deserves more attention, as this complication is closely associated with negative treatment outcomes. It is crucial to highlight that preoperative thrombosis can delay surgical treatment. More seriously, if a thrombus is not detected in time before surgery, orthopedic interventions may cause fragmentation of the thrombus, increasing the risk of pulmonary embolism and other adverse outcomes [16].

Existing studies involving patients with lower limb fractures have repeatedly shown statistically significant differences between the groups of patients with and without DVT, with various risk factors such as age, presence of diabetes, hyper-

Table 2

Results of ROC analysis for the number of points on the Caprini scale as a prognostic criterion for the development of VTE

Criterion	AUROC	p	95 % CI	Cut-off point	Sensitivity %	Specificity %
Caprini Risk Assessment Score	0.845	< 0.001	0.769–0.922	> 10 points	56.3	55.6

tension, fracture location, and preoperative plasma D-dimer levels [17]. According to our data, the vast majority (98 %) of patients with PFF have multiple and diverse additional risk factors for VTE, beyond the femoral fracture itself (on average, 2.66 ± 1.48 factors per patient). This suggests that the standard approach, such as using the Caprini scale, to assess the risk of developing VTE does not account for individual risk factors and their cumulative effects. However, we have established a direct correlation between the number of additional risk factors and the frequency of acute venous thrombosis ($r = 0.504$; $p < 0.001$). In our opinion, this indicates the need to optimize VTE risk analysis in patients with PFF, as well as the likely importance of personalizing their preoperative thromboprophylaxis.

Conclusions

The overall frequency of acute venous thromboembolic complications among patients with proximal femur fractures (PFF) is 13.7 %, with the majority (95.2 %) being deep vein thrombosis (DVT) of the lower limb.

The vast majority (98 %) of patients with PFF have multiple and varied additional risk factors for venous thromboembolism (on average, 2.66 ± 1.48 per patient).

ROC analysis has shown that a cutoff level of > 10 points on the Caprini scale allows for the prediction of "extremely high risk" of thrombosis (AUROC 0.845; 95 % CI 0.769–0.922). We believe that a score of 11 or more points on the Caprini scale requires the personalization of thromboprophylaxis for patients with PFF.

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

Prospects for Further Research. We consider the development and study of the effectiveness and safety of personalized preoperative thromboprophylaxis in patients with PFF as a promising direction for our future research.

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References

1. Sing, C. W., Lin, T. C., Bartholomew, S., Bell, J. S., Bennett, C., ..., & Wong I. C. K. (2023) Global Epidemiology of Hip Fractures: Secular Trends in Incidence Rate, Post–Fracture Treatment, and All–Cause Mortality. *Journal of bone and mineral research, 38*(8), 1064–1075. https://doi.org/10.1002/jbmr.4821
2. Feng, J., Zhang, C., Li, B., Zhan, S., Wang, S., & Song, C. (2023). Global burden of hip fracture: The global burden of disease study. *Osteoporosis international, 35*(1), 41–52. https://doi.org/10.1007/s00198–023–06907–3
3. Hagino, H., Osaki, M., Okuda, R., Enokida, S., & Nagashima, H. (2020). Recent trends in the incidence of hip fracture in Tottori prefecture, Japan: Changes over 32 years. *Archives of osteoporosis, 15*(1). https://doi.org/10.1007/s11657–020–00823–3
4. Gazgalis, A., Simmons, S., Doucet, M., Gorroochurn, P., Cooper, H. J., & Herndon, C. L. (2024). Higher comorbidities are correlated with readmission following arthroplasty for femoral neck fracture. *Arthroplasty today*, 30, 101494. https://doi.org/10.1016/j.artd.2024.101494
5. GBD 2019 Fracture Collaborators. (2021). Global, regional, and national burden of bone fractures in 204 countries and territories, 1990–2019: a systematic analysis from the Global Burden of Disease Study 2019. *Lancet healthy longev, 2*(9), e580–e592. https://doi.org/10.1016/S2666–7568(21)00172–0.
6. Meyer, A. C., Hedström, M., & Modig, K. (2020). The Swedish hip fracture register and national patient register were valuable for research on hip fractures: Comparison of two registers. *Journal of clinical epidemiology*, 125, 91–99. https://doi.org/10.1016/j.jclinepi.2020.06.003
7. Ruan, Y., Wang, F., Du, X., Sun, S. (2023). Rehabilitation nursing after lower limb fracture: Preventing deep vein thrombosis and enhancing quality of life. *Medicine (Baltimore), 102*(47), e36180. https://doi.org/10.1097/MD.0000000000036180
8. Hu, Y., Zhu, L., Tian, X., & Duan, F. (2023). Prevalence of preoperative deep vein thrombosis in long bone fractures of lower limbs: A systematic review and meta–analysis. *Journal of orthopaedics and traumatology, 24*(1). https://doi.org/10.1186/s10195–023–00699–2
9. Kalashnikov, A. V., Lazarenko, Y. V., & Kalashnikov, O. V. (2023). Fractures of the proximal femur: social significance and tactics of surgical treatment (review of literature sources). *Trauma, 24*(1), 79–85. https://doi.org/10.22141/1608–1706.1.24.2023.936
10. Zhang, J., Zhao, K., Li, J., Meng, H., Zhu, Y., & Zhang, Y. (2020). Age over 65 years and high levels of C–reactive protein are associated with the risk of preoperative deep vein thrombosis following closed distal femur fractures: A prospective cohort study. *Journal of orthopaedic surgery and research, 15*(1). https://doi.org/10.1186/s13018–020–02089–4
11. Chan, Y., Chiu, K., Cheng, S., & Ho, P. (2004). The incidence of deep vein thrombosis in elderly Chinese suffering hip fracture is low without prophylaxis: A prospective study using serial duplex ultrasound. *Journal of orthopaedic surgery, 12*(2), 178–183. https://doi.org/10.1177/230949900401200208
12. Hong, G., Zhong, H., Illescas, A., Reisinger, L., Cozowicz, C., Poeran, J., Liu, J., & Memtsoudis, S. G. (2024). Trends in hip fracture surgery in the United States from 2016 to 2021: Patient characteristics, clinical management, and outcomes. *British journal of anaesthesia, 133*(5), 955–964. https://doi.org/10.1016/j.bja.2024.07.022
13. Niu, S., Li, J., Zhao, Y., Ding, D., Jiang, G., Song, Z. (2021). Preoperative deep venous thrombosis (DVT) after femoral neck fracture in the elderly, the incidence, timing, location and related risk factors. *BMC Musculoskelet Disord, 22*(1), 264. https://doi.org/10.1186/s12891–021–04145–4
14. Li, L. (2025). Early rehabilitation nursing prevents postoperative DVT and promotes limb function recovery in patients with traumatic fracture. *American journal of translational research, 17*(4), 2665–2677. https://doi.org/10.62347/wlts7477
15. Liu, D., Zhu, Y., Chen, W., Li, J., Zhao, K., Zhang, J., Meng, H., & Zhang, Y. (2020). Relationship between the inflammation/immune indexes and deep venous thrombosis (DVT) incidence rate following tibial plateau fractures. *Journal of orthopaedic surgery and research, 15*(1). https://doi.org/10.1186/s13018–020–01765–9
16. Wang, T., Guo, J., Long, Y., Yin, Y., & Hou, Z. (2022). Risk factors for preoperative deep venous thrombosis in hip fracture patients: A meta–analysis. *Journal of ortho-*

paedics and traumatology, 23(1). https://doi.org/10.1186/s10195–022–00639–6

17. Chang, W., Wang, B., Li, Q., Zhang, Y., & Xie, W. (2021). Study on the risk factors of preoperative deep vein thrombosis (DVT) in patients with lower extremity fracture. *Clinical and applied thrombosis/hemostasis*, 27. https://doi.org/10.1177/10760296211002900

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ANALYSIS OF THE PREVALENCE AND RISK FACTORS FOR VENOUS THROMBOEMBOLIC COMPLICATIONS IN PATIENTS WITH PROXIMAL FEMORAL FRACTURES

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Radiographic features of knee osteoarthritis in the lateral view depending on joint line obliquity

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Objective. To evaluate the radiographic features of sagittal knee joint morphology in osteoarthritis, taking into account the joint line obliquity determined using an original method (mJLO). Methods. 62 lateral knee radiographs of 45 patients with medial knee osteoarthritis were analyzed. The following radiographic parameters were assessed: posterior distal femoral angle (PDFA); posterior condylar offset ratio (PCOR); posterior tibial slope (PTS); tuberosity-modified tibial slope (TMTS); and tibial tuberosity inflection angle (TTIA). The mJLO was calculated as aMPTA + aLDFA + 6°. Values of mJLO < 177° were defined as apex distal (AD), 177°–183° as apex neutral (AN), and > 183° as apex proximal (AP). Statistical significance was defined as $p \leq 0.05$. Results. AD was found in 43 patients (69.35 %), AN in 16 (25.81 %), and AP in 3 (4.84 %). Higher mJLO values and more proximal joint line orientation were associated with lower PDFA ($\tau = -0.25$, $p = 0.004$) and PCOR ($\tau = -0.22$, $p = 0.01$). Patients with PDFA > 88° had significantly higher odds of AD (OR = 3.63; CI: 1.20–12.33; $p = 0.02$), as did those with PTS > 8° (OR = 5.22; CI: 1.65–19.40; $p = 0.004$). Conversely, AD was less likely in patients with PDFA < 78° (OR = 0.08; CI: 0.01–0.34; $p = 0.0005$) and PTS 3°–8° (OR = 0.25; CI: 0.07–0.76; $p = 0.01$). Patients with PTS > 8° had a lower odds of AN (OR = 0.28; CI: 0.07–0.90; $p = 0.03$). Significantly higher odds of AP were observed in individuals with PDFA < 78° (OR = 49.00; CI: 4.17–6846.81; $p = 0.001$) and PCOR < 0.44 (OR = 11.67; CI: 1.06–1596.60; $p = 0.04$), whereas PCOR > 0.44 decreased the likelihood of this obliquity type (OR = 0.09; CI: 0.0006–0.94; $p = 0.04$). Conclusions. Significant differences in sagittal knee joint morphology parameters in osteoarthritis were demonstrated depending on the mJLO.

Мета. Оцінити рентгенологічні особливості сагітальної морфології колінних суглобів за остеоартриту з урахуванням нахилу суглобової лінії, визначеного за авторською методикою (mJLO). Методи. Проаналізовано 62 рентгенограми колінних суглобів, виконані в боковій проєкції, 45 хворих із медіальним гонартрозом. Серед рентгенографічних критеріїв, вивчали: задній дистальний кут стегнової кістки (PDFA); індекс заднього виросткового зсуву (PCOR); задній нахил плато великогомілкової кістки (PTS); горбистісно-модифікований тібіальний нахил (TMTS); кут інфлексії горбистості великогомілкової кістки (TTIA). Розраховували mJLO за формулою: aMPTA + aLDFA + 6°. Значення mJLO < 177° визначали як дистальний нахил лінії суглоба (AD), mJLO 177°–183° — як нейтральний (AN), mJLO > 183° — як проксимальний (AP). Значущими вважали відмінності за $p \leq 0,05$. Результати. Встановлено AD у 43 (69,35 %) хворих, AN — у 16 (25,81 %), AP — у 3 (4,84 %). Зростання mJLO асоційовано зі зменшенням PDFA ($\tau = -0,25$, $p = 0,004$) та PCOR ($\tau = -0,22$, $p = 0,01$). Вищі шанси AD встановлено за PDFA > 88° (OR = 3,63; CI: 1,20–12,33; $p = 0,02$), PTS > 8° (OR = 5,22; CI: 1,65–19,40; $p = 0,004$). Нижчу ймовірність AD доведено за показників PDFA < 78° (OR = 0,08; CI: 0,01–0,34; $p = 0,0005$), PTS 3°–8° (OR = 0,25; CI: 0,07–0,76; $p = 0,01$). У обстежених зі значеннями PTS > 8° доведено нижчий ризик AN (OR = 0,28; CI: 0,07–0,90; $p = 0,03$). Вищі шанси AP встановлено за PDFA < 78° (OR = 49,00; CI: 4,17–6846,81; $p = 0,001$), PCOR < 0,44 (OR = 11,67; CI: 1,06–1596,60; $p = 0,04$), тоді як наявність PCOR > 0,44 знижує ймовірність вказаного типу нахилу (OR = 0,09; CI: 0,0006–0,94; $p = 0,04$). Висновки. Доведено значущу відмінність досліджуваних параметрів сагітальної морфології колінних суглобів за остеоартриту залежно від mJLO. Ключові слова. Остеоартрит, колінний суглоб, персоналізація, дегенеративно-дистрофічні захворювання суглобів, морфологія.

Keywords. Osteoarthritis, knee joint, personalization, degenerative joint diseases, morphology

Introduction

Osteoarthritis (OA) is a chronic, progressive degenerative joint disease characterized by a spectrum of pathological changes, including degeneration of the articular cartilage, remodeling of the subchondral bone, formation of osteophytes, development of synovitis, and involvement of periarticular structures [1, 2].

Knee OA accounts for about 85 % of the total burden of degenerative joint diseases [3]. More than 250 million people worldwide suffer from knee OA, and according to Y. Lv et al., the number of patients is estimated at 374.7 million [1, 4, 5]. In recent years, a clear upward trend in the prevalence of OA has been observed, which is associated with global population aging and a rising frequency of comorbid conditions [2]. Epidemiological data indicate that between 2005 and 2015, the prevalence of knee OA increased by 32.7 %, and between 1992 and 2021 — by 124.51 % [4, 5].

The knee joint is characterized by complex anatomy and pronounced interindividual morphological variability [6]. In the surgical treatment of knee OA, the concept of kinematic alignment in total knee arthroplasty, which aims to reproduce the natural alignment of the lower limb axis, is gaining popularity. Its application allows restoration of the native spatial relationships and reduction of tissue trauma compared with mechanical alignment [7]. However, most studies on personalized knee arthroplasty have focused on evaluating structural changes in the coronal plane, while sagittal parameters have been investigated in less detail.

One of the most studied sagittal morphological parameters is the posterior tibial slope (PTS). It is known that PTS serves as an informative indicator for evaluating the condition of the tibial articular surface. High interindividual variability of this parameter depending on sex, ethnicity, measurement technique, and disease course has been confirmed by several studies [7–9]. Differences between medial (MPTS) and lateral (LPTS) PTS values within the same joint have also been established [6, 8, 9]. For instance, in a study by M. Meier et al., analysis of Computed Tomography scans from 234 patients with knee OA demonstrated variability in MPTS values ranging from –4.3° to 16.8°, and LPTS from –2.9° to 17.2°, with a mean intraindividual difference of 2.6° ± 2.0° (up to 9.5°) [8]. The difference between MPTS 8.4° ± 4.0° and LPTS 9.2° ± 3.6° in patients with knee OA was also confirmed by A. Siddiqi et al. Moreover, their study demonstrated that, compared with healthy individuals, patients with knee OA had lower MPTS values (8.4° ± 4.0° vs. 9.2° ± 4.0°) and higher LPTS values (9.2° ± 3.6° vs. 7.2° ± 3.3°), highlighting the need for a personalized approach to arthroplasty [9].

An important component of knee joint morphology assessment is the joint line obliquity (JLO). In the Coronal Plane Alignment of the Knee (CPAK) system, developed by S. J. MacDessi et al., JLO is one of the two key parameters for joint phenotyping, calculated as the sum of the mechanical lateral distal femoral angle (LDFA) and the mechanical medial proximal tibial angle (MPTA) [10]. In addition, JLO is also defined as a radiographic angle formed between the line tangent to the tibial plateau and a horizontal line parallel to the ground. The radiographic JLO angle makes it possible to characterize the functional inclination of the joint plane under axial loading of the lower limb [11]. In the context of personalized orthopedics, JLO is considered one of the key factors influencing the restoration of optimal axial balance of the lower limb.

Despite significant progress in the study of coronal parameters of the knee joint, the variability of its sagittal morphology in OA, taking into account the JLO, remains insufficiently investigated, highlighting the need for further research.

The null hypothesis of the study is that there are no differences in the sagittal morphology parameters of the knee joints in medial OA when accounting for the JLO.

Objective: to evaluate the radiographic features of sagittal knee joint morphology in medial osteoarthritis, taking into account the joint line obliquity as determined by the authors' original method joint line obliquity.

Material and Methods

In the present observational cross-sectional study, the results of radiographic examinations of 62 knee joints affected by medial OA in 45 patients who underwent inpatient treatment at the Traumatology Department of the Vinnytsia City Clinical Emergency Hospital during the period 2017–2025 were analyzed. The mean age of patients was (63.84 ± 8.21) years (n = 45), with a mean age of (63.40 ± 8.79) years (n = 62) across the groups. The study group included 17 (37.78 %) men and 28 (62.22 %) women. Unilateral knee OA was recorded in 28 (62.22 %) patients, whereas bilateral involvement was observed in 17 (37.78 %).

Inclusion criteria: primary medial knee OA stage II–III according to the Kellgren-Lawrence classification; secondary medial knee OA, including cases following spontaneous osteonecrosis of the medial femoral condyle; satisfactory condition of the lateral compartment of the knee joint (intact meniscus and full-thickness articular cartilage); integrity of the knee ligamentous structures; ability to achieve full extension of the knee joint or presence of flexion contracture < 10°.

Exclusion criteria: bicompartmental knee OA (Kellgren–Lawrence grades I–IV); secondary post-traumatic OA after tibial plateau fracture; previous surgical interventions in the proximal tibia (except arthroscopic meniscectomy); presence of flexion contracture > 10°; instability of the knee ligaments; secondary OA associated with dysplastic bone changes, metabolic disorders, or other diseases (ochronosis, Gaucher's disease, Paget's disease, osteopetrosis); active or latent infection.

For the analysis, lateral radiographs of the knee joints obtained at 30° of flexion were used. In contrast, standard (short) anteroposterior radiographs of the knee joints under weight-bearing conditions were used to assess the mJLO.

Among the radiographic criteria assessed in the sagittal plane were:

– *Posterior Distal Femoral Angle (PDFA)* — the angle formed between the anatomical axis of the femur and the distal femoral joint orientation line. Reference values for the PDFA were considered to be in the range of 79°–87° [12].

– *Posterior Condylar Offset Ratio (PCOR)* — calculated as the ratio of the distance between two vertical lines, one drawn along the posterior cortical surface of the femur and the other passing through the most prominent point of the posterior condylar surface, to the distance measured from the anterior cortical surface of the femur to the most prominent point of the posterior condylar surface. The reference value of the index was defined as 0.44.

– *Posterior Tibial Slope (PTS)* — the angle between a line tangential to the proximal tibial joint surface and a line perpendicular to the anatomical axis of the tibial shaft. Reference values for PTS were considered within the range of 3°–8° [13].

In addition to the commonly accepted parameters, sagittal morphometric indices of the proximal tibia specifically developed for this study were evaluated:

– *Tuberosity-Modified Tibial Slope (TMTS)* — the angle between a horizontal line drawn along the proximal articular surface of the tibia and an oblique line passing through the most prominent points of the tibial tuberosity and the posterior margin of the tibial plateau.

– *Tibial Tuberosity Inflection Angle (TTIA)* — the angle formed between two lines drawn along the anterior cortical surface of the tibia in proximal and distal directions, intersecting at the most prominent point of the tibial tuberosity.

The present study utilized a common clinical database with our previous publication [13]; however, the subjects of analysis and the approach to patient grouping differed. Morphological assessment was performed using distinct original methods developed by the authors to provide a comprehensive investigation of the pathology.

The assessment of knee JLO was performed according to the authors' method, developed based on the principles of the CPAK system as a prototype. The modified JLO (mJLO) was calculated using the formula: mJLO = aMPTA + aLDFA + 6°, where 6° was considered a correction factor reflecting the valgus deviation of the anatomical axis relative to the mechanical axis [14]. The obtained values were interpreted according to the recommendations of the original method. An mJLO value of < 177° was defined as apex distal (AD); values within 177°–183° were considered apex neutral (AN); and values > 183° were defined as apex proximal (AP) [10]. For internal validation, assessment of measurement repeatability, and evaluation of the stability of patient distribution among the AD, AN, and AP groups when using the mJLO, a sensitivity analysis of the model was performed. In this analysis, the correction coefficient was varied by ± 1° (without shifting the threshold boundaries for AD, AN, and AP), followed by recalculation of the mJLO and subsequent comparison between the groups. A high degree of correlation between morphological knee parameters measured on standard anteroposterior radiographs and those obtained from full-length radiographs was demonstrated in the study by M. Unal et al. [15], which provided the rationale for adopting the CPAK model as a prototype.

The primary hypothesis was to determine differences in sagittal knee morphology in medial osteoarthritis depending on the mJLO. Secondary parameters, such as PDFA, PCOR, PTS, TMTS, and TTIA, were analyzed separately as secondary measures without adjustment for multiple comparisons, since the study was not designed to assess a cumulative effect or hierarchy of parameters.

The relationship between the investigated sagittal morphology parameters and the femorotibial angle (FTA) was also considered. The FTA was determined in the coronal plane as the angle between the anatomical axes of the femur and the tibia [14]. Additionally, the prognostic value of the defined parameters for the identification of the knee JLO in OA was analyzed.

Morphometric measurements were performed by two independent observers. To assess interobserver agreement, the intraclass correlation coefficient (ICC) was calculated using a two-way mixed-effects model with absolute agreement. The established ICC values were > 0.85, indicating the reliability of the obtained measurement results.

The study was conducted in accordance with the ethical principles of the World Medical Association (WMA) Declaration of Helsinki– Ethical Principles for Medical Research Involving Human Subjects (Seventh Revision, adopted at the 64^{th} WMA General Assembly) [16], the Council of Europe Convention on Human Rights and Biomedicine [17], as well as current national ethical standards [18] and approved by the bioethics committee of the Medical Center «Angels Clinic», Vinnytsia (protocol No. 7 dated 19.09.2025). All participants were informed about their involvement in the study, and written informed consent was obtained. Personal data of the examined patients were anonymized to ensure confidentiality.

Statistical analysis of numerical data was performed using StatSoft STATISTICA 13 and the RStudio environment. For evaluation and analysis of quantitative data, descriptive statistical methods were applied. Quantitative variables were presented as mean ± standard deviation (M ± SD), and categorical variables were expressed as absolute numbers (n) and corresponding percentages (%). For comparison between independent groups, the nonparametric Kruskal–Wallis test was used, and associations between variables were assessed using Kendall's rank correlation coefficient (τ). The prognostic value of sagittal morphology parameters in determining joint line obliquity was evaluated using a binary logistic regression model, calculating odds ratios (OR) with 95 % confidence intervals (CI). To minimize potential estimation bias associated with group imbalance and the presence of rare events in the model, Firth's penalized likelihood estimation method was applied. Statistical significance was set at $p \leq 0.05$.

Results

When evaluating the mJLO value, in the majority of examined patients, AD was identified in 43 (69.35 %), AN in 16 (25.81 %), and AP in 3 (4.84 %). The mean mJLO in the study group was 174.89° ± 5.41°. The average mJLO in individuals with AD was 172.40° ± 4.05°, in patients with AN — 179.25° ± 1.81° and 187.33° ± 2.52° in patients with AP; the difference was statistically significant ($p < 0.00001$). With variation of the correction coefficient by ± 1°, the distribution of patients among the AD, AN, and AP groups remained nearly unchanged and statistically nonsignificant, confirming the stability of applying the mJLO formula to short radiographic images.

Analyzing the position of the anatomical axis of the lower limb, it was found that the mean FTA angle in patients with AD was 175.88° ± 4.72°, corresponding to a varus deviation of the lower limb axis; in individuals with AN — a neutral position of the axis (179.97° ± 6.68°); and the highest values, corresponding to valgus deviation of the lower limb axis, were observed in individuals with AP — 185.00° ± 3.00°. The difference was statistically significant ($p = 0.009$). The mean FTA angle in patients of the study group was 177.38° ± 5.73°. A weak positive correlation was found between the FTA angle and mJLO values ($\tau = +0.22$, $p = 0.01$), indicating higher FTA values and, accordingly, a valgus position of the lower limb axis in patients with a more proximal position of the joint line.

When evaluating the morphological parameters of the distal femur, the highest PDFA values were found in the group of patients with AD, the lowest in those with AP, while patients with AN demonstrated intermediate values. The difference was statistically significant ($p = 0.004$) (table 1). In addition, a weak negative correlation was established between the PDFA and mJLO values ($\tau = -0.25$, $p = 0.004$), indicating significantly lower angle values in patients with a more proximal orientation of the joint line. The mean PDFA in patients of the study group was 84.98° ± 5.62°.

PDFA values < 78° were recorded in 10 (16.13 %) patients, including all individuals with AP, 31.25 % with AN, and 4.65 % with AD. The difference was statistically significant ($p < 0.00001$). PDFA values of 79°–87° were observed in 22 (35.48 %) patients, including 37.21 % of those with AD and 37.50 % with AN. In AP patients, values of the angle corresponding to the reference range were not observed; the difference was not statistically significant ($p = 0.43$). PDFA values > 88° were found in the majority of patients — 30 (48.39 %). Increased PDFA values were observed in the vast majority of AD patients (figure 1) and in 31.25 % of those with AN, while in patients with AP such values were not recorded; the difference was statistically significant ($p = 0.04$).

When analyzing the PCOR values, the highest indices were recorded in patients with AD, whereas the lowest were observed in those with AP; patients with AN demonstrated intermediate values. The difference was statistically significant ($p = 0.03$). The mean PCOR in the cohort was 0.44 ± 0.08. Significantly higher PCOR values were associated with lower mJLO values and, consequently, a more distal orientation of the knee joint line ($\tau = -0.22$, $p = 0.01$).

A PCOR value of < 0.44 was established in 25 (40.32 %) patients of the group, including all patients with AP, 50.00 % of those with AN, and 32.56 % of the examined individuals with AD; the difference in frequency indices was statistically significant (p = 0.048). It should be noted that a PCOR ratio of 0.44, which is defined as the reference value, was not observed in any case. In the majority of patients — 37 (59.68 %) PCOR values > 0.44 were recorded. These were identified in most of the examined individuals with AD, as well as in 50.00 % of patients with AN, while such values were not observed in patients with AP; the difference was statistically significant (p = 0.048).

When analyzing the morphological parameters of the proximal tibia in the sagittal plane, the mean PTS angle was found to be 9.00° ± 4.18°. The highest values of this angle were detected in patients with AD, whereas in individuals with AN and AP the mean PTS values corresponded to the reference range (table 2). Comparison of PTS angle values between groups formed according to the position of the knee joint orientation line demonstrated a statistically significant difference (p = 0.04). However, no reliable correlation was found between the PTS angle values and the mJLO (τ = –0.15, p = 0.09).

A PTS value of < 3° was identified in 1 (1.61 %) patient of the group, who had AN; such values were not observed in the groups of patients with AD or AP, and the difference in frequencies was not statistically significant (p = 0.24). PTS values within the range of 3°–8° were found in 31 (50.00 %) patients of the group. In particular, angle values corresponding to the reference range were observed in all examined individuals with AP (Figure 2), the vast majority of patients with AN, and in 39.53 % of those with AD; the difference was statistically significant (p = 0.03). PTS values > 8° were recorded in 30 (48.39 %) individuals of the group. Elevated angle values were observed in the majority of patients with AD, as well as in 25.00 % of those with AN, while such values were not registered in the AP group; the difference was statistically significant (p = 0.01).

The mean TMTS angle was 36.48° ± 6.28°. The highest values of this angle were detected in patients with AP, the lowest in those with AD, while intermediate values were recorded in the AN group (Figure 3). Comparison of TMTS angle values among

Table 1

Characteristics of the morphological parameters of the distal femur

Parameter	mJLO			p
	AD (n = 43)	AN (n = 16)	AP (n = 3)	
PDFA	86.53° ± 4.21°	83.00° ± 6.37°	73.33° ± 1.53°	0.004*
< 78°	2 (4.65 %)	5 (31.25 %)	3 (100.00 %)	< 0.00001*
79°–87°	16 (37.21 %)	6 (37.50 %)	0	0.430
> 88°	25 (58.14 %)	5 (31.25 %)	0	0.040*
PCOR	0.45 ± 0.07	0.42 ± 0.11	0.34 ± 0.02	0.030*
< 0.44	14 (32.56 %)	8 (50.00 %)	3 (100.00 %)	0.048*
0.44	0	0	0	1.000
> 0.44	29 (67.44 %)	8 (50.00 %)	0	0.048*

Note: * — A statistically significant difference was observed at p ≤ 0.05.

Table 2

Characteristics of the morphological parameters of the proximal tibia

Parameter	mJLO			p
	AD (n = 72)	AN (n = 25)	AP (n = 3)	
PTS	9.67 ± 3.87	7.81 ± 4.89	5.67 ± 1.53	0.04*
< 3°	0	1 (6.25 %)	0	0.24
3°–8°	17 (39.53 %)	11 (68.75 %)	3 (100.00 %)	0.03*
> 8°	26 (60.47 %)	4 (25.00 %)	0	0.01*
TMTS	35.41 ± 4.98	37.13 ± 7.66	48.33 ± 1.53	0.02*
TTIA	159.64° ± 7.32°	161.63° ± 4.81°	167.67° ± 3.51°	0.08

Note: * — A statistically significant difference was observed at p ≤ 0.05.

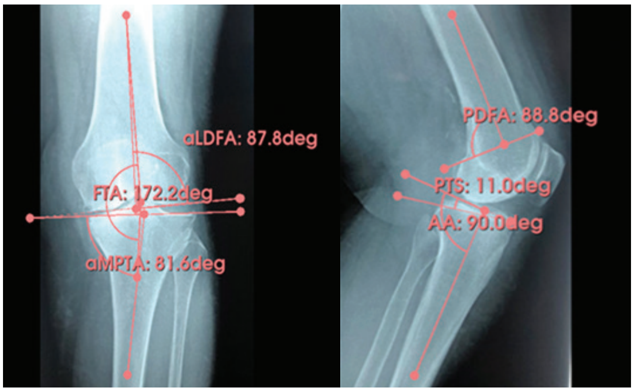

Fig. 1. Anteroposterior and lateral X-ray demonstrating medial compartment osteoarthritis of the left knee, grade 3. mJLO = 87.8° + 81.6° + 6° = 175.4°, indicating AD. FTA = 172.2°; PDFA = 88.8°; PTS = 11.0°; AA (additional angle) = 90°

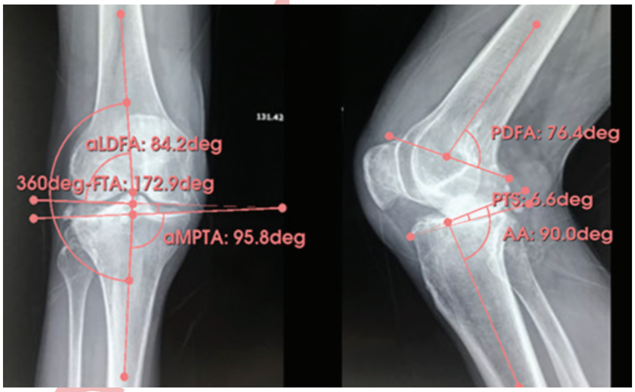

Fig. 2. Anteroposterior and lateral X-rays demonstrating medial compartment osteoarthritis of the right knee, grade 3. mJLO = 84.2° + 95.8° + 6° = 186.0°, indicating AP. FTA = 187.1°; PDFA = 76.4°; PTS = 6.6°; AA (additional angle) = 90°

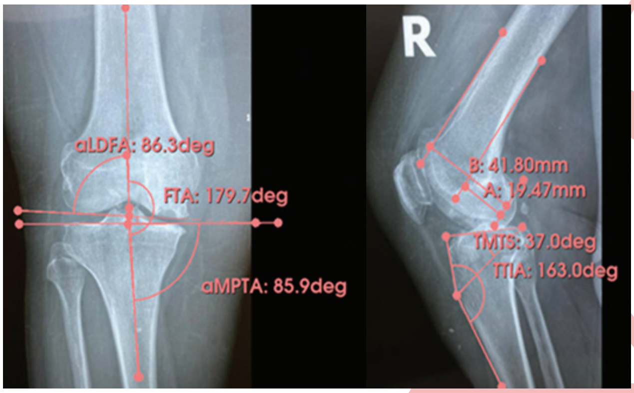

Fig. 3. Anteroposterior and lateral X-ray demonstrating medial compartment osteoarthritis of the right knee medial osteoarthritis of the right knee, grade 2. mJLO = 86.3° + 85.9° + 6° = 178.2°, indicating AN. FTA = 179.7°; PCOR = A : B = 19.47 : 41.80 = 0.47; TMTS = 37.0°; TTIA = 163.0°

groups formed according to the position of the joint orientation line demonstrated a statistically significant difference (p = 0.02). No significant correlation was found between the TMTS angle values and the mJLO (τ = +0.13, p = 0.13).

Evaluating TTIA values, the mean angle was 160.54° ± 6.81°. The highest mean values of this angle were recorded in patients with AP, the lowest in individuals with AD, while intermediate values were found in those with AN. The differences in TTIA angle values among the groups were not statistically significant (p = 0.08). No significant correlation was established between TTIA values and the mJLO (τ = +0.12, p = 0.16).

Assessing the prognostic value of sagittal morphology parameters of the distal femur in determining mJLO variant, we found significantly higher odds of AD in patients with PDFA > 88° (OR = 3.63; CI: 1.20–12.33; p = 0.02) (table 3). Conversely, individuals with PDFA < 78° demonstrated a lower likelihood of AD (OR = 0.08; CI: 0.01–0.34; p = 0.0005) and higher odds of AP (OR = 49.00; CI: 4.17–6846.81; p = 0.001).

It is noteworthy that PCOR < 0.44 was associated with higher odds of AP (OR = 11.67; CI: 1.06–1596.60; p = 0.04), whereas individuals with PCOR > 0.44 demonstrated a lower likelihood of this obliquity type (OR = 0.09; CI: 0.0006–0.94; p = 0.04).

The presence of PTS angle values within the reference range was associated with significantly lower odds of AD (OR = 0.25; CI: 0.07–0.76; p = 0.01). In patients with PTS values > 8°, significantly higher odds of AD were observed (OR = 5.22; CI: 1.65–19.40; p = 0.004) and a lower risk of AN (OR = 0.28; CI: 0.07–0.90; p = 0.03).

Discussion

The obtained results indicate a high variability of the sagittal morphology parameters of the knee joints in OA, depending on the orientation of the joint line. According to the author's method of mJLO assessment, AD was recorded in the majority of examined cases — 69.35 %, AN — in 25.81 %, and AP — in 4.84 %. The stability of intergroup differences in mJLO was preserved when the correction coefficient of + 6° was varied within ± 1°, indicating high robustness of the calculated parameters, internal consistency of the method, and the correctness of the applied formula, even under conditions of minor measurement error and without direct validation on full-length radiographs. A substantial predominance of AD of the knee joint, calculated using the CPAK method, in OA has been confirmed by the results of numerous studies [19–22].

In particular, according to the findings of the original multicenter study by S. J. MacDessi et al., which analyzed orthoradiographs of 500 patients from European and Australian populations with knee OA, AD was identified in 67 %, AN — in 31.8 %, and AP — in 2.6 % [10].

Table 3

Predictive value of the morphological parameters of the distal femur

Parameter	mJLO		
	AD	AN	AP
PDFA			
< 78°	OR = 0.08 CI (0.01–0.34) p = 0.0005	OR = 3.61 CI (0.92–14.40) p = 0.07	OR = 49.00 CI (4.17–6846.81) p = 0.001
79°–87°	OR = 1.25 CI (0.42–3.99) p = 0.70	OR = 1.14 CI (0.35–3.57) p = 0.82	OR = 0.24 CI (0.002–2.62) p = 0.28
> 88°	OR = 3.63 CI (1.20–12.33) p = 0,02	OR = 0.40 CI (0.12–1.25) p = 0.12	OR = 0.14 CI (0.001–1.52) p = 0.15
PCOR			
< 0.44	OR = 0,36 CI (0,12–1,06) p = 0,06	OR = 1.69 CI (0.55–5.25) p = 0.36	OR = 11.67 CI (1.06–1596.60) p = 0.04
> 0.44	OR = 2,75 CI (0,94–8,41) p = 0,06	OR = 0.59 CI (0.19–1.83) p = 0.36	OR = 0.09 CI (0.0006–0.94) p = 0.04

Note: * — CI not available.

Table 4

Predictive value of the morphological parameters of the proximal tibia

Parameter	mJLO		
	AD	AN	AP
PTS			
< 3°	OR = 0.14 CI (0.001–2.78) p = 0.20	OR = 9.00 CI (0.46–1341.77) p = 0.15	OR = 5.57 CI (0.04–128.15) p = 0.38
3°–8°	OR = 0.25 CI (0.07–0.76) p = 0.01	OR = 2.70 CI (0.87–9.29) p = 0.09	OR = 7.74 CI (0.71–1057.63) p = 0.10
> 8°	OR = 5.22 CI (1.65–19.40) p = 0.004	OR = 0.28 CI (0.07– 0.90) p = 0.03	OR = 0.14 CI (0.001–1.52) p = 0.11

Note: * — CI not available.

A similar distribution was reported by S. Agarwal et al., who presented the results of a retrospective analysis of orthoradiographic data of 134 patients (33 men, 101 women; mean age — 70 years) with knee OA. In accordance with the CPAK method, the researchers recorded AD in 66.41 %, AN — in 32.08 %, and AP — in 1.48 % [23].

In a retrospective study by S. E. Kim et al., data from 164 patients with knee OA predominantly affecting the medial compartment were analyzed. The authors established that the mean JLO, according to the CPAK method, was 175.8° ± 2.9° (range: 167.4°–185.7°). AD was observed in 67.1 %, AN — in 32.4 %, and AP — in 0.6 % [24].

When analyzing the morphological parameters of the distal femur determined in the sagittal plane, we established an increase in PDFA values in patients with AD, which was primarily due to the downward displacement of the horizontal axis drawn through the femoral condyles. In patients with AP, a decrease in PDFA values was observed as a result of the upward displacement of the axis passing through the condyles. In patients with degenerative-dystrophic diseases of the knee joint and AN, no general trend of displacement of the horizontal axis through the condyles was identified; in the majority of examined individuals — 37.50 %, the PDFA values corresponded to the reference range. A weak inverse correlation between PDFA and mJLO was established, confirming that a more proximal position of the joint line is associated with lower PDFA values. In addition, it was demonstrated that PDFA > 88° was associated with significantly higher odds of developing AD, whereas PDFA < 78° reduced the likelihood of this obliquity type and was linked to higher odds of AP.

When analyzing PCOR values, the highest indicators were observed in the AD group, whereas the lowest values were recorded in individuals with AP. A weak inverse correlation with mJLO indicated a tendency for PCOR to decrease with a more proximal obliquity of the joint line. In the majority of patients with AD (67.44 %) and in every second patient with AN, PCOR values > 0.44 were identified, which indicated a higher risk of anterior cruciate ligament injury in these groups. In all patients with AP and in half of the individuals with AN, PCOR values < 0.44 were recorded, which are associated with limitations of knee flexion. Notably, PCOR < 0.44 was associated with a higher likelihood of AP, whereas PCOR > 0.44 reduced the odds of developing this obliquity type.

With regard to the proximal tibia, the highest PTS values were recorded in individuals with AD, whereas the lowest values were observed in those with AP. Although the correlation with mJLO was statistically insignificant, the analysis of prognostic value demonstrated that PTS in the range of 3°–8° decreases the probability of AD. The presence of PTS > 8° was associated with a higher risk of AD and a lower likelihood of AN.

Comparable mean PTS values (8.6°–9.1°) were reported by L. Xin et al. in a cohort study of patients with knee OA [25], whereas in the work of S. K. Saidapur et al., this parameter was higher — 11.5° ± 1.34° in patients with early knee OA in the Indian population [26]. The high interethnic variability of PTS values has been confirmed by numerous population-based studies. The mean angle was reported as 9.90° in Americans, 13.30° in Chinese, 4°–7° in Germans, 11° in Japanese, 5.8°–6.6° in the Saudi Arabian population, and 7° in the East African population [27, 28].

Other parameters of sagittal morphology, in particular TMTS and TTIA, demonstrated more selective associations with mJLO.

Summarizing our findings, in patients with AD the leading morphological factors of changes in knee OA are the downward deviation of the axis drawn through the femoral condyles and the associated increase in PDFA and PCOR values, as well as the downward displacement of the axis drawn through the tibial condyles, which results in a decrease in TMTS values and an increase in PTS values. All these transformations indicate a higher risk of anterior cruciate ligament injury in patients with AD. In addition, the anterior displacement of the tibial diaphyseal axis in patients with AD, confirmed by low TTIA values, creates conditions that may lead to excessive tension of the anterior cruciate ligament and its injury.

The importance of PTS as a risk factor for anterior cruciate ligament injury has been confirmed by the findings of Y. Hiranaka et al., who identified an association between higher PTS values and anterior tibial translation [29], as well as by the biomechanical investigations of R. S. Dean et al., which demonstrated a linear increase in tensile stress on the ligament with increasing PTS [30]. In the study by B. Springer et al., it was shown that in OA with varus deformity, the combination of varus ≥ 10° and tibiofemoral subluxation ≥ 6 mm indicates a high probability of functional insufficiency of the ACL [31].

In patients with AP, alterations were observed due to the upward displacement of the axis passing through the femoral condyles, which corresponded to reduced PDFA and PCOR values, as well as increased TMTS angles and decreased PTS angles, resulting from the upward deviation of the axis passing through the tibial condyles. The morphological characteristics of the knee joint in patients with AP indicate a distinct load-bearing axis and potentially a different mechanism of degenerative changes. AP is characterized by higher TTIA values and a corresponding posterior displacement of the diaphyseal axis, which is associated with a lower risk of anterior cruciate ligament overstrain and increased tension of the posterior cruciate ligament.

In individuals with AN, intermediate values of the investigated angles were identified in most cases.

The identified mJLO knee variants may potentially influence the choice of surgical strategy in the treatment of knee osteoarthritis. However, the issue of adapting preoperative planning to a specific morphotype remains a subject of further research and currently lacks sufficient evidence.

The *limitations* of the present study, reflecting actual clinical practice, are the potential variability in the acquisition of radiographs across different medical institutions and the uneven distribution of subjects among groups. Despite the single-center nature of the study, radiographs may have been obtained from different medical facilities before inclusion, potentially affecting baseline data standardization. We were unable to control the technical parameters of external radiographs (beam angle, object distance, patient positioning, equipment type and calibration, image processing settings). Excluding external radiographs was not possible. To minimize the impact of these factors, the analysis focused on angular morphometric parameters, which are less sensitive to projection errors. In the present study, reproducibility of the morphometric measurements was evaluated overall; separate ICC analysis for the newly introduced parameters TMTS and TTIA was not performed. Establishing threshold values and clinical interpretation for these measures requires a dedicated investigation, which is planned for future research. Moreover, the partial overlap of clinical material with our previous studies may limit the generalizability of the results; however, the use of distinct methodological approaches ensured the independence of the obtained results and conclusions. Despite these limitations, the results of the comprehensive morphometric analysis enabled the identification of key morphological markers of degenerative changes in relation to the mJLO.

The results of this study demonstrated differences in the sagittal morphological characteristics of the distal femur and the proximal tibia according to the mJLO variant, thereby allowing *rejection of the null hypothesis.*

Conclusions

A significant difference in the sagittal morphological parameters of the distal femur and the proximal tibia was demonstrated in patients with medial knee osteoarthritis depending on the joint line obliquity, as determined using the authors' method (mJLO).

The apex distal, apex neutral, and apex proximal mJLO variants demonstrated specific and reproducible morphological patterns, indicating that sagittal joint geometry is systematically related to the direction of joint line obliquity.

A comprehensive assessment of morphological parameters may assist in predicting the mJLO variant during preoperative planning; however, further studies are required to clarify these associations, particularly for the less frequent variants.

Conflict of interest. The authors declare no conflict of interest.

Prospects for further research. In future studies, it is advisable to consider the combined use of frontal plane parameters and lateral angles, which would allow for a more comprehensive assessment of knee joint morphology. This approach may facilitate personalized planning of alignment in arthroplasty and osteotomies, minimizing the risk of postoperative imbalance and excessive JLO.

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References

1. Giorgino, R., Albano, D., Fusco, S., Peretti, G. M., Mangiavini, L., & Messina, C. (2023). Knee osteoarthritis: epidemiology, pathogenesis, and mesenchymal stem cells: what else is new? An update. *International journal of molecular sciences, 24*(7), 6405. https://doi.org/10.3390/ijms24076405
2. Jang, S., Lee, K., & Ju, J. H. (2021). Recent updates of diagnosis, pathophysiology, and treatment on osteoarthritis of the knee. *International journal of molecular sciences, 22*(5), 2619. https://doi.org/10.3390/ijms22052619
3. Wang, Y., Lu, J., Wang, Z., Li, Z., Pan, F., Zhang, M., Chen, L., & Zhan, H. (2024). The association between patella alignment and morphology and knee osteoarthritis. *Journal of orthopaedic surgery and research, 19*(1), 509. https://doi.org/10.1186/s13018-024-05001-6
4. Primorac, D., Molnar, V., Rod, E., Jeleč, Ž., Čukelj, F., Matišić, V., Vrdoljak, T., Hudetz, D., Hajsok, H., & Borić, I. (2020). Knee osteoarthritis: a review of pathogenesis and state-of-the-art non-operative therapeutic considerations. *Genes, 11*(8), 854. https://doi.org/10.3390/genes11080854
5. Lv, Y., Sui, L., Lv, H., Zheng, J., Feng, H., & Jing, F. (2025). Burden of knee osteoarthritis in China and globally from 1992 to 2021, and projections to 2030: a systematic analysis from the Global Burden of Disease Study 2021. *Frontiers in public health,* 13, 1543180. https://doi.org/10.3389/fpubh.2025.1543180
6. Lee, S. H., Yoo, J. H., Kwak, D. K., Kim, S. H., Chae, S. K., & Moon, H. S. (2024). The posterior tibial slope affects the measurement reliability regarding the radiographic parameter of the knee. *BMC musculoskeletal disorders, 25*(1), 202. https://doi.org/10.1186/s12891-024-07330-3
7. Handa, M., Takahashi, T., Saitsu, A., Iguchi, M., & Takeshita, K. (2025). Comparison of coronal and sagittal alignment in patients without osteoarthritis but with knee complaints. *Journal of experimental orthopaedics, 12*(1), e70165. https://doi.org/10.1002/jeo2.70165
8. Meier, M., Janssen, D., Koeck, F. X., Thienpont, E., Beckmann, J., & Best, R. (2021). Variations in medial and lateral slope and medial proximal tibial angle. *Knee surgery, sports traumatology, arthroscopy: official journal of the ESSKA, 29*(3), 939–946. https://doi.org/10.1007/s00167-020-06052-y
9. Siddiqi, A., Anis, H., Borukhov, I., & Piuzzi, N. S. (2022). Osseous morphological differences in knee osteoarthritis. *The Journal of bone and joint surgery. American volume, 104*(9), 805–812. https://doi.org/10.2106/JBJS.21.00892
10. MacDessi, S. J., Griffiths-Jones, W., Harris, I. A., Bellemans, J., & Chen, D. B. (2021). Coronal plane alignment of the knee (CPAK) classification. *The bone & joint journal, 103-B*(2), 329–337. https://doi.org/10.1302/0301-620X.103B2.BJJ-2020-1050.R1
11. Sohn, S., Koh, I. J., Kim, M. S., & In, Y. (2022). Risk factors and preventive strategy for excessive coronal inclination of tibial plateau following medial opening-wedge high tibial osteotomy. *Archives of orthopaedic and trauma surgery, 142*(4), 561–569. https://doi.org/10.1007/s00402-020-03660-8
12. Abalkhail, T. B., & McClure, P. K. (2022). Sagittal plane assessment in deformity correction planning: the sagittal joint line angle. *Strategies in trauma and limb reconstruction, 17*(3), 159–164. https://doi.org/10.5005/jp-journals-10080-1569
13. Blonskyi, R. I., & Kylymniuk, L. O. (2025). Sahitalnyi profil morfotypiv kolinnoho suhloba pry osteoartryti [Sagittal profile of knee joint morphotypes in osteoarthritis]. *Modern medical technology, 4*(18), in press.
14. Cassar-Pullicino, V. N., & Davies, A. M. (Eds.). (2020). *Measurements in musculoskeletal radiology.* Springer. 860 p. https://doi.org/10.1007/978-3-540-68897-6
15. Unal, M., Ercan, S., Budeyri, A., Toprak, U., & Şalkaci, A. (2020). Anatomical axis validation of lower extremity for different deformities: A radiological study. *SAGE open medicine*, 8, 2050312120923822. https://doi.org/10.1177/2050312120923822

16. World Medical Association. (1964/2013). *Declaration of Helsinki: Ethical principles for medical research involving human subjects.* Ferney-Voltaire: WMA, from https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/
17. European convention for the protection of vertebrate animalsused for experimental and other scientific purposes: Strasbourg,18 March 1986. (2000).
18. Law of Ukraine No. 3447-IV, article 26. On the protection of animals from cruel treatment. Kyiv, 21 February, 2006. (In Ukrainian)
19. Morrisey, Z., Cruse, J., Barra, M., Carroll, T., & Drinkwater, C. (2024). Posterior tibial slope considered as an important addition to the CPAK classification system. *Journal of orthopaedics,* 51, 54–59. https://doi.org/10.1016/j.jor.2024.01.008
20. Mulpur, P., Desai, K. B., Mahajan, A., Masilamani, A. B. S., Hippalgaonkar, K., & Reddy, A. V. G. (2022). Radiological Evaluation of the Phenotype of Indian Osteoarthritic Knees based on the Coronal Plane Alignment of the Knee Classification (CPAK). *Indian journal of orthopaedics, 56*(12), 2066–2076. https://doi.org/10.1007/s43465-022-00756-8
21. Şenel, A., Eren, M., Sert, S., Gürpınar, T., Çarkçı, E., & Polat, B. (2024). Phenotyping of the Turkish population according to Coronal Plane Alignment of the Knee classification: A retrospective cross-sectional study. *Joint diseases and related surgery, 35*(1), 194–201. https://doi.org/10.52312/jdrs.2023.1464
22. Toyooka, S., Osaki, Y., Masuda, H., Arai, N., Miyamoto, W., Ando, S., Kawano, H., & Nakagawa, T. (2023). Distribution of coronal plane alignment of the knee classification in patients with knee osteoarthritis in Japan. *The journal of knee surgery, 36*(7), 738–743. https://doi.org/10.1055/s-0042-1742645
23. Agarwal, S., Ayeni, F. E., & Sorial, R. (2024). Impact of change in coronal plane alignment of knee (CPAK) classification on outcomes of robotic-assisted TKA. *Arthroplasty (London, England), 6*(1), 15. https://doi.org/10.1186/s42836-024-00239-1
24. Kim, S. E., Yun, K. R., Lee, J. M., Lee, M. C., & Han, H. S. (2024). Preserving coronal knee alignment of the knee (CPAK) in unicompartmental knee arthroplasty correlates with superior patient-reported outcomes. *Knee surgery & related research, 36*(1), 1. https://doi.org/10.1186/s43019-023-00204-3
25. Xin, L., Xingjia, M., Shengjie, G., Yanwei, C., Shuaijie, L., & Chuan, X. (2022). Comparison of Tibial Tubercle Landmark Technique and Range of Motion Technique in Primary Total Knee Arthroplasty: A Retrospective Cohort Study. *Orthopaedic surgery, 14*(12), 3159–3170. https://doi.org/10.1111/os.13486
26. Saidapur, S. K., Srinivas, P. S., Shete, S., Hundekar, A., & Jatti, R. S. (2023). Radiological assessment of the posterior tibial slope as a risk factor for osteoarthritis of the knee in Indian population. *Trends in Clinical Medical Sciences, 3*(Spec Issue 2), 397–402. https://doi.org/10.30538/psrp-tmcs2023.si-imrv061
27. Wu, Y., Lu, W., Li, Z., Xie, H., Tang, L., & Pan, E. (2022). Analysis of the influence of tibial component posterior slope angle on short- and mid-term effectiveness of unicompartmental knee arthroplasty. Zhongguo xiufu chongjian waike zazhi = *Chinese Journal of Reparative and Reconstructive Surgery, 36*(2), 189–195. https://doi.org/10.7507/1002-1892.202110019
28. Hohmann, E., Nel, A., Zyl, R. V., Keough, N., & Mogale, N. (2025). A morphometric study of posterior tibial slope differences by sex and ethnicity in a South African population. *Surgical and radiologic anatomy: SRA, 47*(1), 52. https://doi.org/10.1007/s00276-024-03551-2
29. Hiranaka, Y., Muratsu, H., Tsubosaka, M., Matsumoto, T., Maruo, A., Miya, H., Kuroda, R., & Matsushita, T. (2022). Influence of posterior tibial slope on sagittal knee alignment with comparing contralateral knees of anterior cruciate ligament injured patients to healthy knees. *Scientific reports, 12*(1), 14071. https://doi.org/10.1038/s41598-022-18442-y
30. Dean, R. S., Beck, E. C., & Waterman, B. R. (2021). Knee malalignment: Is there a role for correction in primary ACLR? *Operative techniques in sports medicine, 29*(2), 150833. https://doi.org/10.1016/j.otsm.2021.150833
31. Springer, B., Waldstein, W., Bechler, U., Jungwirth-Weinberger, A., Windhager, R., & Boettner, F. (2021). The functional status of the ACL in varus OA of the knee: the association with varus deformity and coronal tibiofemoral subluxation. *The Journal of arthroplasty, 36*(2), 501–506. https://doi.org/10.1016/j.arth.2020.08.049

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ОСОБЛИВОСТІ РЕНТГЕНОЛОГІЧНОЇ ДІАГНОСТИКИ ОСТЕОАРТРИТУ КОЛІННОГО СУГЛОБА В БОКОВІЙ ПРОЄКЦІЇ ЗАЛЕЖНО ВІД НАХИЛУ СУГЛОБОВОЇ ЛІНІЇ

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Modern concepts of diagnostics of posterolateral corner knee injuries

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Injuries to the posterolateral corner (PLC) of the knee are usually not initially apparent, and diagnosis and treatment require a full understanding of the functional interactions of their structures, as well as a specific history and complete physical examination. Objective. To summarize current concepts regarding the anatomy, biomechanics, and diagnosis of PLC injuries of the knee and to outline directions for improving the diagnostic algorithm. Materials and methods. A narrative review of publications indexed in PubMed, Scopus, and Google Scholar was conducted, focusing on anatomical and biomechanical characteristics, clinical manifestations, imaging modalities, and classification systems for PLC injuries. Results. The lateral collateral ligament, popliteofibular ligament, popliteus tendon, posterolateral capsule, and associated musculotendinous complexes were identified as the key static and dynamic stabilizers resisting varus stress and external rotation of the tibia. PLC injuries are rarely isolated; more commonly, they occur in combination with anterior or posterior cruciate ligament tears and, if not diagnosed in a timely manner, lead to chronic instability and increased load on the medial compartment of the knee. Clinical stress tests and varus stress radiography provide an approximate assessment of instability; however, existing classification systems do not fully capture the variety of injury patterns and their combinations, while the sensitivity of conventional MRI, particularly in chronic cases, remains limited. Arthroscopy may serve as an additional method for intra-articular evaluation. Conclusions. Accurate diagnosis of PLC injuries requires a standardized, multimodal approach with precise identification of the injured structures. The development of an integrated, differentiated diagnostic algorithm supported by machine-learning–based artificial intelligence tools appears to be a promising strategy for improving early detection and optimizing treatment planning.

Ушкодження задньолатерального кута колінного суглоба (ЗЛККС) зазвичай не виявляються спочатку, і для діагностики та лікування потрібне повне розуміння функціональних взаємодій їхніх структур, а також збір конкретного анамнезу та повне фізичне обстеження. Мета. Систематизувати сучасні уявлення про анатомію, біомеханіку та діагностику ушкоджень ЗЛККС й окреслити шляхи удосконалення діагностичного алгоритму. Методи. Проведено огляд публікацій з баз PubMed, Scopus і Google Scholarщодо анатомо-біомеханічним особливостей, клінічних проявів, методам візуалізації та класифікацій ушкоджень ЗЛККС. Результати. Визначено, що латеральна колатеральна, підколінно-малогомілкова зв'язки, підколінний сухожилок, задньобокова капсула та м'язово-сухожилкові комплекси є ключовими статичними й динамічними стабілізаторами, які протидіють варусному навантаженню та задньолатеральній ротації великогомілкової кістки. Ушкодження структур ЗЛККС рідко бувають ізольованими, частіше поєднуються з розривами схрещених зв'язок і за відсутності своєчасної діагностики призводять до хронічної нестабільності та перевантаження медіального відділу коліна. Клінічні стрес-тести та стрес-рентгенографія дозволяють орієнтовно оцінити ступінь нестабільності, проте наявні класифікації не повністю відображають варіанти ушкодження й їх комбінації, а чутливість МРТ, особливо в хронічному періоді, залишається недостатньою. Висновки. Діагностика ушкоджень ЗЛККС потребує стандартизованого багатокомпонентного підходу з чіткою ідентифікацією уражених структур. Перспективним напрямом є створення інтегрованого диференційованого алгоритму з використанням методів машинного навчання та штучного інтелекту для підвищення точності ранньої діагностики й оптимізації лікувальної тактики. Ключові слова. Колінний суглоб, задньолатеральний кут, зв'язки, ушкодження, нестабільність, діагностика.

Keywords. Knee, ligaments, posterolateral corner, injuries, instability, diagnostics

Introduction

The frequency of injuries to the posterolateral corner of the knee joint (PLCK) has increased due to the rise in road traffic accidents and sports injuries. Damage to the PLCK typically occurs in combination with tears of the anterior cruciate ligament (ACL) or the posterior cruciate ligament (PCL). Isolated injuries in this location are very rare, and as a result, they can often go unnoticed or be misdiagnosed [1]. In the case of delayed or absent treatment, chronic pain and residual instability can occur. Therefore, it is crucial to correctly identify and treat such injuries.

PLCK injuries are often not initially detected, and diagnosing and treating them requires a full understanding of the functional interactions between their structures, as well as a thorough patient history and complete physical examination.

Objective: To systematize current understanding of the anatomy, biomechanics, and diagnostics of posterolateral corner knee injuries and to outline ways to improve the diagnostic algorithm.

Materials and Methods

The article complies with all requirements and provisions of the Helsinki Declaration on Human Rights, the Constitution, and the basic legislation of Ukraine on healthcare, as well as ethical norms regarding clinical research (protocol No. 14 dated 26.11.2025 of the Bioethics Committee of Zaporizhzhia Medical and Pharmaceutical University). Relevant literature from the PubMed, Scopus, and Google Scholar databases was analyzed using the following keywords: knee joint, posterolateral angle, ligaments, injuries, instability, diagnostics. Articles and meta-analyses from recent years on the concept of diagnosing posterolateral corner injuries of the knee joint were selected. Inclusion criteria were original experimental and clinical studies. A total of 37 sources were analyzed.

Anatomy, biomechanics, and instability diagnostics are briefly described. The number of patients with posterolateral corner knee injuries has been steadily increasing in recent times due to combat-related injuries. This has led to the necessity of careful examination of patients with PLCK injuries, as such trauma can easily go unnoticed, leading to chronic instability.

Results and Discussion

Anatomically, the key structures in the PLCK include the lateral collateral ligament, the popliteo-fibular and popliteo-femoral ligaments, the popliteus tendon, and the posterolateral capsule (Figure 1). These structures are divided into static (intercondylar ligament and posterolateral capsule) and dynamic (biceps femoris, iliotibial tract, and the popliteal complex) components. The static structures provide resistance to varus forces on the knee. The popliteal complex consists of the tendons of the popliteal joint (musculotendinous junction of the popliteus muscle) and attaches approximately 1.3 mm distally and 0.5 mm anteriorly to the tip of the styloid process of the fibula.

Other structures that affect the stability of the PLCK include the iliotibial tract, the biceps femoris, the interosseous ligament, the middle third of the lateral capsule, and the lateral meniscus. The iliotibial tract provides lateral knee stability when excessive varus tension occurs during knee extension [2]. The biceps femoris muscle has both long and short heads, which help the knee flex and rotate laterally, ensuring dynamic stability during varus angulation. This muscle also controls the internal rotation of the tibia and works with the medial popliteal tendons to prevent excessive anterior translation of the tibia relative to the femur. The middle third of the lateral capsule serves as a secondary stabilizer for varus stability [3]. The coronary ligament of the lateral meniscus extends from the popliteal opening to the popliteomeniscal bundle and plays a role in resisting the knee when in hyperextension or posterior-lateral rotation of the tibia [4].

Therefore, the posterolateral corner of the knee is the primary stabilizer that resists varus load on the knee.

Biomechanics

The structures of the PLCK provide the primary restriction against varus forces on the knee, as well as posterior-lateral rotation of the tibia [5]. Previous biomechanical studies involving selective sectioning

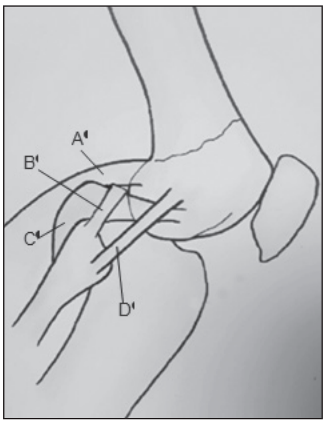

Fig. 1. Anatomical structure of the PLC: a) lateral tendon of the calf muscle; b) popliteofibular ligament; c) popliteus muscle and its tendon; d) lateral collateral ligament

of structures have provided evidence of the importance of the lateral collateral ligament, popliteofibular ligament, and the popliteus tendon in resisting forces on the knee. In the absence of a cruciate ligament, these structures act as secondary stabilizers for both anterior and posterior translation of the tibia [6–10].

The lateral collateral ligament (LCL) is the primary static restraint against varus opening of the knee. Direct measurements of its force during applied varus motion demonstrate a higher reaction force at 30° flexion compared to 90°. The tensile strength of the lateral collateral ligament was determined to be 295 N. After sectioning the LCL, R. F. LaPrade and F. Wentorf [10] showed that the reaction forces at midrange loads on external rotation of the LCL were significantly higher than those of the popliteus tendon and popliteofibular ligament at both 0° and 30° flexion, while the popliteus muscle and popliteofibular ligament exhibited higher loading at these angles.

Regarding external rotation of the tibia, the PLCK structures are the main stabilizers of its external rotation at any flexion angle. Studies such as those by D. L. Gollehon et al. [6] and E. S. Grood et al. [7] demonstrated that isolated sectioning of the PLCK results in an average increase in tibial rotation by 13° at 30° of flexion, which decreased to an average of 5.3° at 90°. Combined injury to the PLCK and posterior-lateral structures led to a significant increase in external rotation of the tibia, particularly at 90° of flexion (20.9°). Thus, combined injuries to the PCL and PLCK structures are more susceptible to external rotation forces. The dominant restraint to posterior translation of the tibia is the PCL [11]. Isolated sectioning of the PCL causes increased posterior translation of the tibia at all flexion angles, with a maximum at 90° (11.4 mm). Additional sectioning of the PLCK structures increases posterior tibial translation at all angles, with a maximum at minimal knee flexion. Thus, the PLCK structures, rather than the PCL, are the primary restraint to posterior tibial translation during near full knee extension. Combined studies of PLCK and PCL structures demonstrated a significant increase in posterior displacement (21.5 mm) at 90° flexion compared to an intact knee or isolated injuries to the PLCK or posterior-lateral insufficiency. Functional interaction between the popliteus muscle and PLCK was also confirmed — the popliteus muscle acts as both a static and dynamic stabilizer of the knee. In a cadaveric study, C. D. Harner and J. Höher [12] found that loading on the popliteus muscle in an intact joint reduced the PCL's response to posterior loading. In contrast, in a PCL-deficient model, loading on the popliteus muscle reduced posterior displacement at a maximum flexion angle of 30°.

Biomechanical analysis of posterior-lateral instability during PCL or ACL reconstruction further demonstrates the interdependent relationship between the structures of the PLCK and these ligaments. R. F. LaPrade et al. [13] noted increased loading on the PCL graft when using varus and combined varus-internal rotational moments. As a result, they recommended reconstruction or restoration of the PLCK, which is considered a secondary primary stabilizer (PCL is the primary stabilizer at lower angles, and the anterolateral ligament at larger flexion angles) to prevent internal rotation.

Any failure to recognize and treat PLCK injuries will lead to increased stress and potential failure in PCL or ACL reconstruction. Therefore, combined restoration of both the PLCK and cruciate ligaments is recommended [14]. Similarly, in the combined model of PLCK and ACL injuries developed by J. K. Sekiya et al. [15], reconstruction of both regions resulted in kinematics of the knee closer to normal.

Recently, there has been a trend toward maximal anatomical restoration, particularly of the three most important biomechanical structures controlling varus and external rotation: the lateral collateral ligament (LCL), popliteofibular ligament (PFL), and popliteus tendon. In a cadaveric study, anatomical reconstruction showed no significant difference between intact and reconstructed joints under varus loading at 0°, 60°, and 90° of flexion or under external rotational moments at any flexion angle [16]. However, some biomechanical experiments, in which all three functional components were anatomically restored, separately documented excessive restriction of internal rotation and varus deviation.

K. H. Yoon et al. [17] reported that a recently developed method of PLCK reconstruction, which does not restore the dynamic popliteus muscle, is not inferior to methods that include anatomical reconstruction of the popliteus tendon. S. Kim et al. [18] noted that the three widely accepted methods (Warren, Larson, and Kim) do not provide full restoration of the native strength of the PLCK structures.

Diagnosis

History taking

The diagnosis of PLCK injuries requires a thorough history and clinical examination to identify the signs and symptoms that may indicate this type of injury. Given the difficulty in initially detecting PLCK injuries, it is essential to gather detailed patient history, including any recent trauma or joint instability, and perform comprehensive physical examinations to assess knee stability and function.

Thorough history taking helps prevent overlooking possible PLCK injuries, a typical symptom of which is pain in the posterior part of the knee. In some patients, neurological symptoms may also be present. J. C. DeLee et al. [19] reported that peroneal nerve injury occurred in 2 out of 12 individuals with isolated posterior-lateral corner knee injuries. R. F. LaPrade et al. [20] and Y. Krukhaug et al. [21] indicated that peroneal nerve damage in patients with posterior-lateral knee injuries was observed in 13-16% of cases. Patients with chronic injuries often complain of significant pain in the medial or posterior-lateral parts of the knee [22, 23]. Additionally, signs of peroneal nerve injury, such as paresthesia or numbness, may be diagnosed. Functional instability can also be noted—during normal walking the knee remains extended, but during descending stairs, it transitions into a hyperextension state [24].

Mechanism of Injury

Posterior-lateral corner knee injuries are typically associated with sports, falls, and road traffic accidents. A direct blow to the proximal tibia while the knee is in the extended position may result in an isolated injury to the posterior-lateral section. A combination of hyperextension and varus forces on the knee, especially when the knee is in a flexed position or the tibia is in external rotation, can also lead to injury of the posterior-lateral structures. A lateral dislocation of the knee joint can also cause these injuries.

Clinical Examination: Symptoms and Signs

Symptoms of posterior-lateral corner injury include a wide range of pain, swelling, and stiffness. In addition, attention should be paid to the alignment of the lower extremities during standing and walking.

Standing Position: Patients with PLCK injury are likely to have an abnormal deviation of the lower extremity axis. In the standing position, varus deformity of the knee may be observed [25, 26].

Gait. When static stabilizers of the knee are injured, dynamic stabilizers cannot function properly due to the lateral joint gap opening and the protrusion of the femoral condyle and lateral tibial plateau. This causes varus deformation during the stance phase of walking, leading to an abnormal gait pattern [27, 28]. Varus displacement of the knee is observed during the stance phase of walking and in cases of long-standing injury to the posterior-lateral structures of the knee (Fig. 2). Typically, the gait pattern is accompanied by the opening of the lateral knee compartment, which increases the load on the medial part of the joint. If the instability is untreated, it leads to cartilage wear in the medial half of the joint [29]. Sometimes, patients exhibit a fixed knee gait due to adaptation to knee instability.

Dial Test. The Dial test is one of the most important physical examinations used to diagnose PLCK injury. When the patient is in a supine position, external rotation of the tibia and the angle between the femur and foot are assessed. This test is performed with the knee flexed at 30° and 90° (Fig. 3). In the case of isolated PCL injury, external rotation of more than 10° is observed at 30° of flexion. For combined injuries of the PCL, more than 10° of external rotation occurs at both 30° and 90° of flexion.

External Rotation and Recurvatum Test. This test can be used to assess posterior-lateral rotational instability of the tibia. Varus deviation is measured by comparison with the contralateral knee.

Posterior-Lateral Drawer Test. This test is performed by applying a posterior-lateral force to the proximal tibia with the hip flexed at 45° and the knee at 90°, externally rotated 15° in a supine position. When the lateral tibial condyle experiences more external rotation than the lateral femoral condyle, it indicates the presence of posterior-lateral injury (Fig. 3).

Posterior-Lateral External Rotation Test. This test is a combination of the Dial test and the posterior-lateral drawer test. The posterior-lateral subluxation of the tibia is tested by simultaneously applying posterior and external rotational forces to the knee joint. Subluxation during flexion at 30° suggests an isolated posterior-lateral injury. With combined injury involving the PCL, subluxation occurs at both 30° and 90° of flexion.

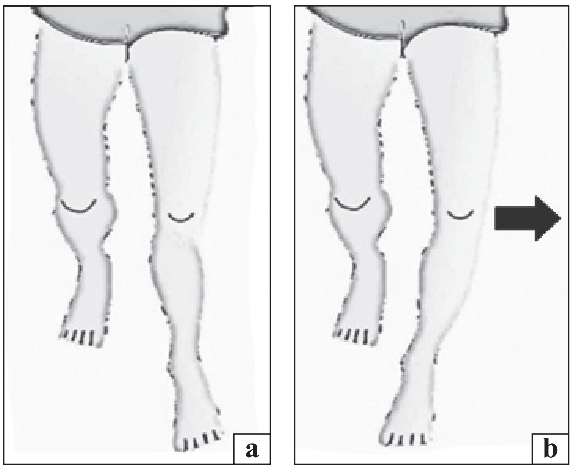

Fig. 2. Images of knee joints during walking: a) normal gait during the knee's reaction phase to load; b) dynamic varus deformity characteristic of posterior-lateral corner injury

Reverse Pivot Shift Test. This test is performed with the knee flexed at 40° and the tibia externally rotated. During extension, the tibia moves with a "clunk", which indicates the presence of PLCK injury. However, when the test is performed under anesthesia, false positive results occur in up to 35 % of cases.

Varus Stress Test. The varus stress test is performed by applying pressure during knee flexion at 20°–30° to diagnose posterior-lateral instability. If the lateral collateral ligament is intact, no increase in the varus gap is observed during 20°–30° of knee flexion. In the case of combined injuries to other structures such as the popliteal tendon or popliteofibular ligament, an increase in the varus gap may be observed. The physician applies pressure along the joint line to stabilize the distal femur, then applies the varus load. The degree of instability is evaluated by measuring the varus gap on a radiograph under load.

Differential Diagnosis. Simple radiography in direct, lateral, and axial projections is conducted to rule out other injuries, such as fractures. In the direct projection, expansion of the lateral joint gap or metaphyseal avulsion fractures of the tibia or fibula can be seen [25].

For chronic injuries, a direct projection of the legs in a standing position may be performed to assess limb alignment. This alignment should be corrected via osteotomy before or during the reconstruction procedure [30, 31].

Radiographic images with load bearing in the posterior-lateral corner of the knee joint in the standing position are highly informative for diagnosing injuries. R. F. LaPrade et al. [32] studied varus stress radiographs of the knee joint at 20° of flexion to provide objective measurements of the lateral compartment gap (Fig. 4).

An increased gap greater than 4 mm may indicate a Grade III posterior-lateral corner injury. Radiographic images also facilitate the objective quantitative evaluation of isolated or combined posterior-lateral corner injuries [33] (Table 1).

Magnetic Resonance Imaging (MRI) can be useful when injuries to the posterior-lateral structures are difficult to diagnose clinically. It helps identify the injured structures. Specifically, coronal oblique projections with T2-weighted imaging are more useful for analyzing posterior-lateral structures than traditional coronal or sagittal views. MRI is more suitable for detecting acute or subacute posterior-lateral corner injuries (Fig. 5). Therefore, MRI should be performed within the first 12 weeks, as only about 26 % of cases may be diagnosed after this period [34].

Arthroscopy provides intra-articular information about the posterior-lateral structures, such as the popliteal complex, the coronary ligament of the lateral meniscus, and the posterior-lateral capsule. It helps determine the appropriate treatment and provides final anatomical information during surgical treatment.

A lateral opening of more than 1 cm under varus loading on the knee joint, which can be confirmed by arthroscopy, is shown in Fig. 6. Additionally, during surgery, one can observe the enlargement of the popliteal opening with internal rotation of the tibia, rupture of the upper and lower popliteomeniscal bundles, and abnormal popliteomeniscal movement during rotation [35].

Classification

PLCK injuries can be classified based on the damaged structures or the degree of posterior-lateral

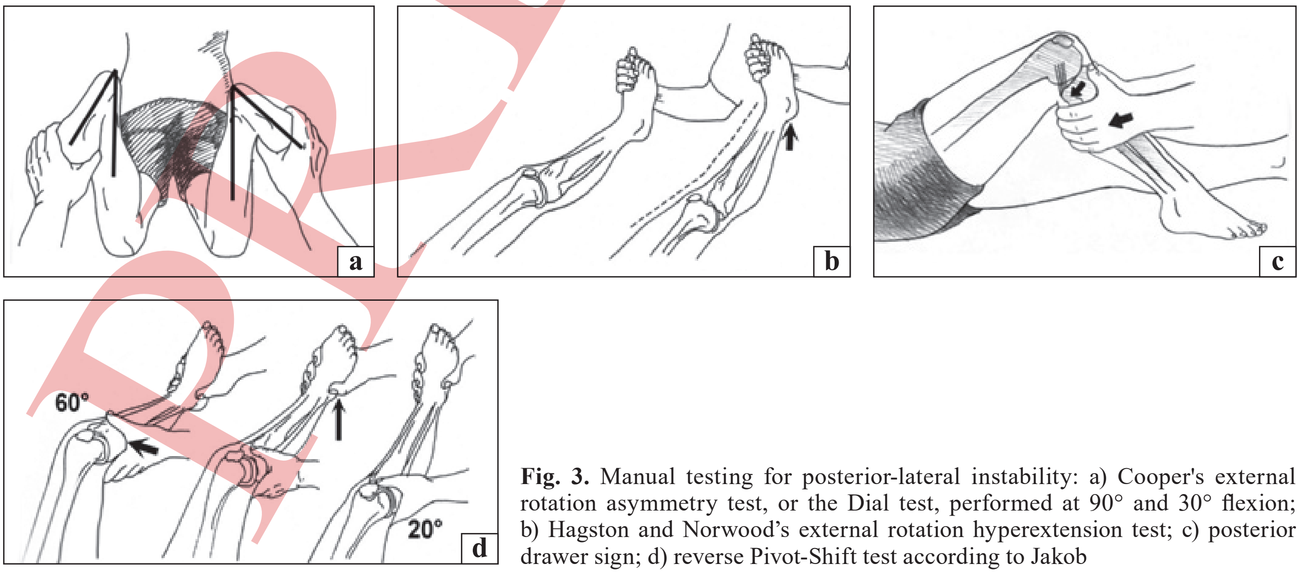

Fig. 3. Manual testing for posterior-lateral instability: a) Cooper's external rotation asymmetry test, or the Dial test, performed at 90° and 30° flexion; b) Hagston and Norwood's external rotation hyperextension test; c) posterior drawer sign; d) reverse Pivot-Shift test according to Jakob

instability. The two most commonly used classifications are:

1. R. Bleday et al. [36] and G. C. Fanelli with R. V. Larson [37] Classification

This classification divides injuries into types A, B, and C based on the injured structures (Table 2):

– Type A — Popliteofibular ligament and popliteus tendon. Clinically, only an increase in external rotation of the tibia is observed.

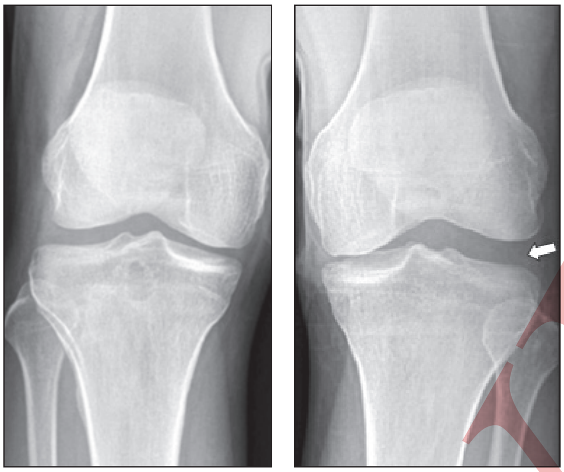

Fig. 4. X-ray with varus loading showing increased lateral joint space widening, indicated by an arrow in the injured knee

– Type B — Popliteofibular ligament, popliteus tendon, and lateral collateral ligament. Mild varus opening is observed during the varus stress test at 30° of knee flexion, along with an increase in external rotation of the tibia.

– Type C — Popliteofibular ligament, popliteus tendon, lateral collateral ligament, lateral capsule avulsion, and cruciate ligament tear. Marked varus instability is observed with knee flexion at 30°.

2. J. Hughston Classification

This classification is based on studying varus or rotational instability under the action of varus stress at full knee extension [22], and it has three grades:

– Grade I — Minimal ligament rupture without abnormal motion.

– Grade II — Partial rupture with mild to moderate abnormal motion.

– Grade III — Complete rupture with pronounced abnormal motion.

The Hughston classification for posterior-lateral instability considers only clinical signs that can be identified through objective manual examination of the patient. It is based on the study of varus and rotational instability (Table 3). Despite its subjectivity and lack of anatomical correlation with dissection

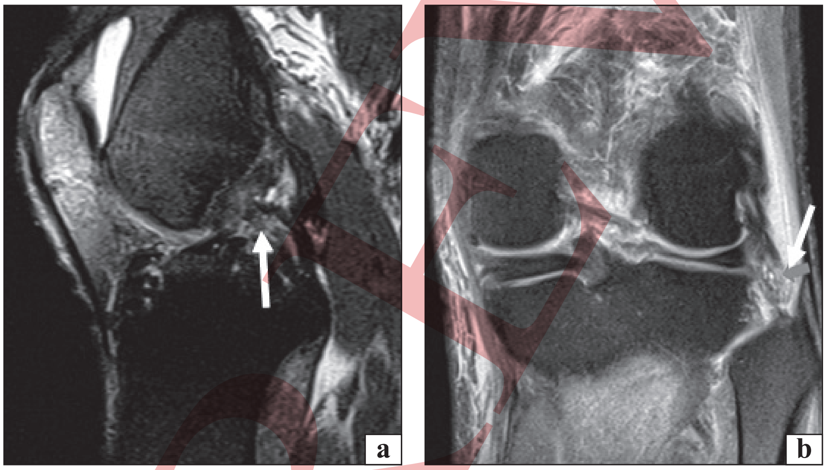

Fig. 5. Sagittal and coronal MRI scans of an angular injury in the left knee: a) rupture of the PCL (arrow) visible in the sagittal projection; b) high signal on the lateral collateral ligament (arrow) visible in the coronal projection

Table 1

Assessment of instability using stress X-rays

Deviation indicator	Injury
Lateral opening during varus stress (mm) < 2,7	Normal or minimal
2,7–4	Complete rupture of the lateral collateral ligament
> 4	Complete injury of the PLCK
Posterior tibial load (mm) < 4	Normal or minimal
4–12	Isolated PCL injury
> 12	Complete PCL and PLCK injury

Table 2

Classification of PLCK injuries by G. C. Fanelli and R. V. Larson

Тип	Description	Structure
A	Increased external rotation of the tibia by 10°	*lig. popliteofibulare,* tendon of the *m. popliteus*
B	Increased external rotation of the tibia by 10°. Lateral compartment opening during varus stress test by 5–10 mm	*lig. popliteofibulare,* tendon of the *m. popliteus* *lig. collaterale fibulare*
C	Increased external rotation of the tibia by 10°. Lateral compartment opening during varus stress test by more than 10 mm	*lig. popliteofibulare,* tendon of the *m. popliteus* *lig. collaterale fibulare* joint capsule, PCL

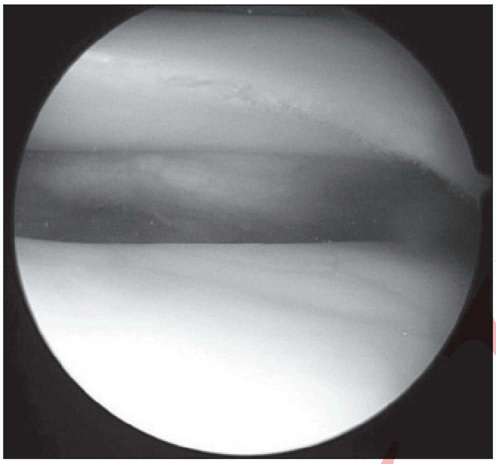

Fig. 6. Lateral compartment opening of the knee joint during arthroscopy,

studies, this classification method remains important for determining the choice of treatment.

Conclusion

The diagnosis of injuries to the structures of the PLCK remains an insufficiently addressed issue in knee joint injury management. There are no clear definitions for the degrees of posterior-lateral instability, and the existing classifications provide only a superficial understanding of the structures and combinations of injuries. The interpretation of clinical symptoms and manual tests is mostly empirical and individualized. Recommendations to use stress radiographs for analyzing the degrees of posterior-lateral instability are not always clearly implementable. The most accurate approach may be to precisely define the damaged structures, but their visualization is complicated by the limited sensitivity of MRI studies in conventional sequences, and coronal oblique projections are usually not employed. MRI sensitivity decreases over time and is significantly reduced after 6 weeks post-injury. Diagnosing injuries to the posterior-lateral corner structures requires a more modern approach, using an integrated, differentiated diagnostic algorithm, possibly incorporating machine learning and artificial intelligence.

Table 3

Classification of posterior-lateral instability by J. Hughston

Degree of injury	Varus and rotational instability
I	0–5 mm and 0°–5°
II	5–10 mm and 6°–10°
III	> 10 mm and > 10°

Posterior-lateral reconstructive surgery has shown better results than simple restoration or suturing when surgically treating PLCK injuries. Anatomical posterior-lateral reconstruction of the structures is recommended both during the acute phase and in the case of chronic instability. There are two types of plastic reconstructions: one based on fixation of the fibula to the femur and the other based on fixation of the tibia and fibula head to the lateral femoral condyle. Currently, the method based on fixation of the tibia to the femur is considered superior to the method involving the binding of the fibular head to the femoral condyle.

The graft used to connect the tibia to the femur acts as a rigid augment for the popliteal muscle, which presents a contradiction. Its fixation point on the posterior surface of the tibia is chosen empirically, in the projection of the popliteus tendon. However, it shortens depending on the rotational movements of the shin relative to the femur, and the tendons are displaced. This augmentation with a constant-length graft to restore the popliteal tendon is not anatomical, and the fixation points are generally debatable.

Thus, the main issues lie in the insufficient anatomical nature of existing reconstruction methods for the structures of the posterior-lateral corner of the knee, their traumatic nature, and the lack of precise positioning of the graft fixation points.

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

Prospects for Further Research. Further research is planned to focus on creating and validating an integrated, differentiated algorithm for diagnosing posterior-lateral corner injuries, considering clinical tests, stress radiographs, and extended MRI protocols, including coronal oblique slices. The use of machine learning methods to enhance imaging sensitivity, objectively assess the degrees of instability, and optimize treatment strategies is promising.

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Authors' Contributions. Holovakha M. L. — Setting the goal and tasks of the study, writing the manuscript. Bondarenko S. A. — Analyzing the primary material. Bezverkhyi A. A. — Accounting for the primary material and performing statistical analysis.

References

1. Castro, M. O., Baptista, D. C., & Afonso, P. D. (2024). Demystifying the "Dark side of the knee": An update on imaging of the Posterolateral corner. *Seminars in musculoskeletal radiology, 28*(03), 305–317. https://doi.org/10.1055/s-0044-1781431
2. Lunden, J. B., Bzdusek, P. J., Monson, J. K., Malcomson, K. W., & Laprade, R. F. (2010). Current concepts in the recognition and treatment of Posterolateral corner injuries of the knee. *Journal of orthopaedic & sports physical therapy, 40*(8), 502–516. https://doi.org/10.2519/jospt.2010.3269
3. Sanchez, A. R., Sugalski, M. T., & LaPrade, R. F. (2006). Anatomy and biomechanics of the lateral side of the knee. *Sports medicine and arthroscopy review, 14*(1), 2–11. https://doi.org/10.1097/00132585-200603000-00002
4. Terry, G. C., & LaPrade, R. F. (1996). The Posterolateral aspect of the knee. *The American journal of sports medicine, 24*(6), 732–739. https://doi.org/10.1177/036354659602400606
5. Dean, R. S., Chahla, J., & Laprade, R. F. (2022). Posterolateral corner of the knee. *Evidence-Based management of complex knee injuries,* 112–126. https://doi.org/10.1016/b978-0-323-71310-8.00009-8
6. Gollehon, D. L., Torzilli, P. A., & Warren, R. F. (1987). The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study. *The journal of bone & joint surgery, 69*(2), 233–242. https://doi.org/10.2106/00004623-198769020-00010
7. Grood, E. S., Stowers, S. F., & Noyes, F. R. (1988). Limits of movement in the human knee. Effect of sectioning the posterior cruciate ligament and posterolateral structures. *The journal of bone & joint surgery, 70*(1), 88–97. https://doi.org/10.2106/00004623-198870010-00014.
8. Shahane, S. A., Ibbotson, C., Strachan, R., & Bickerstaff, D. (1999). The popliteofibular ligament. The journal of bone and joint surgery. *British volume, 81-B*(4), 636–642. https://doi.org/10.1302/0301-620x.81b4.0810636
9. Veltri, D. M., Deng, X., Torzilli, P. A., Warren, R. F., & Maynard, M. J. (1995). The role of the cruciate and Posterolateral ligaments in stability of the knee. *The American journal of sports medicine, 23*(4), 436–443. https://doi.org/10.1177/036354659502300411
10. LaPrade, R. F., & Wentorf, F. (2002). Diagnosis and treatment of Posterolateral knee injuries. *Clinical orthopaedics and related research*, 402, 110–121. https://doi.org/10.1097/00003086-200209000-00010
11. Abu-Mukh, A., Lee, S., Rhim, H. C., & Jang, K. (2025). Exploring the Posterolateral corner of the knee joint: A detailed review of recent literature. *Journal of clinical medicine, 14*(5), 1549. https://doi.org/10.3390/jcm14051549
12. Harner, C. D., & Höher, J. (1998). Evaluation and treatment of posterior cruciate ligament injuries. *The American journal of sports medicine, 26*(3), 471–482. https://doi.org/10.1177/03635465980260032301
13. LaPrade, R. F., Wozniczka, J. K., Stellmaker, M. P., & Wijdicks, C. A. (2009). Analysis of the static function of the Popliteus tendon and evaluation of an anatomic reconstruction. *The American journal of sports medicine, 38*(3), 543–549. https://doi.org/10.1177/0363546509349493
14. Harner, C. D., Vogrin, T. M., Höher, J., Ma, C. B., & Woo, S. L. (2000). Biomechanical analysis of a posterior cruciate ligament reconstruction. *The American journal of sports medicine, 28*(1), 32–39. https://doi.org/10.1177/03635465000280011801
15. Sekiya, J. K., Haemmerle, M. J., Stabile, K. J., Vogrin, T. M., & Harner, C. D. (2005). Biomechanical analysis of a combined double-bundle posterior cruciate ligament and Posterolateral corner reconstruction. *The American journal of sports medicine, 33*(3), 360369. https://doi.org/10.1177/0363546504268039.
16. LaPrade, R. F., Johansen, S., Wentorf, F. A., Engebretsen, L., Esterberg, J. L., & Tso, A. (2004). An analysis of an anatomical Posterolateral knee reconstruction. *The American journal of sports medicine, 32*(6), 1405–1414. https://doi.org/10.1177/0363546503262687
17. Yoon, K. H., Lee, J. H., Bae, D. K., Song, S. J., Chung, K. Y., & Park, Y. W. (2011). Comparison of clinical results of anatomic Posterolateral corner reconstruction for Posterolateral rotatory instability of the knee with or without popliteal tendon reconstruction. *The American journal of sports medicine, 39*(11), 2421–2428. https://doi.org/10.1177/0363546511415656
18. Kim, S., Kim, H., Moon, H., Chang, W., Kim, S., & Chun, Y. (2010). A biomechanical comparison of 3 reconstruction techniques for Posterolateral instability of the knee in a cadaveric model. Arthroscopy: *The journal of arthroscopic & related surgery, 26*(3), 335–341. https://doi.org/10.1016/j.arthro.2009.08.010
19. Delee, J. C., Riley, M. B., & Rockwood, C. A. (1983). Acute posterolateral rotatory instability of the knee. *The American journal of sports medicine, 11*(4), 199–207. https://doi.org/10.1177/036354658301100403
20. LaPrade, R. F., & Terry, G. C. (1997). Injuries to the Posterolateral aspect of the knee. *The American journal of sports medicine, 25*(4), 433–438. https://doi.org/10.1177/036354659702500403
21. Krukhaug, Y., Mølster, A., Rodt, A., & Strand, T. (1998). Lateral ligament injuries of the knee. *Knee surgery, sports traumatology, arthroscopy, 6*(1), 21–25. https://doi.org/10.1007/s001670050067
22. Hughston, J., Andrews, J., Cross, M., & Moschi, A. (1976). Classification of knee ligament instabilities. Part II. The lateral compartment. *The journal of bone & joint surgery, 58*(2), 173–179. https://doi.org/10.2106/00004623-197658020-00002
23. Hughston, J. C., & Jacobson, K. E. (1985). Chronic posterolateral rotatory instability of the knee. *The journal of bone & joint surgery, 67*(3), 351–359. https://doi.org/10.2106/00004623-198567030-00001
24. Covey, D. C. (2001). Injuries of the Posterolateral corner of the knee. *The journal of bone and joint surgery-American volume, 83*(1), 106–118. https://doi.org/10.2106/00004623-200101000-00015
25. Bae, W. H, Ha, J. K., & Kim, J. G. (2010). Treatment of posterolateral rotatory instability of the knee. *Journal Korean knee society*, 22, 1–10.
26. Towne, L. C., Blazina, M. E., Marmor, L., & Lawrence, J. E. (1971). Lateral compartment syndrome of the knee. *Clinical orthopaedics and related research*, 76, 160–168. https://doi.org/10.1097/00003086-197105000-00023
27. Ricchetti, E. T., Sennett, B. J., & Huffman, G. R. (2008). Acute and chronic management of Posterolateral corner injuries of the knee. *Orthopedics, 31*(5), 479–488. https://doi.org/10.3928/01477447-20080501-23
28. Noyes, F. R., Grood, E. S., & Torzilli, P. A. (1989). Current

concepts review. The definitions of terms for motion and position of the knee and injuries of the ligaments. *The journal of bone & joint surgery, 71*(3), 465–472. https://doi.org/10.2106/00004623-198971030-00027
29. Sharma, L. (2001). The role of knee alignment in disease progression and functional decline in knee osteoarthritis. *JAMA, 286*(2), 188. https://doi.org/10.1001/jama.286.2.188
30. Ranawat, A., Baker, C. L., Henry, S., & Harner, C. D. (2008). Posterolateral corner injury of the knee: Evaluation and management. *Journal of the American academy of orthopaedic surgeons, 16*(8), 506–518. https://doi.org/10.5435/00124635-200808000-00012
31. Crespo, B., James, E. W., Metsavaht, L., & LaPrade, R. F. (2015). Injuries to posterolateral corner of the knee: A comprehensive review from anatomy to surgical treatment. *Revista brasileira de ortopedia (English Edition), 50*(4), 363–370. https://doi.org/10.1016/j.rboe.2014.12.008
32. LaPrade, R. F., Heikes, C., Bakker, A. J., & Jakobsen, R. B. (2008). The reproducibility and repeatability of Varus stress radiographs in the assessment of isolated fibular collateral ligament and Grade-III Posterolateral knee injuries. *The journal of bone and joint surgery-american volume, 90*(10), 2069–2076. https://doi.org/10.2106/jbjs.g.00979
33. Jackman, T., LaPrade, R. F., Pontinen, T., & Lender, P. A. (2008). Intraobserver and Interobserver reliability of the kneeling technique of stress radiography for the evaluation of posterior knee laxity. *The American journal of sports medicine, 36*(8), 1571–1576. https://doi.org/10.1177/0363546508315897
34. Pacheco, R. J., Ayre, C. A., & Bollen, S. R. (2011). Posterolateral corner injuries of the knee. The journal of bone and joint surgery. *British volume, 93-B*(2), 194–197. https://doi.org/10.1302/0301-620x.93b2.25774
35. Kim, J. G., Moon, H. T., Hwang, I. H., Kim, J. H., & Song, J. K. (2003). Arthroscopic evaluation of Posterolateral rotatory instability of the knee. *Journal of the Korean orthopaedic association, 38*(1), 29. https://doi.org/10.4055/jkoa.2003.38.1.29
36. Bleday, R., Fanelli, G., Giannotti, B., Edson, C., & Barrett, T. (1998). Instrumented measurement of the posterolateral corner. *Arthroscopy: The journal of arthroscopic & related surgery, 14*(5), 489–494. https://doi.org/10.1016/s0749-8063(98)70077-5
37. Fanelli, G. C., & Larson, R. V. (2002). Practical management of posterolateral instability of the knee. *Arthroscopy: the journal of arthroscopic & related surgery, 18*(2), 1–8. https://doi.org/10.1016/s0749-8063(02)80001-9

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MODERN CONCEPTS OF DIAGNOSTICS OF POSTEROLATERAL CORNER KNEE INJURIES

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Prognostic factors in the treatment of focal osteochondral lesions of the knee and ankle

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Osteochondral lesions of the knee and ankle joints are a common pathology that often results in decreased physical activity and early osteoarthritis. Despite the wide range of available surgical techniques, their efficacy varies considerably. Identifying prognostic factors is essential for optimizing treatment strategies. Studying and taking into account the factors that determine the outcome of treatment is a relevant issue in terms of improving the efficiency of providing care to patients in this category. Objective. To identify prognostic factors and informativeness coefficients in treatment of patients with osteochondral lesions. Methods. A retrospective study included 390 patients with focal osteochondral lesions treated with arthroscopic debridement, microfracture, drilling, or osteochondral autograft transplantation. Treatment effectiveness was evaluated using 21 clinical and morphological parameters and functional scores (Lysholm, AOFAS, SF-36, NRS) at 12–36-month follow-up. Statistical analysis included Bayesian probabilistic methods adapted for clinical research, Kulback's information measure to assess information coefficients, and a heterogeneous sequential procedure based on Wald analysis to determine prognostic coefficients. Results. Positive outcomes were observed in 284 patients (72.8 %), while 106 (27.2 %) had negative outcomes. Key prognostic factors included age, body mass index, lesion size, Kellgren & Lawrence osteoarthritis stage, lesion chronicity, limb axis deviations, and prior surgical history. Conclusions. The identified prognostic and informativeness coefficients have practical value for establishing an individualized approach to selecting the optimal treatment strategy and improving long-term outcomes.

Локальні внутрішньосуглобові кістково-хрящові ушкодження колінного та надп'ятково-гомілкового суглобів є поширеною патологією, що часто призводить до зниження фізичної активності та розвитку остеоартрозу. Незважаючи на великий вибір хірургічних методів, їх ефективність і результативність значно відрізняється. Вивчення та врахування чинників, які детермінують результат лікування є актуальним питанням в аспекті покращення ефективності надання допомоги хворим цієї категорії. Мета. Визначити прогностичні чинники та їхню інформативность у лікуванні пацієнтів із локальними внутрішньосуглобовими кістково-хрящовими ушкодженнями. Методи. Проведено ретроспективне дослідження 390 осіб із локальними кістково-хрящовими травмуваннями, яким застосовували артроскопічний дебридмент, мікрофрактуринг, тунелізацію й остеохондральну аутогенну трансплантацію. Ефективність лікування оцінювали за 21 клініко-морфологічним фактором і функціональними шкалами (Lysholm, AOFAS, SF-36, NRS) у віддаленому періоді (12–36 міс.). Статистичну обробку даних проводили з використанням методів імовірнісного аналізу на основі Байєсових алгоритмів, адаптованих для клінічних досліджень, інформативність окремих клінічних факторів із використанням інформаційної міри Кульбака, а прогностичні коефіцієнти зі застосуванням методики неоднорідної послідовної процедури, яка базується на аналізі Вальда. Результати. Позитивний ефект було досягнуто в 284 (72,8 %) пацієнтів, а негативний — 106 (27,2 %). Виявлено, що найбільш вагомими прогностичними факторами є вік, індекс маси тіла, розмір і давність ушкодження, стадія остеоартрозу за Kellgren & Lawrence, порушення осі кінцівки й хірургічне лікування в анамнезі. Висновки. Визначені прогностичні чинники та коефіцієнти інформативності мають практичну цінність для формування індивідуального підходу до вибору оптимальної тактики лікування та покращення віддалених результатів. Ключові слова. Остеоартроз, колінний суглоб, надп'ятково-гомілковий суглоб, хрящ, реконструктивні операції, лікування.

Keywords. Osteoarthritis, knee, ankle, cartilage, reconstructive surgery, treatment

Introduction

Local intra-articular bone-cartilage injuries of the knee joint (KJ) and ankle joint (AJ) remain one of the most complex problems in modern orthopedics and traumatology, as articular cartilage has an extremely limited potential for self-repair [1]. Injuries that reach the subchondral bone lead to the progression of osteoarthritis and a significant reduction in the quality of life of the patient and their physical activity [2].

There is a wide range of surgical methods for treating bone-cartilage injuries aimed at stimulating the bone marrow (microfracturing, abrasive chondroplasty, tunneling) [1], fixation of bone-cartilage fragments, and procedures aimed at restoring hyaline cartilage (osteochondral autograft transplantation [3], allografting [4], autologous chondrocyte implantation [5]). Nevertheless, in clinical settings, the most frequently employed techniques are those designed to stimulate the bone marrow and are more affordable.

Published clinical studies confirm that the success of treatment for bone-cartilage injuries does not depend solely on the chosen surgical intervention but requires a multifactorial approach and de pends on a number of prognostic criteria [1, 7]. The obtained regenerate of insufficient quality may lead to further development of degenerative-dystrophic changes [8], or an inadequate assessment of the regenerative potential, even with the use of complex and modern techniques, may result in a negative treatment outcome. This emphasizes the need to determine the prognostic factors for the successful treatment of patients in this group.

Objective: To identify prognostic factors and coefficients of informativeness in the treatment of patients with local intra-articular bone-cartilage injuries.

Materials and Methods

The study involved a retrospective analysis of the treatment outcomes of 390 patients with local intra-articular bone-cartilage injuries of the knee and ankle joints. These patients underwent treatment at the clinical bases of the Department of Traumatology and Orthopedics of O.O. Bohomolets National Medical University in 2022–2024. The study was approved by the bioethics committee of the respective institution (protocol No. 162 dated 31.10.2025) in accordance with the Helsinki Declaration of Human Rights and Biomedicine, as well as the current legislation of Ukraine. All patients signed informed consent.

Inclusion criteria: Age between 18 and 60 years, presence of bone-cartilage injury (requiring treatment and confirmed by instrumental diagnostic methods), application of one of the surgical interventions (debridement with abrasive chondroplasty, microfracturing, tunneling, osteochondral autograft transplantation) or their combination, stage 0–II osteoarthritis according to the Kellgren & Lawrence classification [9], absence of joint instability due to damage to the capsuloligamentous apparatus (except in cases where its restoration is performed in a single stage with the procedure for bone-cartilage injury restoration), availability of complete data for evaluating outcomes before surgery and in the long-term period (12–36 months).

Exclusion criteria: Age under 17 or over 60 years, stage III–IV osteoarthritis according to the Kellgren & Lawrence classification, presence of joint instability due to damage to the capsuloligamentous apparatus, acute infectious process, pregnancy and breastfeeding period, presence of absolute contraindications for surgical treatment.

Among the 390 patients, 238 had knee joint injuries, and 152 had ankle joint injuries.

The treatment outcomes were evaluated using the Lysholm functional scale for the knee joint [10], AOFAS scale for the ankle joint [11], quality of life according to the SF-36 scale [12], and pain level according to the numerical rating scale (NRS) [13]. Rehabilitation protocols were standardized according to the type of intervention. A total of 21 clinical-morphological and anamnesis factors were studied.

Statistical analysis was performed using Microsoft Excel 2019 and StatSoft Statistica 10 software. The forecasting methodology we applied was based on Bayesian probability analysis algorithms. This methodology is adapted and widely tested in clinical practice for predicting various pathological processes [14]. The informativeness of individual factors for predicting treatment outcomes was determined based on the use of the Kullback information measure. After assessing the informational significance of the parameters, prognostic coefficients (PC) of successful treatment depending on individual factors were calculated.

The methodological basis of the study was the use of the heterogeneous sequential procedure, based on Wald's analysis. This methodology calculates the sum of prognostic coefficients for individual clinical parameters and compares the total prognostic coefficient with critical threshold values. At the same time, the same type I error (probability of missing the optimal result group) was set at 5 % ($p < 0.05$), and the type II error (incorrect evaluation of the optimal treatment outcome) was set at no more than 20 % of cases.

Results

Analysis of the outcomes at the long-term period (12–36 months) showed that a positive effect was achieved in 284 (72.8 %) patients, while an unsatisfactory result was observed in 106 (27.2 %).

At the end of the study, the coefficient of informativeness and prognostic coefficient for each factor were determined in all 390 patients from the retrospective group (see table).

21 clinical-morphological and history factors were studied, which can be categorized as follows:

– Morphological factors: diameter (mm), area (cm^2), volume (cm^3), depth (mm) of the bone-cartilage injury, degree of damage according to ICRS, osteoarthritis stage according to Kellgren & Lawrence.

– Clinical factors: age (groups under or over 40 years), body mass index (BMI) (under or over 30 kg/m^2), presence of axial deformity (varus, valgus, none), joint instability (no, yes), contracture (flexion, extension, combined, none), synovitis, weight-bearing ability (before and after treatment).

– History factors: gender, duration of injury (less than or more than one year), affected joint (knee, ankle), etiology (traumatic, degenerative), conservative and surgical treatment in the medical history.

Factors examined also included damage to the joint structures (medial or lateral meniscus, anterior or posterior cruciate ligament, lateral collateral or medial collateral ligament of the knee joint, lateral and medial ligament groups of the ankle joint) or their absence, history of previous surgical treatment, zones of injury for the knee and ankle joints.

The threshold values of the prognostic coefficients range from –80 to +80. Exceeding the upper threshold (+80) indicates a high likelihood of an optimal treatment outcome. Intermediate prognostic evaluations are as follows: –80 to –50 (group with a low probability of a satisfactory outcome), –49.9 to +20 (group with a medium probability), +20.1 to +80 (group with a high probability). The prognostic procedure involves an overall evaluation of the selected factors inherent to each patient (sum of prognostic coefficients).

Younger age (< 40 years) has a significantly positive impact on treatment outcomes (PC = +7.7), while older patients (> 40 years) tend to show reduced treatment effectiveness (PC = –3.4). However, in addition to age, factors such as current activity level, anticipated future activity, and functional demands should also be taken into account. BMI also significantly impacts treatment results, as patients with a BMI < 30 kg/m^2 have a good prognostic coef-

Table

Factors and their prognostic coefficients for predicting treatment outcomes in patients with local intra-articular bone-cartilage injuries

Factor	Subgroup	Prognostic coefficient
1	2	3
Gender	male female	–1.1 2.5
Age	under 40 over 40	7.7 –3.4
BMI	less than 30 more than 30	9.5 –9.0
Injury duration	less than one year more than one year	6.9 –2.5
Joint instability	no yes	–6.1 –7.1
Contracture	no flexion extension combined	6.2 0.0 –10.9 0.0
Affected joint	knee ankle	–0.8 1.3
Deformity	none valgus varus	3.2 –11.7 –6.9
Etiology	degenerative traumatic	–1.8 6.1
Conservative treatment	no yes	5.3 –1.4
Surgical treatment (in medical history)	no yes	9.1 –6.7
Cartilage restoration (in medical history)	Microfracturing Tunnelization Osteochondral autograft transplantation None	–4.2 –9.0 –5.0 1.5
Synovitis	no yes	3.9 –5.4
Depth, mm	up to 7 more than 7	6.2 –2.8
Diameter, mm (ankle joint)	up to 10 10–15 more than 15	2.8 –1.9 –4.3
Diameter, mm (knee joint)	up to 10 10–20 mm more than 20	3.4 –2.1 –2.1
Area, cm^2 (ankle joint)	up to 1 1–2 more than 2	–0.1 –3.0 –4.3
Area, cm^2 (knee joint)	up to 1,5 1.5–3 more than 3	4.3 –3.1 –2.1
Volume, cm^3 (ankle joint)	up to 1,5 1.5–3 more than 3	–0.1 –3.0 –4.3

Continuation of the table

1	2	3
Volume, cm^3 (knee joint)	up to 2 2–4 more than 4	4.3 –3.1 –2.1
Kellgren & Lawrence	0 I II	4.8 5.6 –6.3

ficient (PC = +9.5), while those with excess weight show a significantly reduced likelihood of a positive outcome (PC = –9.0). Chronic bone-cartilage injuries have worse prognostic results (PC = –2.5) compared to injuries less than a year old (PC = +6.9), indicating the necessity for timely treatment of this type of injury. The size and depth of bone-cartilage injury directly correlate with treatment prognosis and have a high informational coefficient, which is an important factor in determining the further treatment strategy. The best prognosis is observed in stage 0–I osteoarthritis according to Kellgren & Lawrence (PC = +4.8; +5.6), while stage II already reduces effectiveness (PC = –6.3). The presence of deformity influences the choice of intervention strategy, as failing to restore the biomechanical axis of the limb makes it impractical to treat bone-cartilage injuries. Meanwhile, the absence of contracture (PC = +6.2) and axis deviation (PC = +3.2) are favorable signs. However, the localization of intra-articular bone-cartilage injuries only affects the technical aspects of the surgery and the need for arthroscopic or open access. Additional damage to the structures of the knee or ankle joint results in worse prognostic outcomes and requires additional surgeries to restore these structures.

Discussion

We have identified prognostic criteria in the treatment of patients with local intra-articular bone-cartilage injuries of the knee and ankle joints. The results obtained confirm the conclusions of other studies regarding the role of morphological and clinical factors in determining surgical intervention tactics [15–17].

The study by I. M. van Tuijn et al. [1] confirms that older patients and those with larger bone-cartilage injuries tend to have poorer outcomes after microfracturing. Additionally, patients with a BMI < 30 kg/m² experience better results from microfracturing compared to those with a BMI > 30 kg/m². A history of prior trauma or surgeries, such as partial meniscectomy or anterior cruciate ligament reconstruction, is also associated with worse long-term results in the surgical treatment of these injuries.

V. Gopinatth and colleagues [18] note that bone-cartilage injuries of 2–4 cm² in the knee joint, when treated with microfracturing, lead to further significant progression of osteoarthritis during long-term follow-up, with unsatisfactory subsequent physical activity levels and long-term clinical results after the intervention, although short-term results show positive dynamics in both the functional condition of the joint and return to physical activity. However, the quality of the regenerate obtained and the ability to withstand intense physical load decrease over time, which is especially important to consider in athletes or patients with high functional requirements [19].

Younger age and fresh bone-cartilage injuries are positive prognostic factors for the treatment of these injuries, which correlates with the conclusions of F. Migliorini et al. [20].

The need for total knee arthroplasty, according to the findings of J. S. Everhart et al. [21], increases when a patient has deep (full-thickness) bone-cartilage injuries with a diameter ≥ 2 cm, even at stage I–II osteoarthritis. The authors emphasize that regenerative and chondroplastic techniques are impractical for such significant injuries and suggest considering further stages of surgical treatment, especially in elderly patients.

In the study by J. S. Everhart et al. [22], it was observed that varus and valgus deformities, when combined with bone-cartilage injuries of the knee joint, result in poorer treatment outcomes, faster progression of degenerative-dystrophic changes, and unsuccessful surgical interventions. The authors also emphasize that excess body weight is a contributing factor, accelerating the progression of osteoarthritis and leading to less favorable treatment results.

In a prospective cohort study by P. H. Randsborg et al. [23], comparing microfracturing with arthroscopic debridement, better clinical results were achieved with microfracturing in cases of small injuries. However, the effectiveness of both techniques decreases as the size of the bone-cartilage injury increases.

Previous surgeries aimed at restoring articular cartilage, especially if their results were not sustained in the long term, are associated with a higher risk of unsatisfactory long-term outcomes after subsequent reconstructive procedures [24].

Most modern published studies for determining the size of bone-cartilage injuries rely only on the diameter or area, without considering depth or involvement of the subchondral bone. However, determining all parameters (depth, diameter, area, and volume) provides a more detailed picture, which, in turn, allows for more precise preoperative planning and the identification of the optimal surgical strategy and the overall appropriateness of chondroplastic surgeries.

Published studies evaluate BMI not just as something that adds to mechanical (axial) stress but also link it to metabolic changes. In our observation, we limited ourselves to bone-cartilage injuries in the knee and ankle joints, but for other joints, the coefficients of informativeness and prognostic criteria may change, especially for bone-cartilage injuries of the upper extremity joints. We relied on a standardized rehabilitation program, but individual factors of each patient, which may affect the final treatment outcome, were not considered. Also, according to the literature, patients undergoing restorative surgeries for bone-cartilage injuries are divided into groups before and after 40 years of age. However, in such cases, there is no individual assessment of the patient's desired future activity and functional requirements. A limitation of the observation is also the retrospective design, which is prone to systematic errors. Further prospective randomized studies are necessary to determine the effectiveness of treatment considering the prognostic coefficients and the prediction system for outcomes.

Conclusion

The study identified prognostic factors and informativeness coefficients that affect how effective treatment is for patients with local intra-articular bone and cartilage injuries in the knee and ankle joints. The success of treatment is determined by a combination of interrelated morphological, clinical, and history factors, with the most influential prognostic factors being: age, body mass index, size of the injury, osteoarthritis stage according to Kellgren & Lawrence, duration of the injury, limb axis deviation, and previous surgical treatment. The determination of prognostic and informativeness coefficients holds practical value for forming an individualized approach to selecting the optimal treatment strategy and improving long-term outcomes.

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

Prospects for Future Research. A limitation of this study is its retrospective design, which is prone to systematic errors. Further prospective randomized studies are needed to determine the treatment effectiveness, considering the prognostic coefficients and the prediction system for outcomes.

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References

1. Van Tuijn, I. M., Emanuel, K. S., Van Hugten, P. P., Jeuken, R., & Emans, P. J. (2023). Prognostic factors for the clinical outcome after Microfracture treatment of chondral and Osteochondral defects in the knee joint: A systematic review. *Cartilage, 14*(1), 5–16. https://doi.org/10.1177/19476035221147680
2. Cheng, L., & Wang, X. (2024). Advancements in the treatment of osteochondral lesions of the talus. *Journal of orthopaedic surgery and research, 19*(1), 827. https://doi.org/10.1186/s13018-024-05314-6
3. Pareek, A., Reardon, P. J., Maak, T. G., Levy, B. A., Stuart, M. J., & Krych, A. J. (2016). Long-term outcomes after Osteochondral autograft transfer: A systematic review at mean follow-up of 10.2 years. *Arthroscopy: the journal of arthroscopic & related surgery, 32*(6), 1174–1184. https://doi.org/10.1016/j.arthro.2015.11.037
4. Wang, X., Ren, Z., Liu, Y., Ma, Y., Huang, L., Song, W., Lin, Q., Zhang, Z., Li, P., Wei, X., & Duan, W. (2023). Characteristics and clinical outcomes after Osteochondral allograft transplantation for treating articular cartilage defects: Systematic review and single-arm meta-analysis of studies from 2001 to 2020. *Orthopaedic journal of sports medicine, 11*(9). https://doi.org/10.1177/23259671231199418
5. Ossendorff, R., Franke, K., Erdle, B., Uhl, M., Südkamp, N. P., & Salzmann, G. M. (2019). Clinical and radiographical ten years long-term outcome of microfracture vs. autologous chondrocyte implantation: a matched-pair analysis. *International orthopaedics, 43*(3), 553–559. https://doi.org/10.1007/s00264-018-4025-5
6. Goyal, D., Keyhani, S., Lee, E. H., & Hui, J. H. (2013). Evidence-based status of Microfracture technique: A systematic review of level I and II studies. *Arthroscopy: the journal of arthroscopic & related surgery, 29*(9), 1579–1588. https://doi.org/10.1016/j.arthro.2013.05.027
7. Migliorini, F., Maffulli, N., Eschweiler, J., Götze, C., Hildebrand, F., & Betsch, M. (2022). Prognostic factors for the management of chondral defects of the knee and ankle joint: A systematic review. *European journal of trauma and emergency surgery, 49*(2), 723–745. https://doi.org/10.1007/s00068-022-02155-y
8. Kuo, Y., Chiu, S., Chang, W., Chen, C., Chen, C., Liaw, C., Tan, C., & Weng, P. (2025). A prospective randomized controlled trial comparing biphasic cartilage repair implant with microfracture in small chondral lesions of knee: Findings at five-year-follow-up. *Journal of orthopaedic surgery and research, 20*(1). https://doi.org/10.1186/s13018-024-05392-6
9. Kellgren, J., & Lawrence, J. (1957). Radiological assessment of osteo-arthrosis. *Annals of the rheumatic diseases, 16*(4), 494–502. https://doi.org/10.1136/ard.16.4.494
10. Lysholm, J., & Gillquist, J. (1982). Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. *The American journal of sports medicine, 10*(3), 150–154. https://doi.org/10.1177/036354658201000306
11. SooHoo, N. F., Vyas, R., & Samimi, D. (2006). Responsiveness of the foot function index, AOFAS clinical rating systems, and SF-36 after foot and ankle surgery. *Foot & ankle international, 27*(11), 930–934. https://doi.org/10.1177/107110070602701111
12. Beaudart, C., Biver, E., Bruyère, O., Cooper, C., Al-Daghri, N., Reginster, J. Y., & Rizzoli, R. (2018). Quality of life assessment in musculo-skeletal health. *Aging clinical and experimental research, 30*(5), 413–418. https://doi.org/10.1007/s40520-017-0794-8
13. Thong, I. S. K., Jensen, M. P., Miró, J., & Tan, G. (2018). The validity of pain intensity measures: what do the NRS, VAS, VRS, and FPS-R measure?. *Scandinavian journal of pain, 18*(1), 99–107. https://doi.org/10.1515/sjpain-2018-0012
14. Matviychuk, O. (2017). Biomarkers of inflammatory in tertiary peritonitis. *Ukrainian journal of surgery, 0*(2.33), 37–40.

https://doi.org/10.22141/1997-2938.2.33.2017.107648
15. Kutaish, H., Klopfenstein, A., Obeid Adorisio, S. N., Tscholl, P. M., & Fucentese, S. (2025). Current trends in the treatment of focal cartilage lesions: a comprehensive review. *EFORT open reviews, 10*(4), 203–212. https://doi.org/10.1530/EOR-2024-0083
16. Bai, L., Zhang, Y., Chen, S., Bai, Y., Lu, J., & Xu, J. (2023). Analysis of factors affecting the prognosis of osteochondral lesions of the talus. *International orthopaedics, 47*(3), 861–871. https://doi.org/10.1007/s00264-022-05673-x
17. Jung, S., Jung, M., Chung, K., Kim, S., Park, J., Hong, J., Choi, C., & Kim, S. (2024). Prognostic factors for clinical outcome and cartilage regeneration after implantation of Allogeneic human umbilical cord blood-derived Mesenchymal stem cells in large-sized cartilage defects with osteoarthritis. *Cartilage, 15*(4), 375–388. https://doi.org/10.1177/19476035241231372
18. Gopinatth, V., Jackson, G. R., Touhey, D. C., Chahla, J., Smith, M. V., Matava, M. J., Brophy, R. H., & Knapik, D. M. (2024). Microfracture for medium size to large knee chondral defects has limited long-term efficacy: A systematic review. *Journal of experimental orthopaedics, 11*(4). https://doi.org/10.1002/jeo2.70060
19. Haslhofer, D. J., Shatrov, J., Jones, M., Abdul, W., Moteshaerei, A., Ball, S. V., & Williams, A. (2025). Microfracture for full-thickness chondral lesions of the knee in elite athletes leads to high return-to-play rates. *Knee surgery, sports traumatology, arthroscopy*. https://doi.org/10.1002/ksa.12808
20. Migliorini, F., Maffulli, N., Eschweiler, J., Götze, C., Hildebrand, F., & Betsch, M. (2022). Prognostic factors for the management of chondral defects of the knee and ankle joint: A systematic review. *European journal of trauma and emergency surgery, 49*(2), 723–745. https://doi.org/10.1007/s00068-022-02155-y
21. Everhart, J. S., Abouljoud, M. M., Kirven, J. C., & Flanigan, D. C. (2019). Full-Thickness Cartilage Defects Are Important Independent Predictive Factors for Progression to Total Knee Arthroplasty in Older Adults with Minimal to Moderate Osteoarthritis: Data from the Osteoarthritis Initiative. *The Journal of bone and joint surgery. American volume, 101*(1), 56–63. https://doi.org/10.2106/JBJS.17.01657
22. Everhart, J. S., Abouljoud, M. M., Poland, S. G., & Flanigan, D. C. (2018). Medial compartment defects progress at a more rapid rate than lateral cartilage defects in older adults with minimal to moderate knee osteoarthritis (OA): Data from the OA initiative. *Knee surgery, sports traumatology, arthroscopy, 27*(8), 2401–2409. https://doi.org/10.1007/s00167-018-5202-1
23. Randsborg, P., Aae, T. F., Visnes, H., Birkenes, T., Benth, J. Š., Lian, Ø. B., Hanvold, H. A., & Årøen, A. (2025). Microfracture versus Arthroscopic debridement for the treatment of symptomatic cartilage lesions of the knee: 2-Year results from a multicenter double-blinded randomized controlled trial. *The American journal of sports medicine, 53*(9), 2107–2117. https://doi.org/10.1177/03635465251346961
24. Angele, P., Zellner, J., Schröter, S., Flechtenmacher, J., Fritz, J., & Niemeyer, P. (2022). Biological reconstruction of localized full-thickness cartilage defects of the knee: A systematic review of level 1 studies with a minimum follow-up of 5 years. *Cartilage, 13*(4), 5–18. https://doi.org/10.1177/19476035221129571

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PROGNOSTIC FACTORS IN THE TREATMENT OF FOCAL OSTEOCHONDRAL LESIONS OF THE KNEE AND ANKLE

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Analysis of the results of surgical treatment of patients with the consequences of obstetric Duchenne-Erb paralysis

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To improve upper limb function in obstetric palsy, a number of surgical techniques have been proposed worldwide. However, achieving the desired rehabilitation effect is not always possible. Objective. To analyze the treatment outcomes in patients with the sequelae of Duchenne–Erb obstetric palsy depending on the severity of pathology, the diagnostic methods applied, and the chosen surgical tactics. Methods. A retrospective and prospective study was conducted to evaluate the treatment outcomes of children with Duchenne–Erb obstetric palsy who underwent surgery at the Pediatric Orthopedics Department of the SI «Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine». The retrospective group consisted of 6 patients; the prospective group included 16 patients, divided into two subgroups of eight: Group I — without bony deformities; Group II — with secondary bony deformities. Tendon-muscle transfers were performed in Group I, while a two-stage surgical intervention was applied in Group II. Parents of the children completed questionnaires. Results. In the retrospective group, after L'Episcopo surgery, an improvement in the function of the affected limb according to the Mallet scale was observed in two patients, while in the prospective group (in the long-term postoperative period) improvements were recorded in 10 cases. Group II demonstrated more pronounced and statistically significant positive changes in upper-limb function ($p < 0.05$). The frequency of functional improvement according to the Mallet scale between the prospective and retrospective groups did not reach statistical significance ($p > 0.05$). Differences in postoperative muscle strength between Groups I and II were not statistically significant ($p > 0.05$). After treatment, parents' assessment of their child's functional status increased by (5.1 ± 1.3) points, satisfaction with life — by (4.3 ± 1.3) points, and overall quality of life — by (9.4 ± 2.6) points ($p < 0.001$). Conclusions. A differentiated approach to choosing treatment tactics allows not only improving the function of the affected limb but also enhancing patients' quality of life, improving their psycho-emotional state, and increasing life satisfaction.

Із метою поліпшення функції верхньої кінцівки в разі акушерського паралічу у світі запропоновано низку методик оперативних втручань. Утім, досягти бажаного ефекту реабілітації хворого вдається не завжди. Мета. Проаналізувати результати лікування пацієнтів з наслідками акушерського паралічу Дюшена-Ерба залежно від тяжкості патології, застосування методів діагностики та тактики хірургічного втручання. Методи. Проведено ретроспективне та проспективне дослідження результатів лікування дітей з акушерським паралічем Дюшена-Ерба, яким виконували операцію в клініці дитячої ортопедії ДУ «ІПХС ім. проф. М. І. Ситенка НАМН України». Ретроспективну групу склали 6; проспективну — 16, їх розподілили на дві підгрупи по 8 осіб: I — без кісткових деформацій; II — хворі зі вторинними кістковими деформаціями. Пацієнтам I підгрупи виконано сухожилково-м'язові транспозиції, II — двохетапне хірургічне втручання. Проведено анкетування батьків дітей. Результати. У ретроспективній групі після втручання за методикою L'Episcopo покращення функції ураженої кінцівки за шкалою Mallet спостерігалось у двох хворих, а у проспективній (у віддаленому післяопераційному періоді) — у 10 випадках. У II підгрупі зафіксовано більш виражені та статистично значущі позитивні зміни функціонального стану верхньої кінцівки ($p < 0,05$). Частота покращення функціонального стану ураженої кінцівки за шкалою Mallet серед пацієнтів проспективної та ретроспективної груп не мала статистичної значущості ($p > 0,05$). Відмінності показників сили м'язів після операції у I та II підгрупах були статистично не значущі, $p > 0,05$. Після лікування оцінка функціонального стану хворої дитини з погляду батьків збільшилась на $(5,1 \pm 1,3)$ бала, задоволеності життям — на $4,3 \pm 1,3$, загальна якість життя — на $(9,4 \pm 2,6)$ бала ($p<0,001$). Висновки. Диференційований підхід до вибору тактики лікування дозволяє не лише покращити функцію ураженої кінцівки, а й підвищити якість життя хворих, поліпшити їхній психоемоційний стан і задоволеність життям. Ключові слова. Акушерський параліч Дюшена-Ерба, плечовий суглоб, вторинні кісткові деформації, плечове сплетення, м'язові транспозиції, шкала Mallet, хворобо-специфічний інструмент.

Key words. Duchenne-Erb obstetric palsy, shoulder joint, secondary bone deformities, brachial plexus, muscle transpositions, Mallet scale, disease-specific instrument

Introduction

Erb-Duchenne obstetric paralysis (Erb's paralysis due to birth trauma according to ICD-10, code P14.0) is the most common impairment among brachial plexus injuries.

The disease progresses through three distinct stages:

– Acute period (during the first 3 months after birth);

– Recovery period (from 3 months to 3 years);

– Residual signs (from 3 years and continuing throughout life).

Most injuries are of a neuropraxic nature, which over time allows for partial recovery of limb function. Recovery of nerve structures is more effective when treatment is applied during the first two periods of the disorder [1–3]. In the stage of residual signs, nerve innervation of the limb is generally not recoverable, and the treatment approach involves reconstructive-plastic orthopedic interventions to eliminate joint contractures and increase the range of function.

Considering this, it is particularly important in the treatment of Erb-Duchenne obstetric paralysis (EDOP) to use a broad diagnostic toolkit as early as possible, including X-ray, ultrasonography (US), electromyography (EMG), electroneurography (ENG), computerized tomography (CT), magnetic resonance imaging (MRI), and others. Additionally, timely and qualified application of a comprehensive treatment strategy during each period of the disease depending on the severity of the injury is significant, including pharmacological, physiotherapy, orthotic treatment, and, if necessary, surgical intervention [3–8]. When conservative treatment is the only approach, limb function in patients with EDOP is restored up to 55–70 % of cases by the age of three, depending on the severity of the injury [9].

To improve the function of the upper limb in cases of obstetric paralysis, several surgical techniques have been proposed worldwide, directly targeting nerve structures, the tendon-muscle system, bones, and joints. However, each surgical treatment method has a certain percentage of complications and failure to achieve the desired rehabilitation effect [10].

Objective: To analyze the results of treatment in patients with the consequences of Erb-Duchenne obstetric paralysis depending on the severity of the pathology, the application of diagnostic methods, and the tactics of surgical intervention.

Materials and Methods

The study materials were reviewed and approved by the Bioethics Committee (protocol dated 19 May 2025, No. 252) of Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine. The parents of all patients gave informed consent.

The treatment results of 22 patients aged 3 to 13 years with the consequences of EDOP, who were admitted to Professor M.I. Sytenko Institute of Spine and Joint Pathology during the periods 1996–2003 (retrospective study) and 2014–2022 (prospective study), were analyzed.

For the retrospective study and analysis of treatment results of EDOP, 6 medical histories were selected from patients aged 4 to 11 years. Among them were 3 girls and 3 boys, with an average age of (7.3 ± 2.8) years. Right brachial plexus injury was observed in 5 patients and left brachial plexus injury in 1 patient.

The prospective group consisted of 16 patients with EDOP aged from 3 to 17 years, including 10 boys (62.50 %) and 6 girls (37.50 %), with an average age of (10.1 ± 6.1) years. Right brachial plexus injury was observed in 6 patients and left brachial plexus injury in 10 patients. In 8 patients, bone deformities were diagnosed: elevation, rotation, and shear deformation of the scapula (SHEAR), including 2 cases on the right side and 6 on the left.

The patients in the prospective group (n = 16) were additionally divided into two subgroups based on the severity of pathological changes and types of surgical interventions:

– Group I (n = 8) — individuals with no diagnosed bone deformities who underwent active tendon-muscle transpositions;

– Group II (n = 8) — children with secondary bone deformities who underwent active tendon-muscle transpositions combined with osteotomy of the upper limb girdle bones.

All patients underwent clinical examination, including range of motion (ROM) evaluation in the affected shoulder joint using the “0” pass method. The function of the joint and upper limb was assessed using the modified Mallet scale [11], along with X-ray and electrophysiological examinations. Children in the prospective group with SHEAR bone deformity were additionally referred for CT with multiplanar reconstruction of the shoulder joint and scapula.

X-ray examinations of the shoulder joint were performed in anteroposterior and lateral projections, visualizing the scapula before surgical treatment in patients with significant adduction and internal rotation contractures, including 4 patients from the retrospective group and 8 from the prospective group. X-ray and fluoroscopy systems OPERA T90cex were used. The main criteria for identifying the presence or absence of SHEAR deformity were the position of the humeral head in the joint socket and the scapula standing height.

For the retrospective group, EMG (electromyography) was performed on both upper limbs, examining the bioelectrical activity of the shoulder girdle muscles: *m. supraspinatus, m. deltoideus, m. biceps, m. triceps, m. latissimus dorsi, and m. pectoralis major.*

For the prospective group, electrophysiological examination included performing both interference and stimulating EMG. The first bioelectrical activity was recorded bilaterally during maximum voluntary contraction of the following muscles: *m. deltoideus, m. supraspinatus, m. biceps brachii, m. triceps, m. abductor pollicis brevis,* and *m. abductor digiti minimi.* For stimulating EMG, the brachial plexus point (Erb's point) was stimulated, and motor responses from *m. deltoideus, m. supraspinatus, m. biceps brachii, m. triceps, m. abductor pollicis brevis,* and *m. abductor digiti minimi* were recorded. Latency, amplitude, and duration of M-responses were measured from the median, ulnar, axillary, radial, and musculocutaneous nerves. Reference values from the literature were accepted as normal [12]. Signals were recorded on a four-channel electromyograph ("NeuroMVP"). The input signal range was 30 mV, lower frequency 20 Hz, and upper frequency 10,000 Hz.

The results of each patient's examination before surgical intervention and in the long-term postoperative period (2–4 years later) were recorded in a specially designed questionnaire. During the observation of the prospective group, the muscle strength of the upper limbs was also evaluated using the modified Medical Research Council (MRC) scale [13]. Furthermore, to assess the quality of life of the patients before and after treatment, parents of the affected children were surveyed using the modified Disease-Specific Questionnaire (DSQ) [14]. This questionnaire included relevant questions for children with impaired upper limb function due to EDOP, focusing on functional status and ability to perform daily activities (functional scale), as well as on psychological well-being and life satisfaction (satisfaction scale).

To compare quantitative changes, the t-test for independent samples was used. Frequency data were compared using Fisher's exact test (φ*). A difference was considered statistically significant if $p \leq 0.05$.

Results and Discussion

According to the clinical examination results of shoulder joint and upper limb function using the Mallet scale in the preoperative period, among the patients in the retrospective group, 4 individuals showed second-degree limitation (Mallet II), and 2 patients showed third-degree limitation (Mallet III). During the X-ray examination at the preoperative stage, no bone changes were found in 2 individuals, while in 4 patients, hypoplasia of the shoulder joint socket and subluxation of the humeral head were observed (Fig. 1). According to EMG data, all patients had a 30 % reduction in the electrical bio-potentials of the upper limb muscles compared to the healthy contralateral side.

All 6 patients in the retrospective group underwent intervention using the L'Episcopo method [15]: the subscapularis muscle was transposed to the tendon of the teres minor muscle, and the attachment point of the teres major muscle was moved to the posteromedial surface of the humerus. As a result, the internal rotators of the shoulder joint were repositioned into the external rotator position. After 2–4 years following the treatment, 2 (33.3 %) patients showed improved function of the affected limb, from Mallet II to Mallet III (Table 1).

Among the patients in the prospective group, clinical examination results before surgery showed functional limitation of the upper limb at the Mallet II level in 4 (25.0 %) cases, Mallet III in 11 (68.8 %), and Mallet IV in 1 (6.2 %) patient.

More significant functional impairments were found among patients in Group II. In this subgroup, functional limitations were observed at Mallet II in 3 (37.5 %) and at Mallet III in 5 (62.5 %) individuals. In Group I, limitations at the Mallet II level were

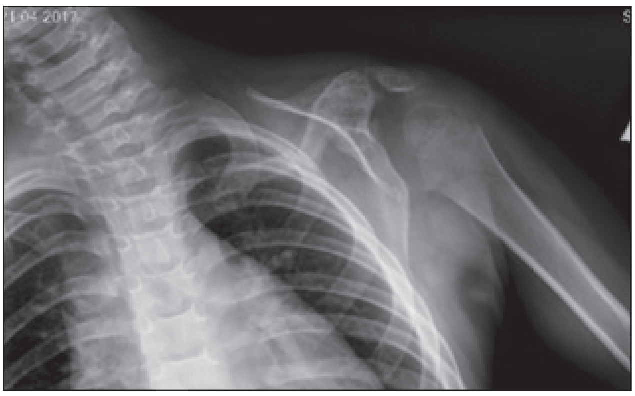

Fig. 1. X-ray of a 7-year-old patient S. Hypoplasia of the scapular glenoid cavity, posterior subluxation of the humeral head.

noted in only 1 (12.5%) patient, at Mallet III in 6 (75.0 %), and at Mallet IV in 1 (12.5 %).

According to X-ray studies, in the preoperative period, among the 16 patients in the prospective group, 8 patients showed flattening of the humeral head with partial deformation of the shoulder socket, 2 patients had subluxation of the acromioclavicular joint and Looser's zone in the acromial process of the scapula, 3 patients had hypoplasia of the shoulder socket, subluxation of the humeral head, and in 3 additional cases, hypoplasia of the clavicle and shoulder socket, along with subluxation of the humeral head (Fig. 2).

In all patients of the prospective group, there was significant paresis of the affected limb muscles at the start of treatment. Muscle strength assessment using the MRC scale in Group I ranged from 16 to 22 points, with an average of 19.5 ± 2.3 ($p < 0.001$). Among individuals in Group II, the muscle strength of the affected limb was somewhat lower: the maximum score on the MRC scale was 19, the minimum was 14, and the average was 16.3 ± 1.5 ($p < 0.001$). The differences between the average muscle strength values in the affected limb in Group I and Group II before treatment were statistically significant, $p < 0.01$.

To further clarify the assessment of muscle functional capacity and the severity of limb injury, EMG

Table 1

Dynamics of functional status evaluation of the upper limb using the Mallet scale after surgical treatment in patients of the retrospective group (n = 6)

Dynamics of evaluation using the Mallet scale	Patient
Improvement in the function of the affected limb	2
Functional status of the affected limb unchanged:	
– Mallet II;	2
– Mallet III	2

Fig. 2. X-ray of a 9-year-old patient T. Hypoplasia of the left scapula's glenoid, hypoplasia of the distal part of the left clavicle, subluxation of the left humeral head downward and backward.

studies were conducted on 8 children from the prospective group. 5 of them underwent stimulation methods, 2 received total surface myography, and in 1 case, both studies were performed. The analysis was done by comparing motor response indicators from the healthy and affected limbs. Electrophysiological data were highly variable: a reduction in the amplitude of the motor response, as well as prolonged latency and duration, was observed. For example, 3 patients were found to have a reduction in the amplitude of the deltoid muscle M-response, ranging from 28 % to 64 %, and an increase in latency and duration of the M-response up to 49 %. In 1 patient, the amplitude of the deltoid muscle was 33 % higher than in the healthy limb, but in other cases, there was no significant difference between the affected and healthy limbs.

Regrettably, the preoperative evaluation did not include testing of the *pectoralis major, teres major,* or *teres minor muscles*, as there was no established diagnostic algorithm available. However, dysfunction of these specific muscles is critical in the development of internal rotation contractures in the shoulder joint and secondary bone deformities of the shoulder girdle. Given that electrophysiological studies in patients with obstetric paralysis allow for accurate diagnosis of damage localization, severity, and the degree of neurological deficit in the brachial plexus [12, 16], the results of EMG were an important marker for choosing the surgical intervention strategy and further patient monitoring.

Considering the significant pathological changes identified during clinical and X-ray examinations, 5 patients in Group II underwent CT scanning, which revealed hypoplasia and rotation of the scapula. Additionally, in 4 (80%) cases, hypoplasia of the humeral head and glenoid (shoulder socket) hypoplasia were also diagnosed (Fig. 3). On average, the hypoplastic scapula was 12 % smaller than the contralateral side. Scapular hypoplasia and its rotational deformation changed the angle of the acromioclavicular joint, which could later provoke an impingement syndrome with the humeral head [11].

In these cases, performing CT scans with 3D modeling was deemed essential for diagnosing and detailing secondary bone deformities, SHEAR deformities, and for clarifying the surgical intervention plan. However, CT scanning could not be applied to all patients for diagnostic purposes due to significant limitations for younger age groups, considering the radiation dose: X-ray — 0.1 mSv, and CT (low-dose protocols) — 2.2–3.3 mSv [17–19]. Furthermore, sedation is required for such procedures in children, which often causes negative reactions from parents and leads to refusals.

Considering the localization, severity, and degree of manifestation of neurological deficits and bone deformities detected during diagnostics, appropriate surgical tactics and methods were selected for each case.

In Group I, no bone deformities were identified during the diagnostic procedures. To improve external rotation of the shoulder joint and abduction of the arm, patients in this subgroup underwent tendon-muscle transpositions. The surgical procedure involved the transposition of the latissimus dorsi and teres major muscles to the teres minor muscle, as well as a release of the pectoralis major muscle. Additionally, depending on the severity of the pathology, subscapularis muscle separation and decompression of the axillary nerve were performed.

Given that Group II had more severe manifestations of the impairment, with significant secondary bone deformities, these patients underwent two sequential surgical interventions on the bones and soft tissue structures of the shoulder girdle with a time gap of one year between the stages. Initially, surgical correction of bone deformities was performed: osteotomy of the acromial process of the clavicle and middle third of the clavicle, which allowed for changing the plane of the acromioclavicular triangle and centralized the humeral head into a neutral position in the joint socket. In the second stage, muscle transposition and/or release surgeries were performed depending on the existing pathological changes.

The analysis of findings in the prospective group before and after surgery demonstrated an improvement in the upper limb function after performing stage-based surgical intervention. The surgery had a positive impact on both the muscle and bone components of the shoulder joint and scapula deformity, specifically in eliminating impingement syndrome and scapular lowering. However, based on CT imaging of the shoulder joint, in 2 cases of SHEAR deformation, there was a persistent torsion of the humeral bone (Fig. 4). This highlights the need for a more detailed diagnosis of pathological changes to refine the surgical intervention strategy. Specifically, for patients with congenital brachial plexus paralysis who are in the late stage of shoulder dysplasia, which prevents the release of soft tissues and tendon repositioning, it would be reasonable to add corrective derotational osteotomy of the humeral bone to the surgical strategy, the effectiveness of which has been demonstrated in similar cases by other researchers [20].

After treatment, functional improvement of the affected limb in the long-term post-operative period (2–4 years) was observed in 10 (62.5 %) patients of the prospective group. In 2 (12.5 %) cases, there was an increase in functional capacity of the affected limb from Mallet II to Mallet IV, in 2 (12.5 %) others from Mallet II to Mallet III, and in 6 (37.5 %) cases from Mallet III to Mallet IV.

After treatment, upper limb function remained unchanged, at Mallet IV level in 1 (6.2 %), Mallet III in 5 (31.3 %) patients. The most significant and statistically significant positive changes in the functional state of the upper limb in the long-term post-operative period were observed among patients in Group II ($p < 0.05$) (Table 2).

However, the difference in the frequency of positive changes in the functional state of the affected limb using the Mallet scale between the prospective and retrospective groups was not statistically significant ($\phi^* = 1.238$, $p = 0.1079$). This proves that the tactics and methods of treatment in both groups were correctly chosen and effective, despite literature indicating a high percentage

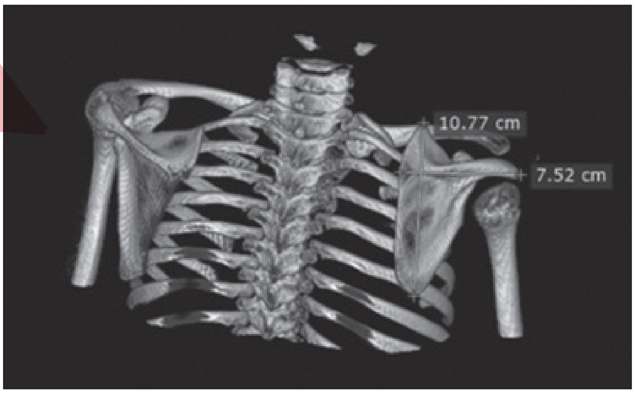

Fig. 3. CT scan of a patient with EOP. Measurement of SHEAR deformity (patient O., 9 years old): SHEAR deformity I (2.5 % of scapular standing above the clavicle in the frontal plane of CT).

Fig. 4. Postoperative CT scan of the shoulder joint of a 10-year-old patient S. with EOP, showing torsion of the humeral bone.

of short-term effectiveness and recurrence after surgeries using the L'Episcopo method [21, 22].

During the MRC scale muscle strength assessment in the long-term post-operative period, it was found that the muscle strength increased in all patients of the prospective group by an average of (4.5 ± 1.9) points ($p < 0.001$). The differences between Group I and Group II were not statistically significant ($p > 0.05$) (Table 3). Considering that Group I patients had greater upper limb muscle strength before treatment compared to Group II ($p < 0.01$), the post-operative results indicate that the choice of surgical tactics and methods was correct, taking into account the identified pathological changes.

The quality of life of patients in the prospective group before and after treatment demonstrated a significant improvement in the functional status of the upper limbs and the ability of patients to perform daily activities, their psychological well-being, and life satisfaction.

Before treatment, parents of patients in the prospective group assessed the upper limb function using the DSQ questionnaire with an average score of (6.4 ± 1.8) points, and life satisfaction was 7.3 ± 2.4. The overall quality of life score was (13.6 ± 4.1) points ($p < 0.001$). After treatment, the functional status of the affected child improved by an average of (5.1 ± 1.3) points, life satisfaction increased by 4.3 ± 1.3 points, and the overall quality of life score improved by 9.4 ± 2.6 points ($p < 0.001$). There was no statistically significant difference in the functional status and satisfaction scores between Groups I and II before treatment ($p > 0.05$). However, after treatment, a statistically significant difference was found in the improvement of psychological well-being and life satisfaction, and thus overall quality of life improved more among patients in Group II compared to Group I ($p \leq 0.05$) (Table 4).

The life satisfaction score in Group I increased by an average of (3.4 ± 0.7) points, while in Group II it increased by 5.6 ± 0.9, with the statistical significance of the difference being $p < 0.001$. The overall quality of life score in Group I increased by an average of 8.0 ± 1.1, while in Group II it increased by (11.4 ± 2.3) points, with the statistical significance of the difference being $p < 0.05$ (Table 5). Considering the significantly worse objective functional state indicators of the affected limb in Group II patients before treatment and the dynamics of positive changes in the long-term post-operative period according to the diagnostic data, it can be concluded that the intervention was effective due to the correct choice of tactics and methods based on the severity of the identified pathological changes in Groups I and II. The lack

Table 2

Dynamics of functional status evaluation of the upper limb using the Mallet scale after surgical treatment in patients of the prospective group

Indicator	Prospective group, total number of patients, (%)	Group I, number of patients, (%)	Group II, number of patients, (%)
Improvement in the function of the affected limb, total, including an increase in the grading level:	10 (62.5 %)	3 (37.5 %)	7 (87.5 %)
– From Mallet II to Mallet III;	2 (12.5 %)	1 (12.5 %)	1 (12.5 %)
– From Mallet II to Mallet IV;	2 (12.5 %)	—	2 (25.0 %)
– From Mallet III to Mallet IV	6 (37.5 %)	2 (25.0 %)	4 (50.0 %)
Functional state of the affected limb without changes:	6 (37.5 %)	5 (62.5 %)	1 (12.5 %)
– Mallet III;	5 (31.3 %)	1 (12.5 %)	1 (12.5 %)
– Mallet IV	1 (6.2 %)	4 (50.0 %)	—
Fisher's exact test (□*), p-value	—	φ* = 2.201, p = 0.0139	

Table 3

Average muscle strength scores after treatment among patients in the prospective group according to the MRC scale (in points)

Indicator	Subgroup	Score	Comparison of mean values, p-value
Muscle strength after treatment	I	23.1 ± 1.4	p > 0.05
	II	21.3 ± 1.0	
Increase in muscle strength after treatment	I	3.6 ± 1.9	p > 0.05
	II	5.4 ± 1.3	

Notes. Results are presented as (M ± SD); where M is the mean value of the indicator in the group, and SD is the standard deviation.

Table 4

Average quality of life scores before and after treatment for patients in Subgroup I and Subgroup II of the prospective group based on parent surveys using the DSQ questionnaire (in points)

Scale	Subgroup	Period of observation	Score	p-value		
Upper limb functionality	I	before treatment	6.4 ± 1.4	$p^1 < 0{,}001$	$p^2 = 1.000$	$p^3 = 0.140$
		after treatment	10.9 ± 1.6			
	II	before treatment	6.4 ± 1.4			
		after treatment	12.1 ± 1.6			
Life satisfaction	I	before treatment	7.3 ± 41.5		$p^2 = 0.615$	$p^3 = 0.051$
		after treatment	10.6 ± 0.9			
	II	before treatment	6.8 ± 2.3			
		after treatment	12.4 ± 2.1			
Overall score	I	before treatment	13.6 ± 2.8		$p^2 = 0.794$	$p^3 = 0.001$
		after treatment	21.6 ± 2.3			
	II	before treatment	13.1 ± 4.4			
		after treatment	24.5 ± 3.4			

Notes. The results are presented as (M ± SD), where M is the mean value of the indicator in the group, SD is the standard deviation; p^1 — comparison of the mean values before and after treatment; p^2 — comparison of the results before treatment in both subgroups; p^3 — comparison of the results after treatment in both subgroups.

Table 5

Increase in quality of life indicators after treatment in patients of Subgroups I and II of the prospective group, based on parent surveys using the DSQ questionnaire (in points)

Score	Increase in the indicator after treatment	
	Subgroup I	Subgroup II
Function	↑ 4.5 ± 0.5	↑ 5.8 ± 1.7
p-value	p = 0.0632	
Life satisfaction	↑ 3.4 ± 0.7	↑ 5.6 ± 0.9
p-value	p = 0.0001	
Overall	↑ 8.0 ± 1.1	↑ 11.4 ± 2.3
p-value	p = 0.0019	

Notes. The results are presented as (M ± SD), where M is the mean value of the indicator in the group, SD is the standard deviation; p is the comparison of the mean values between the two groups, ↑ — increase.

of statistically significant difference in the assessment of the limb's functional state by the parents of the patients after treatment can be explained by the subjectivity of their evaluation.

The obtained data are consistent with other studies [2, 5, 7, 8] and highlight the importance of timely and high-quality diagnosis of pathological changes, as well as the choice of tactics and treatment methods depending on the severity of the damage.

Conclusions

The results of the study indicate that the accuracy of diagnosis using modern technologies and the rational choice of surgical methods, taking into account the degree of neurological disorders and the nature of pathological bone changes and deformities, are key factors in the effective treatment of patients with persistent upper limb function disorders due to Duchenne-Erb obstetric paralysis.

The data confirm that a differentiated approach to determining the treatment strategy allows for obtaining high-quality results in improving the functional capability of the affected limb and significantly improving quality of life indicators, including psychological and emotional well-being.

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

Prospects for Further Research. In the future, the development and implementation of a standardized diagnostic algorithm and treatment protocol for patients with the consequences of Duchenne-Erb obstetric paralysis are of interest.

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References

1. Chung, K. C., Lynda, J.-S., & McGillicuddy, J. E. (Eds.). (2012). Practical management of pediatric and adult brachial plexus palsies. Elsevier
2. Shah, V., Coroneos, C. J., & Ng, E. (2021). The evaluation and management of neonatal brachial plexus palsy. *Paediatrics & child health, 26*(8), 493–497. https://doi.org/10.1093/pch/pxab083
3. Pondaag, W., & Malessy, M. J. (2020). Evidence that nerve surgery improves functional outcome for obstetric brachial plexus injury. *Journal of hand surgery (European Volume), 46*(3), 229–236. https://doi.org/10.1177/1753193420934676
4. Eckstein, K. L., Allgier, A., Evanson, N. K., & Paulson, A. (2020). Brachial plexus birth injuries and the association between pre-procedure and post-procedure pediatric outcomes data collection instrument scores and Narakas classification. *Journal of pediatric rehabilitation medicine, 13*(1), 47–55. https://doi.org/10.3233/PRM-190603
5. Arrigoni, C., Facchi, R., & Catena, N. (2025). The role of glenoid osteotomy in the treatment of shoulder dysplasia in brachial plexus birth palsy: A systematic review. *Journal of clinical medicine, 14*(16), 5610. https://doi.org/10.3390/jcm14165610
6. Basit, H., Ali, C. D. M., & Madhani, N. B. (2023). Erb palsy. In StatPearls. StatPearls Publishing
7. Li, H., Chen, J., Wang, J., Zhang, T., & Chen, Z. (2023). Review of rehabilitation protocols for brachial plexus injury. *Frontiers in neurology*, 14, 1084223. https://doi.org/10.3389/fneur.2023.1084223
8. Komar, T., Koval, O., & Khmara, T. (2024). Morphological prerequisites of origin upper, middle, and lower syndromes of injury of the primary bundles of the brachial plexus. *Clinical anatomy and operative surgery, 23*(2), 108–113. https://doi.org/10.24061/1727-0847.23.2.2024.37
9. Strafun, S. S., Borzikh, O. V., Naumenko, L. Yu., & Ipatov, A. V. (2011). Obstetric paralysis. In L. Yu. Naumenko (Ed.), Medical and social examination and rehabilitation in pathology of the musculoskeletal system. Porogy
10. Khmyzov, S., Hrytsenko, A., Kykosh, G., & Hrytsenko, A. (2023). Birth injury, Duchenne-Erb's obstetric palsy: Diagnosis and treatment (literature review). *Orthopaedics, traumatology and prosthetics*, (3), 69–78. https://doi.org/10.15674/0030-59872023369-78
11. Umut, G. U., Hoşbay, Z., Tanrıverdi, M., Yılmaz, G. G., Altaş, O., Korucu, A., & Aydın, A. (2024). Obstetric brachial plexus palsy and functional implications. *Medicina, 60*(11), 1850. https://doi.org/10.3390/medicina60111850
12. Hafner, P., Manzur, A., Smith, R., Jaiser, S., Schutz, P., Sewry, C., Muntoni, F., & Pitt, M. (2019). Electromyography and muscle biopsy in paediatric neuromuscular disorders. *Neuromuscular disorders, 29*(1), 14–20. https://doi.org/10.1016/j.nmd.2018.10.003
13. Conde, R. M., Pena, L. A. P., Elias, A. H. N., Guerreiro, C. T., Pereira, D. A., Sobreira, C. F. R., Marques Jr, W., & Barreira, A. A. (2023). Inter-rater reliability of the Rasch-modified MRC scoring criteria. *Journal of the peripheral nervous system, 28*(1), 119–124. https://doi.org/10.1111/jns.12534
14. Peters, M., & Crocker, H. (2023). Disease-Specific Questionnaire. In Encyclopedia of Quality of Life and Well-Being Research. Springer. https://doi.org/10.1007/978-3-031-17299-1_756
15. Thamer, S., Kijak, N., Toraih, E., Thabet, A. M., & Abdelgawad, A. (2023). Tendon transfers to restore shoulder function for obstetrical brachial plexus palsy. *JBJS Reviews, 11*(1). https://doi.org/10.2106/JBJS.RVW.22.00165
16. Berényi, M., Szeredai, M., & Cseh, Á. (2022). Neonatal brachial plexus palsy — Early diagnosis and treatment. *Ideggyógyászati szemle, 75*(7–8), 247–252. https://doi.org/10.18071/isz.75.0247
17. Rudoy, A., & Tereshchenko, M. (2021). Efficiency estimation of monitoring radiation doses during CT. *Bulletin of Kyiv polytechnic institute. instrument making, 61*(1), 85–90. https://doi.org/10.20535/1970.61(1).2021.237111
18. Wiertel-Krawczuk, A., Szymankiewicz-Szukała, A., & Huber, J. (2024). Brachial plexus injury influences efferent transmission. *Biomedicines, 12*(7), 1401. https://doi.org/10.3390/biomedicines12071401
19. Cebula, A., Cebula, M., & Kopyta, I. (2021). Muscle ultrasonographic elastography in children. *Children, 8*(11), 1042. https://doi.org/10.3390/children8111042
20. Azer, A., Mendiratta, D., Saad, A., Duan, Y., Cedarstrand, M., Chinta, S., Hanna, A., Shinora, D., McGrath, A., & Chu, A. (2023). Outcomes of humeral osteotomies versus soft-tissue procedures. *Frontiers in surgery*, 10, 1267064. https://doi.org/10.3389/fsurg.2023.1267064
21. Boileau, P., Baba, M., McClelland, W. B. Jr., Thélu, C.-É., Trojani, C., & Bronsard, N. (2018). Isolated loss of active external rotation. *Journal of shoulder and elbow surgery, 27*(3), 499–509. https://doi.org/10.1016/j.jse.2017.07.008
22. Bonnevialle, N., Elia, F., Thomas, J., Martinel, V., & Mansat, P. (2021). Osteolysis at the insertion of L'Episcopo tendon transfer. *Orthopaedics & traumatology: surgery & research, 107*(4), 102917. https://doi.org/10.1016/j.otsr.2021.102917

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ANALYSIS OF THE RESULTS OF SURGICAL TREATMENT OF PATIENTS WITH THE CONSEQUENCES OF OBSTETRIC DUCHENNE-ERB PARALYSIS

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The effect of depth of anesthesia on the incidence of early postoperative complications during surgery in the beach chair position

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Objective: To investigate the effect of BIS-controlled anesthesia depth on hemodynamic changes and early postoperative complications during shoulder surgery in the BCP. Methods. The prospective study involved 50 patients who underwent shoulder surgery in the BCP. Group I (n = 25) — patients whose BIS values were maintained intraoperatively within the range of 40–48, Group II (n = 25) — patients whose BIS monitoring values were maintained at the level of 49–57. Intraoperative BIS fluctuations beyond the range of 40–60 were not allowed in patients of both groups. The average age of patients in the I group was 43.2 ± 12.5 years, in the II group — 41.8 ± 10.2 years. After induction of propofol/fentanyl in a standard dosage, tracheal intubation, the patient was transferred to the BCP. For postoperative pain relief, patients received paracetamol and non-steroidal anti-inflammatory drugs without the use of narcotic analgesics. BIS monitoring with COVIDEN was used to control the depth of sedation. The Mini-mental state examination (MMSE) scale and the number linking test were used to assess cognitive impairment 24 hours before surgery and 2 days after surgery. Pain was assessed using a visual analogue scale (VAS). Results. Haemodynamic parameters were assessed before induction, after induction, and 20 minutes after positioning. Patients in group I had a significantly higher pulse rate (79.04 ± 7.51 vs. 72.76 ± 9.46 mm Hg, p < 0.05). No significant changes in MMSE and number binding test were found when comparing pre- and postoperative indicators. Significant differences in the intensity of pain syndrome were found between the groups: 3.72 ± 1.06 vs. 5.11 ± 0.90 points on the first day after surgery (p < 0.001). In group 1, 12.0 % of patients experienced postoperative nausea and vomiting on day 1, compared to 20.0 % in group 2. The time of extubation showed a significant difference between groups 1 and 2: 19.08 ± 2.87 versus 15.30 ± 2.55 points (p < 0.001). Conclusions. Maintaining the level of sedation under BIS monitoring at 49–57 in patients during surgery in NSP conditions is accompanied by less postoperative pain and a lower incidence of PONV.

Мета. Дослідити вплив глибини анестезії під контролем BIS на зміни гемодинаміки та ранні післяопераційні ускладнення під час проведення оперативних втручань на плечі в напівсидячому положенні (НСП). Методи. До проспективного дослідження було залучено 50 пацієнтів, яким виконувалась операція на плечовому суглобі в НСП. Група I (n = 25) — особи, яким інтраопераційно підтримували показники BIS у межах 40–48, група II (n =25) — хворі, показники BIS-моніторингу яких підтримували на рівні 49–57. У пацієнтів обох груп не допускалося інтраопераційних коливань BIS за межі 40–60. Середній вік у I групі складав (43,2 ± 12,5) років, у II — 41,8 ± 10,2. Після проведення індукції пропофол/фентанілу в стандартному дозуванні, інтубації трахеї хворий переводився у НСП. Для післяопераційного знеболення пацієнти отримали парацетамол і нестероїдні протизапальні препарати без використання наркотичних анальгетиків. Із метою контролю глибини седації використовували BIS-моніторінг COVIDEN. Для оцінки когнітивних порушень застосовували шкалу Mini-mental state examination (MMSE) і тест зв'язування чисел (ТЗЧ) за 24 год до оперативного втручання та на 2-гу добу після. Біль визначали за візуальною аналоговою шкалою (ВАШ). Результати. Показники гемодинаміки оцінювали до та після індукції та через 20 хв після позиціонування. Пацієнти групи I мали достовірно частіший пульс (79,04 ± 7,51 проти (72,76 ± 9,46) уд./хв, p < 0,05). Достовірних змін MMSE і ТЗЧ під час порівняння перед- та після операції виявлено не було. Відмінності в інтенсивності больового синдрому виявлені між групами: 3,72 ± 1,06 проти (5,11 ± 0,90) балів на 1-шу добу після втручання (p < 0,001). У групі I — в 12,0 та в II — 20,0 % на 1-шу добу спостерігалась післяопераційна нудота та блювання. Час екстубації мав достовірну різницю між групами: 19,08 ± 2,87 проти (15,30 ± 2,55) балів (p < 0,001). Висновки. Підтримання рівня седації під контролем BIS-моніторингу на рівні 49–57 у пацієнтів під час операції в умовах НСП супроводжується меншим післяопераційним больовим синдромом і нижчою частотою ПОНБ. Ключові слова. Напівсидяче положення, BIS-моніторинг, когнітивні дисфункції, післяопераційна нудота та блювання.

Keywords. Semi-sitting position, BIS monitoring, cognitive dysfunction, postoperative nausea and vomiting

Introduction

Accurately determining the depth of sedation remains a constant challenge for anesthesiologists. Excessively deep anesthesia can cause hemodynamic changes, while overly shallow sedation carries the risk of awakening during surgery [1]. Awakening during anesthesia is a serious complication that can have long-term psychological consequences, such as anxiety and post-traumatic stress disorder. Traditional monitoring of sedation depth is mostly assessed through clinical signs and symptoms of the patient: changes in heart rate, blood pressure, pupil size, and eye or limb movements [2]. The Bispectral Index (BIS) monitoring system was introduced in the United States in 1994 and approved by the FDA in 1996 to measure the level of consciousness using algorithmic analysis of electroencephalograms (EEG) during general anesthesia. BIS monitoring is a technology used in anesthesia to assess the level of consciousness and the hypnotic effect of anesthetic agents. It helps reduce intraoperative awakening incidents and provides an objective and accurate method for tracking the depth of anesthesia, which is a key component of some Enhanced Recovery After Surgery (ERAS) recommendations [3]. By quantitatively determining excitatory or inhibitory states of the cerebral cortex using power and frequency analysis in the EEG, BIS provides a numerical value corresponding to a specific level of consciousness that reflects the functional state of the cortex. This enables continuous non-invasive monitoring of anesthesia depth throughout the entire perioperative period, aligning with ERAS goals to optimize patient recovery, minimize complications, and accelerate recovery.

A multicenter study [4] has shown that the depth of anesthesia can influence postoperative complications. When comparing target BIS levels of 50 and 35, it was found that the quality of sedation did not affect the one-year mortality rate, but deeper anesthesia was associated with a higher risk of hemodynamic disturbances. Similar data regarding operations in a semi-sitting position (SSP) have not been found, although such a position could create a risk of brain hypoperfusion even with minor hemodynamic disturbances. Earlier reports have indicated that BIS values depend on intraoperative positioning and are significantly lower in the semi-sitting position compared to the lying position [5], although the mechanism of this phenomenon remains unclear. Given this, it is relevant to determine the safe level of BIS in the semi-sitting position.

Objective: To investigate the effect of BIS-controlled anesthesia depth on hemodynamic changes and early postoperative complications during shoulder joint surgeries in the semi-sitting position.

Materials and Methods

The study was conducted at the State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine and was approved by the local Bioethics Committee (Protocol No. 231, dated 20 May 2023) of the relevant institution in accordance with the ICH GCP guidelines, the Helsinki Declaration of Human Rights and Biomedicine, and current Ukrainian legislation. All patients involved were informed about the plan and conditions of the study and provided both written and oral consent.

The prospective study involved 50 patients who underwent shoulder joint surgery (arthroscopic rotator cuff repair) in a SSP. The patients were divided into two groups: Group I (n = 25) consisted of individuals in whom intraoperatively BIS values were maintained within the range of 40–48, and Group II (n = 25) consisted of patients whose BIS index was maintained between 49–57. In both groups, intraoperative BIS fluctuations were not allowed outside the range of 40–60. The mean age of patients in Group I was (43.2 ± 12.5) years, and in Group II, it was (41.8 ± 10.2). Inclusion criteria: age 18–65 years, ASA I–II, undergoing shoulder joint surgery in SSP. Exclusion criteria: history of central nervous system diseases, gastroesophageal reflux disease, post-cholecystectomy syndrome (as these conditions increase the risk of postoperative nausea and vomiting (PONV) [6]).

After ensuring venous access, both groups received a volumetric load of 12 ml/kg [7]. Anesthesia induction was performed with a 1 % propofol solution at a dose of 2 mg/kg and fentanyl at a dose of 100 mcg. Myoplegia for tracheal intubation was induced with succinylcholine at a dose of 0.1 mg/kg, followed by maintenance of muscle relaxation with atracurium besilate at a dose of 0.3 mg/kg. General anesthesia was maintained with a 1 % propofol solution according to the BIS-monitoring parameters. Postoperative analgesia was provided with paracetamol and non-steroidal anti-inflammatory drugs without the use of narcotic analgesics. For the prevention of PONV, all patients received ondansetron 4 mg and dexamethasone 4 mg [8].

Mechanical ventilation was provided using the Drager Atlan A300 ventilator, and peripheral blood saturation (SpO2), non-invasive systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP) were monitored using the Mediana YM 6000 monitor. BIS monitoring COVIDEN was used to control the depth of sedation and adjust the propofol infusion. According to the manufacturer, the BIS system has a processing delay of 5–10 seconds [9]. Considering that CO_2 is a vasodilator and that a low level of carbon dioxide is thought to cause cerebral vasoconstriction [10], continuous monitoring of end-tidal CO2 concentration was performed in both groups, and the values were maintained within the range of 35–45 mm Hg.

To assess potential early cognitive impairment, the Mini-Mental State Examination (MMSE) and the number connection test (NCT) were used: assessments were conducted 24 hours before surgery and on the second postoperative day. Pain was assessed using the visual analog scale (VAS). In the postoperative period, the frequency of nausea and vomiting, extubation time, and the recovery of spontaneous breathing were analyzed.

The statistical analysis of the obtained data was performed using IBM SPSS version 9.0 software. The normality of the distribution of the samples was tested using the Kolmogorov–Smirnov test. Mean values and standard deviations were calculated. Comparisons of parameters between the groups were made using the Student's t-test.

Results

Hemodynamic indicators were assessed before and after induction and intubation, as well as 20 minutes after positioning. As expected, there were no differences in values between the groups during the first and second stages. However, at the third stage, 20 minutes after positioning, and against the backdrop of preloading, no differences in blood pressure between the groups were observed (Table 1). At the same time, patients with more superficial anesthesia (Group I) had a significantly higher pulse rate (79.04 ± 7.51 vs. 72.76 ± 9.46 beats per minute, $p < 0.05$).

Cognitive function was evaluated 24 hours before surgery and two days after. No significant changes in MMSE scores or in the number connection test were found when comparing preoperative and postoperative values (Table 2).

Pain assessment was conducted on the 1st and 2nd postoperative days using the Visual Analog Scale. Statistically significant differences were found in the intensity of pain between patients in Group I and Group II: 3.72 ± 1.06 vs. 5.11 ± 0.90 points on the first postoperative day ($p < 0.001$). On the 2nd postoperative day, no significant differences were observed (Table 3).

Postoperative nausea and vomiting were observed in 5 patients (12.0 %) in Group I and 3 patients (20.0 %) in Group II on the first postoperative day. On the second day after surgery, no instances of postoperative nausea or vomiting were recorded in any patient.

Recovery of adequate spontaneous breathing was considered to occur when CO_2 levels were maintained below 50 mm Hg. Extubation was performed when the BIS level reached 85. The time to extubation showed a significant difference between Group I and Group II: 19.08 ± 2.87 minutes vs. 15.30 ± 2.55 minutes ($p < 0.001$) (Table 5).

Discussion

This study examined how anesthesia depth, measured by BIS, affects peripheral hemodynamics, neuropsychological status, pain perception, and post-

Table 1

Hemodynamic changes in patients of the studied groups, M ± SD

Group	SBP, mmHg	DBP, mmHg	MAP, mmHg	Pulse, bpm
I	Initial level			
	126.32 ± 8.57	83.88 ± 7.65	95.7 ± 7.82	78.96 ± 10.87
	After induction			
	98.72 ± 9.96	65.12 ± 10.48	73.86 ± 3.75	74.76 ± 7.73
	20 Minutes after positioning			
	97.6 ± 5.38	63.92 ± 2.88	74.25 ± 3.48	79.04 ± 7.51
II	Initial level			
	125.84 ± 12.25	85.88 ± 10.67	97.73 ± 5.34	74.84 ± 10.57
	After induction			
	103.69 ± 12.54	69.38 ± 9.20	75.32 ± 4.42	81.30 ± 10.69
	20 Minutes after positioning			
	98.07 ± 5.57	64.69 ± 2.72	75.58 ± 4.84	72.76 ± 9.46

Table 2

Dynamics of cognitive functions in the patients of the study groups, M ± SD

Group	MMSE, score	TCT, sec
I	24 hours before surgery	
	27.92 ± 1.15	65.96 ± 18.50
	2 days after surgery	
	28.28 ± 2.33	65.84 ± 22.62
II	24 hours before surgery	
	27.65 ± 1.12	71.73 ± 7.65
	2 days after surgery	
	27.88 ± 0.99	72.92 ± 12.51

Table 3

Study of pain syndrome levels in patients, M ± SD

Group	VAS (score)	
	Day 1	Day 2
I	3.72 ± 1.06	2.92 ± 1.28
II	5.11 ± 0.90 *	3.5 ± 0.86

Note: * p < 0.001 — differences in pain syndrome scores between Group I and Group II on the first postoperative day.

Table 5

Study of differences in recovery time of spontaneous breathing and extubation in patients

Group	Spontaneous breathing recovery, min	Extubation, min
I	10.36 ± 1.95	19.08 ± 2.87 *
II	9.03 ± 1.86	15.30 ± 2.55

Note: * p < 0.001 - differences in extubation time between groups.

operative recovery quality after shoulder surgery under general anesthesia. Our findings showed that with deeper sedation (BIS 40–48), as compared to superficial sedation (BIS 49–57), there were no significant changes in hemodynamic parameters, which is particularly important for surgeries in the SSP. Patients with deeper sedation reported less intense pain and fewer episodes of nausea and vomiting.

In studies by Y. Gu et al., postoperative nausea and vomiting were analyzed, and it was found that in the group where BIS monitoring was used during anesthesia (1,556 patients), there was no reduction in the incidence of postoperative nausea and vomiting compared to the group where standard clinical monitoring was used (1,645 patients) [11]. Similarly, in a study of 247 patients by J.L. Vance et al., no statistical differences were found between the depth of anesthesia under BIS control, the length of stay in the intensive care unit, or the overall duration of hospitalization [12]. A recent meta-analysis of 26 randomized controlled trials, involving 10,743 patients, showed that based on depth of anesthesia monitoring, deeper sedation was associated with lower pain scores during the first hour after surgery, but with a higher incidence of postoperative delirium [13]. Another meta-analysis of 15 studies with 5,392 participants demonstrated that aiming for a relatively high BIS level was associated with a reduction in postoperative dementia and cognitive dysfunction, but no significant differences were found in terms of hospital length of stay or mortality [14].

In a study involving 50 patients aged 18–60 years, it was found that BIS-guided anesthesia promotes earlier extubation and reduces the consumption of anesthetics [15].

Conclusions

Comparison of deeper anesthesia (BIS 49–57) with more superficial anesthesia (BIS 40–48) in patients undergoing shoulder joint surgery in the SSP showed that the former is associated with less postoperative pain and a lower frequency of PONV, without leading to significant changes in intraoperative hemodynamics, which is especially important for surgeries performed in the SSP.

The level of anesthesia depth based on BIS parameters does not affect the detection of cognitive disorders in the early postoperative period.

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

Prospects for Future Research. The obtained data allow for the optimization of anesthesiological management of patients under BIS monitoring, contributing to the reduction of complication rates.

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References

1. Froese, L., Dian, J., Gomez, A., Batson, C., Sainbhi, A. S., & Zeiler, F. A. (2021). Association between processed electroencephalogram-based objectively measured depth of sedation and cerebrovascular response: a systematic scoping overview of the human and animal literature. *Frontiers in neurology*, 12, 692207. https://doi.org/10.3389/fneur.2021.692207
2. Himalaya Dutta, Suchismita Mallick, Baisakhi Laha, Sarbari Swaika, Uday Sankar Mandal, & Sarmila Ghosh. (2024). Monitoring of general anesthesia by qCON and qNOX indices versus conventional clinical parameters in urological surgery: A randomized controlled clinical trial. *Asian journal of medical sciences, 15*(3), 20–25. https://doi.org/10.3126/ajms.v15i3.59955
3. Feldheiser, A., Aziz, O., Baldini, G., Cox, B. P., Fearon, K. C., Feldman, L. S., Gan, T. J., Kennedy, R. H., Ljungqvist, O., Lobo, D. N., Miller, T., Radtke, F. F., Ruiz Garces, T., Schrick-

er, T., Scott, M. J., Thacker, J. K., Ytrebø, L. M., & Carli, F. (2016). Enhanced Recovery After Surgery (ERAS) for gastrointestinal surgery, part 2: consensus statement for anaesthesia practice. *Acta anaesthesiologica Scandinavica, 60*(3), 289–334. https://doi.org/10.1111/aas.12651

4. Short, T. G., Campbell, D., Frampton, C., Chan, M. T. V., Myles, P. S., Corcoran, T. B., Sessler, D. I., Mills, G. H., Cata, J. P., Painter, T., Byrne, K., Han, R., Chu, M. H. M., McAllister, D. J., Leslie, K., Australian and New Zealand College of Anaesthetists Clinical Trials Network, & Balanced Anaesthesia Study Group (2019). Anaesthetic depth and complications after major surgery: an international, randomised controlled trial. *Lancet, 394*(10212), 1907–1914. https://doi.org/10.1016/S0140-6736(19)32315-3
5. Lee, S. W., Choi, S. E., Han, J. H., Park, S. W., Kang, W. J., & Choi, Y. K. (2014). Effect of beach chair position on bispectral index values during arthroscopic shoulder surgery. *Korean journal of anesthesiology, 67*(4), 235–239. https://doi.org/10.4097/kjae.2014.67.4.235
6. Kwon, Y. S., Choi, J. W., Lee, H. S., Kim, J. H., Kim, Y., & Lee, J. J. (2020). Effect of a preoperative proton pump inhibitor and gastroesophageal reflux disease on postoperative nausea and vomiting. *Journal of clinical medicine, 9*(3), 825. https://doi.org/10.3390/jcm9030825
7. Lyzogub, K., & Lyzogub, M. (2025). The impact of preoperative volume overload on hemodynamic parameters during shoulder arthroscopy. *Orthopaedics traumatology and prosthetics,* (1), 45–49. https://doi.org/10.15674/0030-59872025145-49
8. Gan, T. J., Belani, K. G., Bergese, S., Chung, F., Diemunsch, P., Habib, A. S., Jin, Z., Kovac, A. L., Meyer, T. A., Urman, R. D., Apfel, C. C., Ayad, S., Beagley, L., Candiotti, K., Englesakis, M., Hedrick, T. L., Kranke, P., Lee, S., Lipman, D., Minkowitz, H. S., … Philip, B. K. (2020). Fourth consensus guidelines for the management of postoperative nausea and vomiting. *Anesthesia and analgesia, 131*(2), 411–448. https://doi.org/10.1213/ANE.0000000000004833.
9. Ferreira, A. L., Mendes, J. G., Nunes, C. S., & Amorim, P. (2019). Avaliação do tempo de atraso do índice bispectral na resposta à indução da anestesia: estudo observacional [Evaluation of Bispectral Index time delay in response to anesthesia induction: an observational study]. *Brazilian journal of anesthesiology (Elsevier), 69*(4), 377–382. https://doi.org/10.1016/j.bjan.2019.03.008
10. Deng, R. M., Liu, Y. C., Li, J. Q., Xu, J. G., & Chen, G. (2020). The role of carbon dioxide in acute brain injury. *Medical gas research, 10*(2), 81–84. https://doi.org/10.4103/2045-9912.285561
11. Gu, Y., Hao, J., Wang, J., Liang, P., Peng, X., Qin, X., Zhang, Y., & He, D. (2024). Effectiveness Assessment of Bispectral Index Monitoring Compared with Conventional Monitoring in General Anesthesia: A Systematic Review and Meta-Analysis. Anesthesiology research and practice, 2024, 5555481. https://doi.org/10.1155/2024/5555481
12. Vance, J. L., Shanks, A. M., & Woodrum, D. T. (2014). Intraoperative bispectral index monitoring and time to extubation after cardiac surgery: secondary analysis of a randomized controlled trial. *BMC anesthesiology,* 14, 79. https://doi.org/10.1186/1471-2253-14-79
13. Long, Y., Feng, X., Liu, H., Shan, X., Ji, F., & Peng, K. (2022). Effects of anesthetic depth on postoperative pain and delirium: A meta-analysis of randomized controlled trials with trial sequential analysis. *Chinese medical journal, 135*(23), 2805–2814. https://doi.org/10.1097/cm9.0000000000002449
14. Ling, L., Yang, T. X., & Lee, S. W. (2022). Effect of anaesthesia depth on postoperative delirium and postoperative cognitive dysfunction in high-risk patients: A systematic review and meta-analysis. *Cureus.* https://doi.org/10.7759/cureus.30120
15. Sk, A., Kadlimatti, D. V., Kumar, S., Divya, P. S., & Ajith, M. (2025). Time required for extubation while using bispectral index monitoring compared to end-tidal anesthetic gas concentration in patients undergoing general anesthesia. *Cureus, 17*(6), e86742. https://doi.org/10.7759/cureus.86742

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THE EFFECT OF DEPTH OF ANESTHESIA ON THE INCIDENCE OF EARLY POSTOPERATIVE COMPLICATIONS DURING SURGERY IN THE BEACH CHAIR POSITION

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Results of surgical treatment of degenerative lumbar scoliosis in adults

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Degenerative lumbar scoliosis represents a significant medical and social issue, most frequently diagnosed in patients over 50 years of age. The condition may present as a primary deformity (scoliosis de novo) or as a progression of idiopathic scoliosis. Its clinical course varies from asymptomatic cases to severe pain syndromes, neurological deficits, and loss of trunk balance. Objective. To evaluate the outcomes of surgical treatment in patients with degenerative lumbar scoliosis and to assess the effectiveness of deformity correction and functional recovery. Methods. A retrospective analysis was conducted in 37 patients aged 48–73 years (mean age, 56.6 years). The assessment included clinical examination, radiographic parameters (Cobb angle, PI-LL, SVA, PT, Th1PA, L1PA), and Oswestry Disability Index and Visual Analog Scale (VAS) scores. All patients underwent transpedicular fixation with posterior column osteotomy; in some cases, spinal canal decompression was additionally performed. The mean length of instrumented fusion was 5.1 segments. Comorbidities and postoperative complications were also analyzed. Results. The mean Cobb angle decreased from 47.7° preoperatively to 20.7° at 3 months and 23.7° at 1 year. Sagittal and coronal balance parameters approached reference values, indicating the achievement of solid fusion. The Oswestry Disability Index improved from 52.1 % (severe disability) to 22.7 % (mild disability) at 1 year. VAS scores demonstrated a significant reduction in pain: from 67.2 mm (back) and 69.2 mm (leg) to 19.3 mm and 21.5 mm, respectively. Postoperative complications occurred in 48.6 % of patients, most commonly wound healing disorders and transient neurological deficits, but did not significantly affect final outcomes. Conclusions. Notably, substantial functional improvement was achieved only one year after surgery.

Дегенеративний поперековий сколіоз є актуальною медико-соціальною проблемою, яка найчастіше діагностується в пацієнтів старше 50 років. Захворювання проявляється як первинна деформація (scoliosis de novo) або як наслідок прогресування ідіопатичного сколіозу. Його перебіг може варіювати від безсимптомного до тяжких больових синдромів, неврологічних розладів і втрати балансу тулуба. Мета. Проаналізувати результати хірургічного лікування пацієнтів із дегенеративним поперековим сколіозом, оцінити ефективність корекції деформації та відновлення функціонального стану. Методи. Проведено ретроспективне дослідження результатів лікування 37 пацієнтів віком 48–73 роки (середній вік — 56,6). До аналізу включалися дані клінічного обстеження, рентгенометрії (кут Cobb, PI-LL, SVA, PT, T1PA, L1PA), шкал Oswestry та візуальної аналогової шкали (ВАШ). Усім хворим здійснено транспедикулярну фіксацію з остеотомією заднього опорного комплексу, у частини виконувалась декомпресія хребтового каналу. Середня довжина зони інструментального спондилодезу становила 5,1 сегмента. Також вивчалися супутні захворювання та частота післяопераційних ускладнень. Результати. До втручання середній кут Cobb складав 47,7°; через 3 місяці — 20,7°; рік — 23,7°. Показники сагітального та фронтального балансів наблизились до референтних значень, що підтверджує досягнення якісного спондилодезу. За шкалою Oswestry середнє значення знизилося з 52,1 % (значні порушення) до 22,7 % (легкі порушення) через рік. Відзначено істотне зменшення інтенсивності болю за ВАШ: з 67,2 («спина») та 69,2 мм («нога») до 19,3 і 21,5 мм відповідно. Післяопераційні ускладнення спостерігалися у 48,6 % пацієнтів, найчастіше — проблеми зі загоєнням рани та транзиторні неврологічні порушення. Проте вони не вплинули на кінцеві результати лікування. Висновки. Зафіксовано відчутне покращення функціонального стану пацієнтів, яке виявлено не раніше ніж через рік після операції. Досягнуто відновлення сагітального та фронтального балансів тулуба. Ключові слова. Дегенеративний сколіоз, хірургічне лікування, спондилодез, післяопераційні ускладнення.

Keywords. Degenerative scoliosis; surgical treatment; spinal fusion; postoperative complications. Restoration of sagittal and frontal balance of the trunk has been achieved

Introduction

Degenerative lumbar scoliosis typically develops in patients over 50 years of age as a primary condition (*scoliosis de novo*) or because of degenerative changes in the spine following pre-existing adolescent idiopathic scoliosis. The course of degenerative scoliosis can be asymptomatic or accompanied by severe pain, signs of neural compression, and disturbances in the frontal and sagittal balance of the spine.

The prevalence of scoliosis in the adult population, according to various studies, ranges from 2 % to 32 %; recent observations conducted among elderly volunteers have shown a prevalence of degenerative scoliosis ranging from 6 % to 68 % [1–3]. Due to the aging population and increasing attention to quality of life relative to the cost of medical care, degenerative scoliosis has become a significant healthcare issue — not only from a cosmetic standpoint but also as a major cause of significant pain and disability [4].

Most patients with degenerative scoliosis receive conservative treatment, while some with severe clinical symptoms require surgical intervention. The primary goal of such surgery is spinal decompression, achieving a stable bony block, and correcting frontal and sagittal torso shifts [5]. A retrospective analysis by the Scoliosis Research Society (SRS) reported that the incidence of surgical complications in degenerative scoliosis was 13.4 %, although other studies report figures as high as 40 %. The most common complications include damage to the dura mater, implant fractures, superficial and deep wound infections, and neurological deficits. Patients who are obese, smoke, have osteoporosis, or are over 65 years old are at increased risk. Proximal junctional kyphosis occurs in 20–40 % of patients and can manifest either early or late after surgery. The rate of reoperations varies from 16.7 % within the first 90 days to 40 % over a period of 11 years [6].

These findings lead many surgeons to reconsider the appropriateness of performing surgical interventions on patients in this category. Therefore, to change this mindset and reduce the incidence of complications during and after surgery, it is necessary to analyze the results of surgical treatment of degenerative lumbar scoliosis.

Objective: To study the outcomes of surgical treatment for patients with degenerative lumbar scoliosis.

Materials and Methods

A retrospective analysis was conducted on the results of surgical treatment of degenerative lumbar scoliosis in 37 patients (29 women, 8 men) aged 48–73 years (mean age 56.6). The study was approved by the expert committee of the Professor M. F. Rudnev Municipal Multidisciplinary Clinical Hospital for Mothers and Children (Protocol No. 1, dated 01.01.25). The research was carried out in accordance with the requirements and provisions of the Helsinki Declaration on Human Rights, the Council of Europe's Convention on Human Rights, the basic health care legislation of Ukraine, and current national ethical standards for clinical research. All participants provided written informed consent.

Inclusion Criteria: Patients with degenerative lumbar scoliosis, Lenke-Silva group II–III (Cobb > 45°, lateral shift 2 mm), available clinical and radiological data, no previous spinal surgeries, infections, trauma, or rheumatoid arthritis.

The following data were analyzed: presentation, radiometric study results such as Cobb angle of curvature, the difference between pelvic slip and lumbar lordosis (PI–LL), sagittal vertical axis (SVA), pelvic tilt (PT), T1PA and L1PA angles (Fig. 1a, b). For measuring the frontal and sagittal components of curvature, the reference values from the Schwab scoliosis classification [7] were chosen. Normal values for the T1PA and L1PA angles were taken from the studies by [8, 9].

Additionally, the types of surgical interventions performed were determined, including the average number of spinal segments fixed with transpedicular implants, the presence of comorbidities in patients, and postoperative complications. All patients were assessed using the Visual Analog Scale (VAS) for back pain and leg pain (“VAS back” and “VAS leg”), as well as the Oswestry Disability Index (ODI) before surgery, 3 months, and 1 year after surgery. According to the scale, 0–20 % indicated minimal, 21–40 % moderate, 41–60 % significant, 61–80 % severe, and 81–100 % substantial functional impairment. Bone block quality was assessed using radiological imaging and computed tomography.

Results

Table 1 presents the average results of radiometric measurements in the study group. From this table, we can observe that the preoperative Cobb angle was 47.7°, 3 months after surgery it was 20.7°, and 1 year later it was 23.7°. Similar changes were observed in other measurements. For example, the difference between PI and LL (PI–LL) was 17.3° preoperatively, 9.5° at 3 months, and 8.7° at 1 year. The SVA value changed from 54.5 mm preoperatively to 30.5 mm at 3 months and 32.1 mm at 1 year on average. Pelvic tilt (PT) was 29.5° preoperatively, 14.9° at 3 months, and 15.3° at 1 year. The T1PA and L1PA angles were 27.1°

and 15.5° preoperatively, 18.3° and 11° at 3 months, and 19.5° and 11.3° at 1 year after surgery.

Curve correction with indirect decompression of the spinal canal by changing its shape was performed in 11 patients, while 26 patients underwent direct decompression of the spinal canal. A wide decompression was performed in 7 patients, and a limited decompression through flavectomy, foraminotomy, and interlaminectomy was done in 19 patients. The average length of the instrumented spinal fusion zone was 5.1 segments (ranging from 3 to 10 segments). All patients underwent Smith-Peterson posterior column osteotomy at the apex of the deformity.

Table 2 presents the comorbidities identified in the study group. Most patients had hypertension (78 %) and decreased bone mineral density (54 %). If indicated, patients received preoperative treatment for comorbidities to reduce the number of postoperative complications.

The average Oswestry Disability Index score before surgery was 52.1 %, indicating a significant degree of functional impairment. Three months after surgery, the score decreased to 49.3 % (indicating significant impairment), and one year later, it dropped to 22.7 % (indicating mild impairment) (Fig. 1).

A similar trend was observed in the assessment of pain using the VAS (Fig. 2). The "VAS back" score was 67.2 mm preoperatively, 44.3 mm at 3 months after surgery, and 19.3 mm at 1 year, while the "VAS leg" score was 69.2 mm preoperatively, 39.7 mm at 3 months, and 21.5 mm at 1 year.

Table 3 presents the causes and frequency of complications, which occurred in 48.6 % of patients on average. The most common complications were poor wound healing (15 %) and transient neurological issues, including radiculopathy and lower limb paresis, which occurred in 11 % of patients in the study group.

Discussion

Surgical treatment of degenerative lumbar scoliosis in adult patients presents a significant challenge for surgeons, as the disease is multifaceted with a diverse clinical presentation and potential for unexpected outcomes, both for the patients and the medical professionals.

When developing a treatment plan, several factors need to be considered, such as comorbidities, the patient's social status, and lifestyle. Most patients become aware of their diagnosis through radiological imaging, and conservative treatments are often selected empirically by specialists of various profiles, including general practitioners, neurologists, and rehabilitation specialists [10].

Indications for surgical intervention in younger, more active adults differ from those in elderly patients with comorbidities. Therefore, there is no unified consensus regarding recommendations for performing various types of surgeries. However, it is widely acknowledged that the most common indications include ineffective conservative treatment, severe pain, neurological disorders, low quality of life, and, very rarely, cosmetic deformities [11]. Ultimately, the goal is decompression of neural structures with restoration of sagittal and frontal spinal balance [12]. Modern trends in surgery aim to reduce invasiveness to prevent potential intra- and postoperative complications.

In a systematic review and meta-analysis [13], the results of decompression without instrumental fixation in patients with degenerative lumbar scoliosis were evaluated. Fifteen studies with a minimum postoperative follow-up of 2 years were analyzed. The average improvement in the Oswestry index

Table 1

Average results of radiometric measurements in the study group

Indicator	Before surgical treatment	3 months after surgery	1 year after surgery
Cobb angle, °	47.7	20.7	23.7
PI–LL, °	17.3	9.5	8.7
SVA, mm	54.5	30.5	32.1
PT, °	29.5	14.9	15.3
T1PA, °	27.1	18.3	19.5
L1PA, °	15.5	11.0	11.3

Table 2

Concomitant diseases in patients

Disease	Patient	Percentage
Diabetes	6	15
Hypertension	29	78
Myocardial ischemia	15	40
Osteoporosis	20	54
Chronic kidney diseases	3	8

Table 3

Incidence of complications in patients

Complication	Patient	Percentage
Wound healing	6	15.0
Neurological disorders	4	11.0
Intraoperative bleeding	1	2.7
Comorbidities	2	5.9
Pseudoarthrosis	3	8.1
Infection	2	5.9

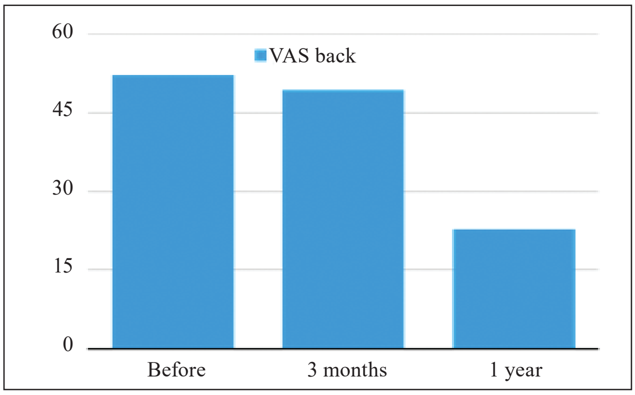

Fig. 1. Diagram of changes in Oswestry scale scores before, 3 months, and 1 year after surgical intervention

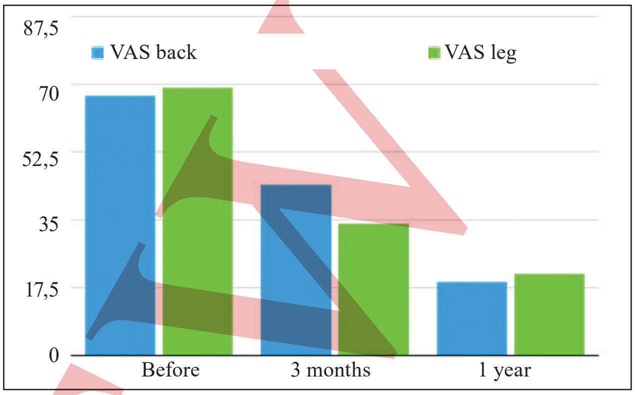

Fig. 2. Diagram of changes in “VAS back” and “VAS leg” scale scores before, 3 months, and 1 year after surgical intervention

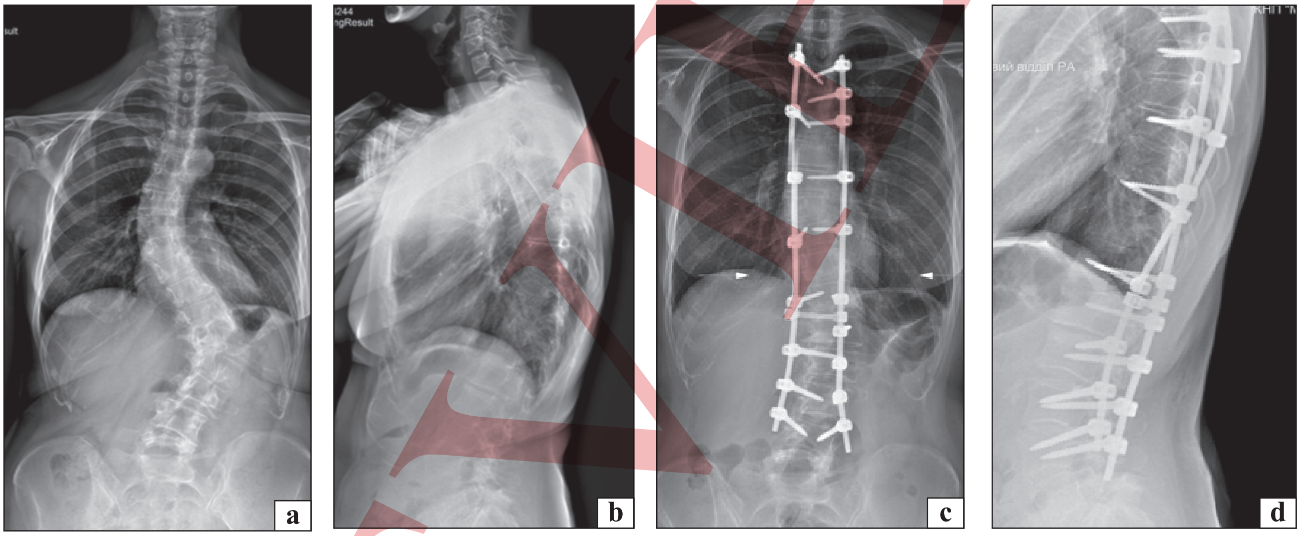

Fig. 3. X-rays of a 60-year-old patient with combined scoliosis in the anterior-posterior (a, b) and lateral (b, g) projections before and after surgical intervention. Thoracic Cobb angle before surgery — 45º, after — 23º. Lumbar Cobb angle before surgery — 56º, after — 30º. Thoracic kyphosis before surgery — 45º, after — 31º. Lumbar lordosis — 62º before and after PI value — 54º

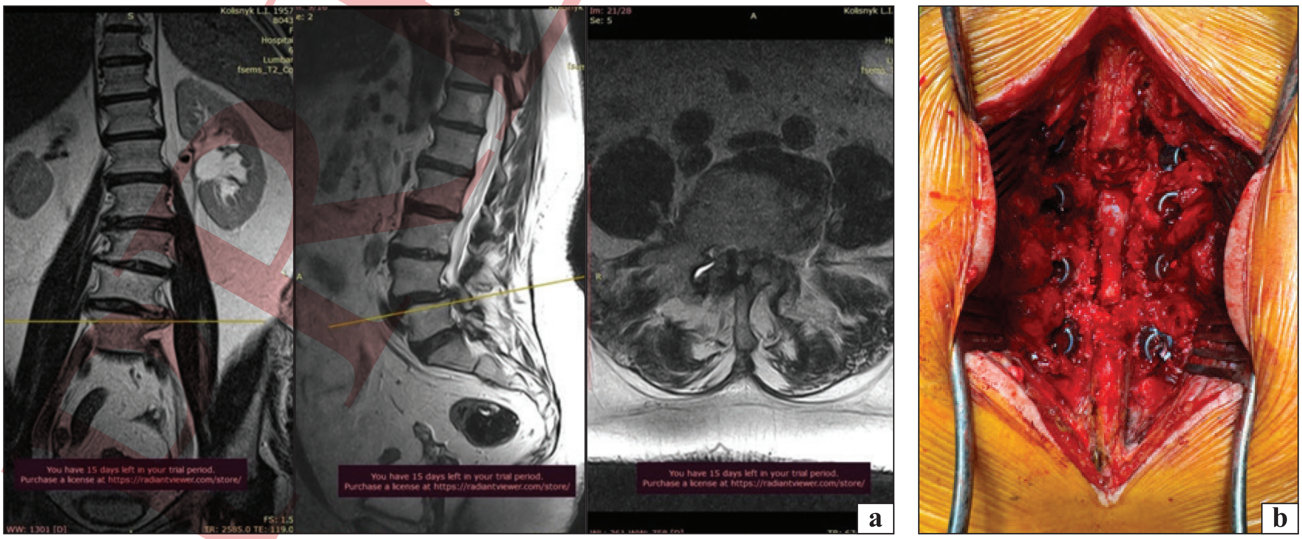

Fig. 4. Magnetic resonance imaging of the lumbar spine (a) in frontal, lateral, and axial projections of a patient with degenerative lumbar scoliosis at the LIV, LV levels, and the appearance of the surgical wound (b) after decompression of the spinal canal and fixation with pedicle screws.

was around 29 %, patient satisfaction was 71 %, and the progression of the Cobb angle was minimal (1.8°). The frequency of reoperations ranged from 3 % to 33 %. The results suggest that decompression without fixation is an effective and relatively safe method for carefully selected patients with small scoliosis angles and no significant instability. The authors emphasize the limited available data and the need for further high-quality prospective studies. However, it should be noted that this approach will not be effective in patients with unstable, progressive spinal deformities.

M. Echt and colleagues conducted a study comparing clinical outcomes and perioperative morbidity in patients with adult degenerative lumbar scoliosis who underwent minimally invasive decompression or short-segment spinal fixation. In a retrospective analysis using paired matching and probability scoring, 31 pairs of patients were formed. The results showed that minimally invasive decompression was associated with shorter operation and hospitalization times and less blood loss, while short-segment spinal fixation provided significant improvements in the Oswestry index and mental health, as well as a reduction in back pain one year after surgery. The time to reach the minimal clinically significant difference was similar in both groups. These findings suggest the need for an individualized approach when choosing a surgical strategy, balancing perioperative morbidity with clinical improvement through stabilization of spinal segments with implants.

A systematic review and meta-analysis by B. Zheng compared the effectiveness and safety of long versus short spinal fixation in patients with degenerative lumbar scoliosis. Thirteen studies with a total of 1,261 patients were analyzed. Long fixation provided better correction of the Cobb angle and both coronal and sagittal balance, but was associated with greater blood loss, longer surgery duration, and higher complication rates. Short fixation had less surgical invasiveness, while clinical outcomes (VAS, Oswestry scale) and the frequency of reoperations were similar in both groups. Thus, it is important to tailor the choice of fixation length to the degree of spinal deformity and the clinical condition of the patient [15].

This ongoing debate over the type and extent of surgical interventions reinforces the importance of individualized treatment plans. Each case of degenerative lumbar scoliosis must be approached carefully, considering not only the severity of the spinal deformity but also the patient's overall health, lifestyle, and the presence of comorbid conditions. By optimizing the approach to surgery, outcomes can be improved, complications minimized, and patients can enjoy a better quality of life postoperatively.

The study conducted by N. Fan and colleagues evaluated the clinical and radiological outcomes of endoscopic decompression for the treatment of lumbar spinal stenosis in patients with degenerative lumbar scoliosis. A retrospective study analyzed 97 patients with both lumbar stenosis and degenerative lumbar scoliosis, who underwent surgery between 2016 and 2021, with an average follow-up of 52.9 months. A control group of 97 patients with lumbar stenosis but without deformity was also included. The results demonstrated significant improvement in VAS scores for back and leg pain, as well as ODI scores in both groups, measured 2 weeks post-surgery and at the final follow-up ($p < 0.001$). There were no significant differences in the complication rates or patient satisfaction levels between the groups. However, patients with scoliosis reported more intense back pain at the final follow-up compared to those without the deformity. Radiological data showed no significant deterioration in frontal imbalance or intervertebral disc height in either group. The authors concluded that endoscopic decompression is a safe and effective surgical technique for treating lumbar spinal stenosis, particularly in elderly patients with poor overall health [16]. However, the presence of axial pain in the spine may indicate the need for spinal instrumentation.

In a systematic review published in the Global Spine Journal, the authors also examined the role of short-segment versus long-segment spinal fixation in the surgical treatment of adult scoliosis. Nine studies involving 660 patients who underwent either short-segment (less than 3 levels) or long-segment (more than 4 levels) fixation were analyzed. The findings revealed that short-segment fixations provide similar clinical outcomes with fewer perioperative risks and shorter operation times compared to long-segment fixations. However, for patients with severe deformities and sagittal or frontal imbalance, long-segment fixations were recommended. The authors emphasized the need for an individualized approach when selecting the extent of spinal fixation based on clinical and radiological parameters [17].

In our study, we analyzed the outcomes of surgical treatment in patients with unstable forms of degenerative lumbar scoliosis (Lenke-Silva II and III deformities) who underwent spinal fixation with transpedicular implants. In all cases, the goal was to restore trunk balance in all planes, decompress neural structures, and achieve a mature bony fusion. Through corrective spinal procedures (Smith-Peterson osteotomy), we were able to correct the frontal imbalance by approximately 56.6 % and bring both global and regional sagittal spinal balance closer to normative values (Figure 3). Neurological improvement and regression of deficits were achieved through both indirect (spinal shape and spinal canal correction) and direct decompression (laminectomy) (Figure 4). The absence of significant changes in radiometric measurements one year post-surgery, along with no instances of implant fractures, indicates successful spinal fusion in all patients in the study group.

The postoperative complication rate (48.6 %), considering the nature of the disease and the invasiveness of the surgical interventions, was acceptable and did not adversely affect the final treatment outcome for all patients.

This analysis reinforces the importance of careful patient selection, individualized surgical planning, and the choice of appropriate surgical techniques. In patients with degenerative lumbar scoliosis and associated deformities, achieving optimal spinal balance and neural decompression while minimizing complications remains the primary goal for successful surgical management.

The observation of the dynamics of changes in the Oswestry Disability Index, Visual Analog Scale for Back Pain, and Visual Analog Scale for Leg Pain is particularly interesting. This study showed that patients with degenerative lumbar scoliosis do not experience significant improvement within 3 months post-treatment, but a substantial reduction in pain syndrome, clinical manifestations, and functional improvements is achieved after one year following the treatment.

Conclusions

Surgical treatment of degenerative lumbar scoliosis enables the restoration of both sagittal and frontal balance of the trunk, improving the clinical symptoms of the disease and the quality of life of patients.

The rate of postoperative complications in the surgical treatment of degenerative lumbar scoliosis in our study was acceptable, but remains relatively high. Therefore, improving the patient's somatic condition before the surgical intervention can help prevent unsatisfactory outcomes.

The reduction of pain and the improvement of functional status in patients are achieved one year after surgery. This should be communicated to the patients during preoperative planning and preparation stages.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Future Research Prospects. Conducting prospective comparative studies of short-segment and long-segment fixation for degenerative lumbar scoliosis in adults.

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References

1. Aebi, M. (2005). The adult scoliosis. *European spine journal, 14*(10), 925–948. https://doi.org/10.1007/s00586-005-1053-9
2. Anasetti, F., Galbusera, F., Aziz, H. N., Bellini, C. M., Addis, A., Villa, T., Teli, M., Lovi, A., & Brayda-Bruno, M. (2010). Spine stability after implantation of an interspinous device: An in vitro and finite element biomechanical study. *Journal of neurosurgery: spine, 13*(5), 568–575. https://doi.org/10.3171/2010.6.spine09885
3. Vanderpool, D. W., James, J. I., & Wynne-Davies, R. (1969). Scoliosis in the elderly. *The journal of bone & joint surgery, 51*(3), 446–455. https://doi.org/10.2106/00004623-196951030-00002
4. Chang, D., Lui, A., Matsoyan, A., Safaee, M. M., Aryan, H., & Ames, C. (2024). Comparative review of the socioeconomic burden of lower back pain in the United States and globally. *Neurospine, 21*(2), 487–501. https://doi.org/10.14245/ns.2448372.186
5. Zheng, B., Zhou, Q., Liu, X., & Qiang, Z. (2025). Efficacy and safety of long fusion versus short fusion in degenerative scoliosis: A systematic review and meta-analysis. *Journal of orthopaedic surgery and research, 20*(1). https://doi.org/10.1186/s13018-025-05466-z
6. Cristante, A. F., Silva, R. T., Costa, G. H., & Marcon, R. M. (2020). Escoliose degenerativa do adulto. *Revista brasileira de ortopedia, 56*(01), 001–008. https://doi.org/10.1055/s-0040-1709736
7. Patel, R. V., Yearley, A. G., Isaac, H., Chalif, E. J., Chalif, J. I., & Zaidi, H. A. (2023). Advances and evolving challenges in spinal deformity surgery. *Journal of clinical medicine, 12*(19), 6386. https://doi.org/10.3390/jcm12196386
8. Fisher, M. R., Das, A., Yung, A., Onafowokan, O. O., Williamson, T. K., Rocos, B., Schoenfeld, A. J., & Passias, P. G. (2025). An analysis of the usage and limitations of the T1 pelvic angle. *The bone & joint journal, 107-B*(3), 346–352. https://doi.org/10.1302/0301-620x.107b3.bjj-2024-0800.r2
9. Chanbour, H., Waddell, W. H., Vickery, J., LaBarge, M. E., Croft, A. J., Longo, M., Roth, S. G., Hills, J. M., Abtahi, A. M., Zuckerman, S. L., & Stephens, B. F. (2023). L1-pelvic angle: A convenient measurement to attain optimal deformity correction. *European spine journal, 32*(11), 4003–4011. https://doi.org/10.1007/s00586-023-07920-0
10. Bayram, F., Karatekin, B. D., Erhan, B., Pasin, O., & Yumusakhuylu, Y. (2024). Conservative treatment in adult degenerative scoliosis: A prospective cohort study. *Maedica — a journal of clinical medicine, 1*(1). https://doi.org/10.26574/maedica.2024.19.1.23
11. Abul, K. (2019). Decision making for surgery in adult scoliosis review of the current literature. *Journal of turkish spinal surgery, 30*(4), 276–283. https://doi.org/10.4274/jtss.galenos.2019.0012
12. Wang, H., Liu, X., Li, Y., Ren, J., Sun, Z., Sun, N., & Li, R. (2024). The selection of a surgical strategy for the treatment of adult degenerative scoliosis with "pear-shaped" decompression under open spinal endoscopy. *Scientific reports, 14*(1).

https://doi.org/10.1038/s41598-024-67003-y
13. Echt, M., De la Garza Ramos, R., Geng, E., Isleem, U., Schwarz, J., Girdler, S., Platt, A., Bakare, A. A., Fessler, R. G., & Cho, S. K. (2022). Decompression alone in the setting of adult degenerative lumbar scoliosis and stenosis: A systematic review and meta-analysis. *Global Spine Journal, 13*(3), 861–872. https://doi.org/10.1177/21925682221127955
14. Echt, M., Bakare, A. A., Varela, J. R., Platt, A., Abdul Sami, M., Molenda, J., Kerolus, M., & Fessler, R. G. (2023). Comparison of minimally invasive decompression alone versus minimally invasive short-segment fusion in the setting of adult degenerative lumbar scoliosis: A propensity score–matched analysis. *Journal of neurosurgery: spine, 39*(3), 394–403. https://doi.org/10.3171/2023.4.spine221047
15. Zheng, B., Zhou, Q., Liu, X., & Qiang, Z. (2025). Efficacy and safety of long fusion versus short fusion in degenerative scoliosis: A systematic review and meta-analysis. *Journal of orthopaedic surgery and research, 20*(1). https://doi.org/10.1186/s13018-025-05466-z
16. Fan, N., Wang, A., Yuan, S., Du, P., Wang, T., & Zang, L. (2025). Clinical and radiological outcomes of lumbar endoscopic decompression for treating lumbar spinal stenosis and degenerative lumbar scoliosis: A retrospective study at mean 4.4 years follow-up. *Frontiers in surgery*, 11. https://doi.org/10.3389/fsurg.2024.1525843
17. Sardi, J. P., Lazaro, B., Buell, T. J., Yen, C. P., Shaffrey, C., Berven, S., & Smith, J. S. (2025). Determining the magnitude of surgery in patients with adult scoliosis: A systematic review of the role of limited fusions. *Global spine journal, 15*(3_suppl). https://doi.org/10.1177/21925682231203656

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RESULTS OF SURGICAL TREATMENT OF DEGENERATIVE LUMBAR SCOLIOSIS IN ADULTS

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Degenerative changes in rat ankle cartilage induced by varus extra-articular femoral deformation

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Objective. To evaluate the structure of ankle joint articular cartilage in rats following experimentally induced deformation of the middle third of the femur over a six-month observation period. Methods. An experimental study was conducted on 18 six-month-old male rats divided into two groups. In the experimental group, extra-articular femoral deformation was modeled by inserting a Kirschner wire fragment bent at a 35° angle into the medullary cavity; the control group remained intact. Animals were evaluated at 1, 3, and 6 months. Structural changes in the articular cartilage were assessed using the Osteoarthritis Research Society International (OARSI) scale, and the height of the articular cartilage of the ankle joint was measured. Results. At 1 month, structural changes were observed only in the talar cartilage, corresponding to OARSI grades 0–1. At 3 months, changes in the tibial cartilage corresponded to grades 1–2, in the talar cartilage to grades 1–3, and in the contralateral limb to grades 0–1 for both surfaces. At 6 months, tibial cartilage changes reached grade 2, talar cartilage grade 2–3, and the contralateral limb grade 1–2. Cartilage height in rats with deformity decreased 1.2-fold from the 3rd month (p < 0.001) and did not differ from the contralateral limb at 6 months. Compared with intact rats, talar and tibial cartilage height in rats with deformity also decreased from the 3rd month by 1.4-fold (p < 0.001) and 1.1-fold (p = 0.022), respectively. Conclusions. Extra-articular deformation of the middle third of the femur induces degenerative changes in talar articular cartilage beginning at 1 month, and in tibial cartilage from 3 months after modeling.

Мета. Дослідити структуру суглобового хряща надп'ятково-гомілкового суглоба після моделювання деформації середньої третини стегнової кістки в щурів протягом півроку спостереження. Методи. Експериментальне дослідження проведено на 18 щурах самцях віком 6 міс. у двох групах: перша — моделювали позасуглобову деформацію стегнової кістки шляхом введення в кістково-мозковий канал фрагмента спиці Кіршнера, вигнутого під кутом 35°, друга — інтакт. Спостереження тривало 1, 3 та 6 міс. Оцінювали структурні зміни за шкалою Osteoarthritis Research Society International (OARSI) та вимірювали висоту в суглобовому хрящі надп'ятково-гомілкового суглоба. Результати. Через місяць у щурів із деформацією стегнової кістки виявлено структурні зміни лише в суглобовому хрящі надп'яткової кістки, що відповідали 0–1 ступеням за шкалою OARSI. Через 3 міс. зміни в суглобовому хрящі великогомілкової кістки відповідали 1–2, надп'яткової — 1–3, а у контралатеральній кінцівці для обох поверхонь — 0–1 ступеням за шкалою OARSI. Через 6 міс. структурні зміни в суглобовому хрящі великогомілкової кістки оцінили як 2, надп'яткової кістки — 2–3, а у контралатеральній кінцівці — 1–2 ступені за шкалою OARSI. Висота суглобового хряща обох суглобових поверхонь у щурів із деформацією знизилася з 3-го місяця в 1,2 рази і не відрізнялася через 6 міс. (p = 0,105) як порівняти з контралатеральною кінцівкою. Висота суглобового хряща обох суглобових поверхонь у щурів із деформацією знизилася з 3-го місяця в 1,2 рази (p < 0,001) і не відрізнялася через 6 міс. у порівнянні з контралатеральною кінцівкою. Порівняно з інтактом висота суглобового хряща надп'яткової та великогомілкової кісток у щурів із деформацією також знизилася з 3-го місяця в 1,4 рази (p < 0,001) та 1,1 рази (p = 0,022) відповідно. Висновки. Змодельована позасуглобова деформація середньої третини стегнової кістки щурів викликає дегенеративні зміни в суглобовому хрящі надп'яткової кістки з першого місяця, а з третього — великогомілкової кістки в надп'ятково-гомілковому суглобі. Ключові слова. Надп'ятково-гомілковий суглоб, суглобовий хрящ, дегенерація, деформація стегнової кістки, варусна деформація, щур.

Key words. Ankle joint, Articular cartilage, Degeneration, Femoral deformity, Varus deformity, Rat model

Introduction

According to various authors, the incidence of femoral shaft fractures at the level of the middle third is approximately 10–37 cases per 100,000 population, with two age peaks (youth and elderly) [1, 2]. It has been reported that the development of post-traumatic deformities ranges from 6 to 13 % [3, 4], though this is more common when the fracture is located at the distal or proximal third of the femur [5].

Femoral shaft fractures can be associated with complications such as nonunion [6], malrotation [7], and further deformity. These complications are characterized by impaired functioning of the entire lower limb and the development of degenerative changes in the knee and hip joints as a result [8, 9]. However, a 22-year follow-up of 62 patients with post-traumatic deformities and axial alignment disturbances due to femoral shaft fractures revealed no signs of osteoarthritis in the knee joint, though mild pain was present [10].

Typically, the treatment for femoral shaft fractures is surgical, often involving the use of an intramedullary nail for fixation [11]. However, according to a Cochrane review, the use of retrograde intramedullary nails increases the risk of valgus/varus deformities in the future [12]. At the same time, it has been shown that individuals with rotational malalignment of fragments with an angle < 10° after fracture treatment can adapt to this condition and remain pain-free [13], though the chances are low if the angle of deformity exceeds 30° [7]. It has also been found that patients with similar malalignment report pain in the knee, hip, and patellofemoral joints [14, 15]. Furthermore, there is still controversy regarding whether external or internal rotational deformities cause more complications. Two clinical studies [13, 14] suggest that external rotational deformity is better tolerated, while R. L. Jaarsma et al. [16] reported a higher number of complaints from patients with this type of deformity.

Thus, most modern studies focus on rotational post-traumatic deformities of the femur rather than axial ones. This is due to differences in treatment approaches between developed countries and Ukraine. In these countries, intramedullary fixation of the femoral shaft fragments is the standard for final fixation, while in Ukraine, this is mostly done with extramedullary osteosynthesis and external fixation devices. The widespread use of the latter is explained by the specifics of treating combat-related injuries. At the same time, the widespread use of intramedullary fixation, as noted by B. Cunningham et al. [17], has significantly reduced the frequency and significance of post-traumatic deformities of the femur with axial alignment disturbances.

Displacement of the physiological axis of the lower limb due to femoral bone deformity alters the distribution of load not only on the knee joint but possibly also on the ankle joint. However, secondary osteoarthritis of the ankle joint has received little attention in both clinical [18] and experimental studies [19]. Some studies have examined the development of osteoarthritis of the ankle joint due to fractures of the calcaneus [20] and have created an experimental model based on intra-articular fractures of bones [21]. However, the possibility of complications from higher-placed fractures remains unclear. Experimentally, it has been established that non-physiological loading of the articular cartilage can lead to chondrocyte deformation [22], alter the content of proteoglycans in the cartilage matrix depending on the area of load [22], and cause microfractures under low cyclic loading [23].

Objective: To investigate the structure of the articular cartilage of the ankle joint after modeling a deformity of the femoral shaft in rats over a six-month follow-up period.

Methods

Experiments were conducted on 18 male white laboratory rats (6 months old at the start of the study), purchased from the Experimental Biology Clinic of the State Institution Professor M.I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine. The study protocol was approved by the local bioethics committee (No. 117 dated 22.04.2013), in accordance with the rules of the "European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes" and the Law of Ukraine on the Protection of Animals from Cruelty [24, 25].

Surgical Intervention

The rats were operated on under general anesthesia (ketamine, 50 mg/kg intramuscularly) in aseptic and antiseptic conditions (Fig. 1). After preparing the surgical site with Betadine® solution, the skin was incised, and a lateral intermuscular approach was used to expose the middle third of the femoral diaphysis (Fig. 1a). A transverse osteotomy was performed using a disc saw (Fig. 1b). To model a varus deformity (9 rats), a Kirschner wire fragment was inserted into the bone marrow canal (Fig. 1g), matching its dimensions and length, and bent at an angle of 35° (Fig. 1d) [26]. A comparison group consisted of 9 intact rats of the same age and sex. After 1, 3, and 6 months post-surgery, 5 animals from each group were euthanized using a lethal dose of anesthetic (sodium thiopental, 90 mg/kg intramuscularly).

All rats underwent radiographic examination immediately after surgery (Fig. 2a).

Histological Analysis

After euthanasia, the ankle joints from both hind limbs of the rats were harvested. The fragments were fixed for 4 days in a 10 % neutral formalin solution, then decalcified in 10 % formic acid, dehydrated through a series of increasing concentrations of isopropyl alcohol (80, 90, 90, 100, 100, 100 %), infiltrated with a mixture of paraffin and isopropyl alcohol, followed by paraffin embedding. Sagittal sections, taken through the central axis of the limb, were 5–6 µm thick and stained with hematoxylin and eosin. The histological sections were analyzed using a BX53 microscope and photographed using a DP73 camera.

Structural changes in the articular cartilage covering the articular surfaces of the tibia and talus were assessed according to the general guidelines for determining cartilage damage stages, developed by the Osteoarthritis Research Society International (OARSI) for rats. A grade of 0 indicates normal cartilage, while 5 represents severe degenerative changes [27].

The total thickness of the articular cartilage (both calcified and non-calcified) on the distal end of the tibia and the proximal end of the talus was measured (Fig. 2b) using the “CellSens Dimension 1.8.1” software.

Statistical Methods

Results are presented as the mean ± standard deviation. To determine the effect of femoral shaft deformity on cartilage thickness, data comparisons were made using the Student’s t-test. Comparisons between the deformed limb and contralateral limb were also conducted using the paired samples t-test. A difference was considered statistically significant if $p < 0.05$. Statistical analysis was performed using IBM SPSS Statistics 20.

Results

Histological Analysis

One month after modeling the femoral deformity, the articular surfaces in the ankle joint were congruent. The structure of the articular cartilage of the tibia corresponded to the age norm, with clear zonality. In the superficial zone, chondrocytes formed 1–2 layers in a weakly eosinophilic matrix. In the middle zone, chondrocytes with large hypochromic nuclei were evenly distributed, forming isogenic groups of 2–3 cells. The matrix was evenly stained. The basophilic line was observed across the entire surface of the articular cartilage. The calcified cartilage zone maintained a characteristic normal structure (Fig. 3a).

In the articular cartilage covering the lateral side of the talus, moderate destructive changes were detected, corresponding to grade 0–1 on the OARSI scale. Specifically, irregularities in the contours of the superficial zone were noted. At the boundary between the middle zone and the calcified cartilage, isogenic groups of 4 chondrocytes were observed (Fig. 3b). Additionally, areas without chondrocytes were noted. The matrix showed uneven staining. No structural changes were found in the articular cartilage of the contralateral ankle joint.

Three months after modeling the deformity, degenerative changes were observed in the articular cartilage of the distal end of the tibia, corresponding to 1–2 degrees on the OARSI scale. The superficial zone showed loosening, and the matrix staining was uneven. In the middle zone, some chondrocyte nuclei were hyperchromatic, and there were focal areas of matrix destruction with collagen fibers being unmasked. The basophilic line was interrupted, but the calcified cartilage zone retained its characteristic features (Fig. 4a).

In the contralateral limb, structural changes were found only in the superficial zone (Fig. 4b), corresponding to grades 0–1 on the OARSI scale.

In the articular cartilage of the talus on the deformed limb, the matrix showed uneven staining, and dead chondrocytes were present in the superficial zone. In the middle zone, chondrocytes were necrotic and had low density. The basophilic line was irregular, and in the calcified cartilage zone, focal areas of bone tissue were formed, occasionally extending to the basophilic line (Fig. 4g). Degenerative changes were graded as 1–3, while in the contralateral limb's articular cartilage, they were grade 0–1. In the contralateral limb, chondrocytes in the middle zone were disorganized, and the basophilic line was uneven (Fig. 4d).

Six months after creating the deformity, the superficial zone in the articular cartilage of the distal end of the tibia was no longer visible, and the middle zone (Fig. 5a) was significantly narrower compared to the contralateral limb (Fig. 5b) and intact limb (Fig. 5c). In this zone, the matrix was unevenly stained, and the acellular areas occupied a larger area than at the previous time point. The basophilic line was intermittently absent, and the calcified cartilage zone had widened nearly twice as much as the middle zone (Fig. 5a).

In the contralateral limb, acellular areas were detected in the middle zone, and the calcified carti-

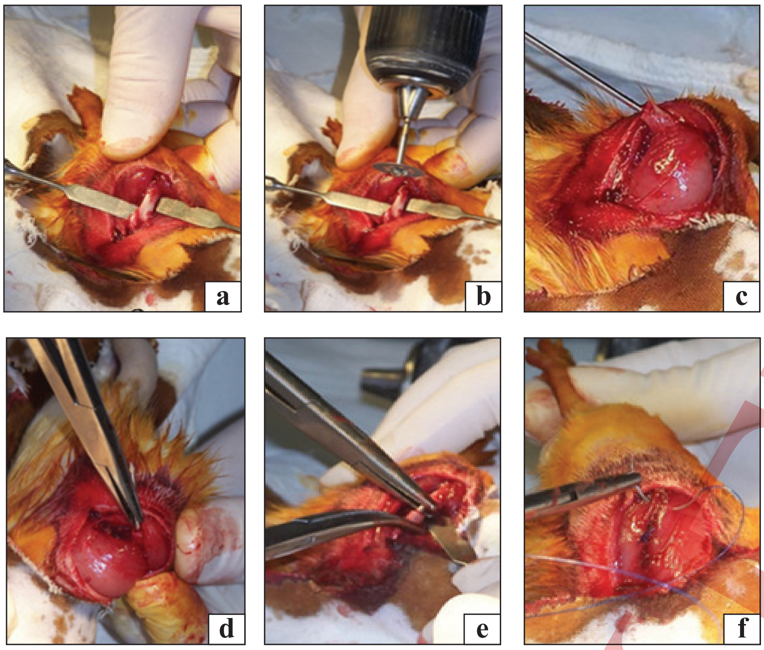

Fig. 1. Stages of performing the surgical procedure for modeling femoral deformity in rats. The middle third of the diaphysis of the bone (a); transverse osteotomy (b); insertion of a Kirschner pin fragment into the bone marrow canal (c); bending the Kirschner pin at a 35° angle (d); applying sutures (e).

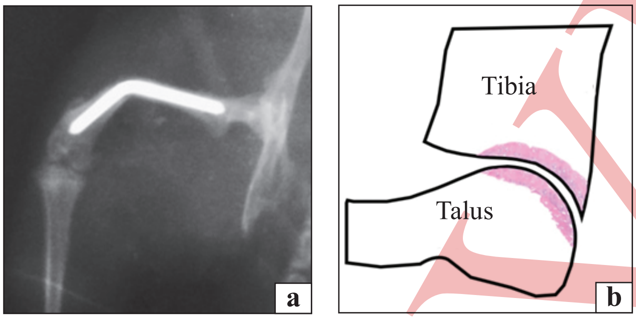

Fig. 2. Radiographic image of a rat with a limb with a modeled femoral deformity (a). Schematic representation of the articular cartilage of the talocrural joint (b).

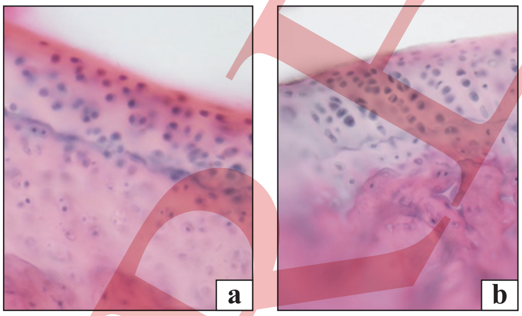

Fig. 3. Articular cartilage of the tibia (a) and talus (b) in the talocrural joint of a rat 1 month after modeled femoral deformity. Fibrillation of the surface zone of the talus articular cartilage (b). Staining with hematoxylin and eosin. Magnification 400x.

lage zone was narrower compared to the intact limb (Fig. 5b). In the superficial zone of the articular cartilage of the intact limb, a decrease in chondrocyte density in the middle zone was also observed, characteristic of the age norm for rats (12 months). According to the OARSI scale, the structural changes in the deformed limb corresponded to grade 2, grade 1–2 in the contralateral limb, and grade 0–1 in the intact animals.

On the surface of the talus bone, the articular cartilage, 6 months after the femoral deformity, showed significant structural changes compared to the distal end of the tibia. The characteristic zonality was lost. There was observed delamination of the superficial zone, significant areas without cells or with chondrocytes in a state of necrosis and necrobiotic changes. The basophilic line was either completely absent or sharply basophilic. The calcified cartilage zone was very narrow and almost devoid of cells (Figure 5d). In the contralateral limb, the middle zone showed low chondrocyte density (Figure 5e). In the articular cartilage of the intact rats, the characteristic zonality was preserved with a reduction in the width of the calcified cartilage zone (Figure 5f), which was related to the age of the animals (12 months). According to the OARSI scale, the structural changes corresponded to the following: 2–3 degrees for the deformed limb, 1–2 degrees for the contralateral limb, and 0–1 degrees for the intact rats.

Histomorphometry

In the limbs of animals with deformed bones, the height of the articular cartilage of the talus and tibia was 1.2 times (60.23 ± 7.14 vs. 49.23 ± 7.70 µm; $p < 0.001$) and 1.4 times (66.14 ± 13.64 vs. 48.09 ± 9.48 µm; $p < 0.001$) greater at 1 month, 1.2 times smaller at 3 months (43.55 ± 5.30 vs. 53.50 ± 8.65 µm; 46.84 ± 7.09 vs. 57.53 ± 6.27 µm; $p < 0.001$), and did not differ at 6 months (54.51 ± 10.18 vs. 53.46 ± 5.44 µm; p =

0.570; 58.28 ± 10.08 vs. 55.16 ± 8.50 µm; p = 0.105) when compared to the contralateral limb, respectively (Figure 6).

Compared to the intact rats, the height of the articular cartilage of the talus and tibia was greater by 1.2 and 1.3 times at 1 month (47.39 ± 5.88 µm; 55.03 ± 6.98 µm; p < 0.001), smaller by 1.4 times (59.39 ± 8.16 µm; p < 0.001) and 1.1 times (53.47 ± 5.84 µm; p = 0.022) at 3 months, smaller by 1.1 times (61.82 ± 10.60 µm; p < 0.001) for the talus, but did not differ for the tibia (60.82 ± 10.08 µm; p = 0.178) at 6 months (Figure 6).

In the contralateral limb of rats with femoral deformity, compared to intact animals, the height of the articular cartilage of the talus did not differ at 1 month, was smaller by 1.1 times (p = 0.018) at 3 months, and smaller by 1.2 times (p < 0.001) at 6 months. The tibia cartilage was smaller by 1.1 times (p = 0.006) at 1 month, larger by 1.1 times (p = 0.023) at 3 months, and smaller by 1.1 times (p = 0.005) at 6 months (Figure 6).

Discussion

In the conducted experimental study, we demonstrated that extra-articular femoral deformity leads to degenerative changes in the articular cartilage of the talocrural joint in rats. However, the severity of these changes is less pronounced compared to the knee joint, which we had previously studied [28]. In the articular cartilage of the talus, structural changes began earlier than at the distal end of the tibia. Already one month after the deformity, these changes corresponded to 0–1 degrees on the OARSI scale [27]. Degenerative changes progressed over time and reached 2–3 degrees after 6 months of observation. In the articular cartilage at the distal end of the tibia, destructive changes were observed later, starting from 3 months of observation, but their degree of manifestation was similar after 6 months, as in the talus bone. The height of the articular cartilage on both surfaces at the first month of observation was higher compared to the contralateral limb and intact animals, but by 3 months, it became smaller, and at 6 months, it was smaller only for the talus surface. These changes align with structural alterations that progressed more in the talus of the limb with deformity. At the same time, the likely increased height of the articular cartilage at the first month of observation is associated with a reduction in load on the limb due to the injury.

Degenerative changes in the articular cartilage, leading to osteoarthritis, begin in the superficial zone, followed by the loss of its distinct contour and chondrocyte death. One of the factors contributing to this is impaired biomechanics/instability, either due to post-traumatic osteoarthritis or excessive loads in obesity [29]. In the model of femoral deformity, we believe that an abnormal load distribution on the limb and talocrural joint also occurs. We observed the development of degenerative changes more on the side of the articular cartilage surface than in the calcified zone, which is characteristic of excessive loading, rather than aging [29].

By the end of the observation period, delamination of part of the superficial zone was detected, indicating chondrocyte death, which secretes matrix components, and subsequent cracking of the matrix. S. Santos et al. [23] showed that mechanical loading induces microcracks in the collagen network of articular cartilage samples.

The biomechanics of the hind limbs of rats differ from those of humans, which may influence the development of osteoarthritis, and this needs to be considered. However, S. H. Chang et al. [30] found no differences when comparing structural changes in the talocrural joint in three mouse models of osteoarthritis with human samples. It remains unknown how this applies to the talocrural joint in rats. Currently, there is little information regarding the condition of the talocrural joint in patients with extra-articular femoral deformity [8, 15]. Clinical studies typically focus on the knee joint [7, 10], where biomechanical changes closer to the defect lead to more pronounced alterations and osteoarthritis development. But biomechanically, it has been shown that axial alignment disturbances in femoral fragments after surgical treatment of a fracture lead to excessive loading on the talocrural joint [14]. We obtained similar results in a previously conducted study, where we modeled femoral deformity and found an increase in maximal stress on the articular surfaces [31]. However, there is a lack of clinical observations regarding osteoarthritis development in the talocrural joint in individuals with femoral deformity [18]. This may be due to the fact that degenerative changes in this location in such patients do not cause significant pain or noticeable functional impairment, especially when compared to the knee joint. Additionally, pain in osteoarthritis, according to recent data, is not associated with damage to the articular cartilage, which lacks nerve endings [32]. This disease in the early stages in the talocrural joint can be effectively controlled with therapy using non-steroidal anti-inflammatory drugs [33].

However, femoral deformity causes systemic changes in the axis of the limb that affect the function of all its joints [14], and likely even in the con-

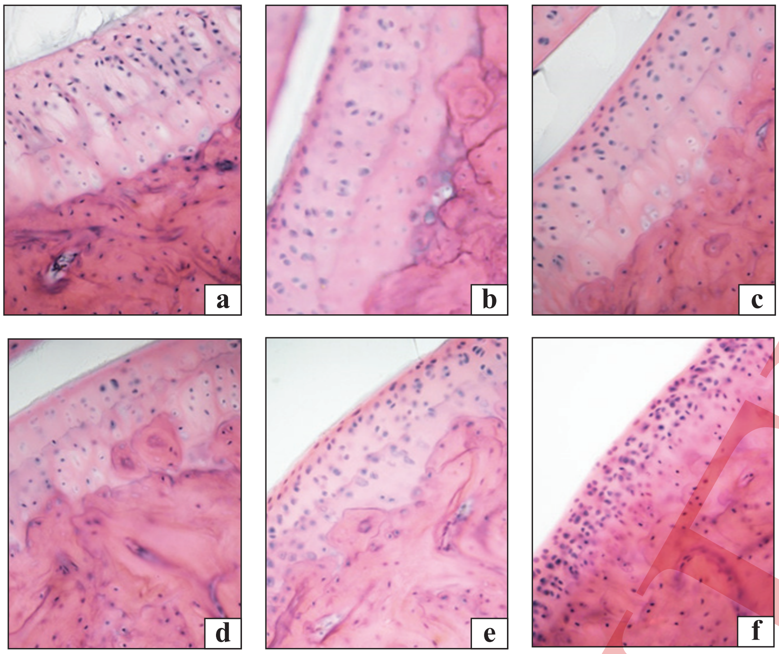

Fig. 4. Articular cartilage of the tibia (top row) and talus (bottom row) in the talocrural joint of rats 3 months after modeling femoral deformity (a, d), compared with the contralateral limb (b, e) and intact (c, f). Disruption of histoarchitecture (a), areas without cells, cells in a state of necrobiosis, uneven matrix staining (d) after deformity. Moderate disruption of cartilage histoarchitecture in the contralateral limb (b, e). Staining with hematoxylin and eosin. Magnification 400x.

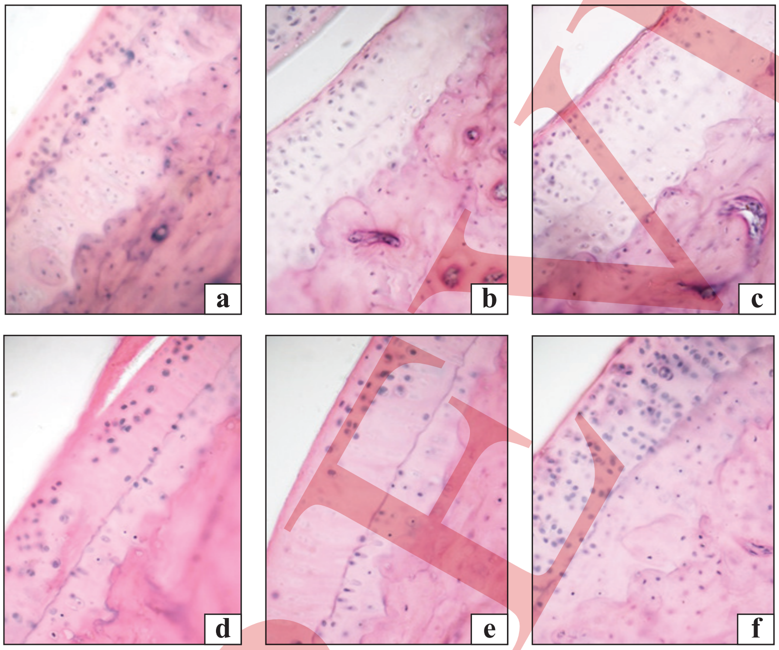

Fig. 5. Articular cartilage of the tibia (top row) and talus (bottom row) in the talocrural joint of rats 3 months after modeling femoral deformity (a, d), compared with the contralateral limb (b, e) and intact (c, f). Narrow middle zone with sparsely located chondrocytes, uneven matrix staining (a), detachment of the surface zone (d) after deformity. Disruption of the histoarchitecture of the articular cartilage, areas without cells (b, e).

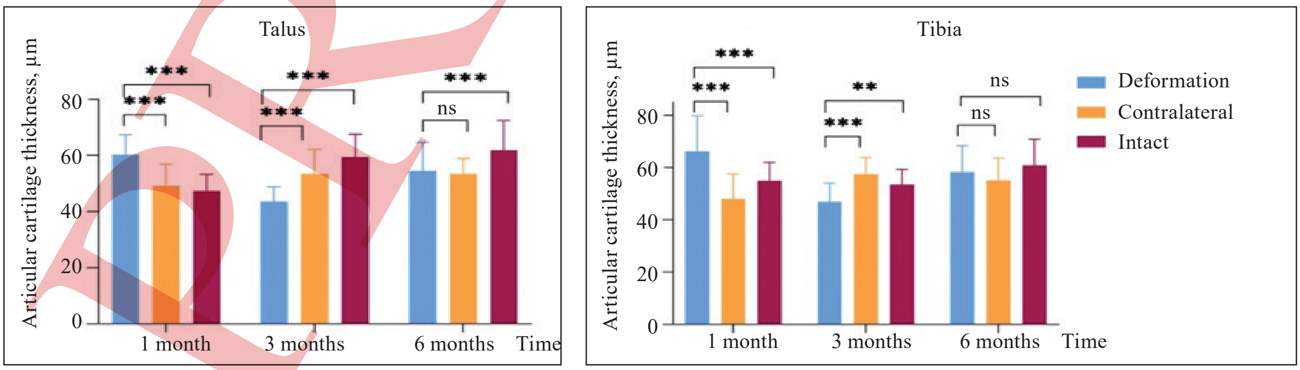

Fig. 6. Comparison of articular cartilage thickness of the distal tibia and proximal talus in the limbs of rats with femoral deformity versus the contralateral limb and the intact group of rats. Notation: ** $p < 0.01$; *** $p < 0.001$; ns — no differences.

tralateral limb, as we demonstrated in the articular cartilage of the distal end of the tibia in the contralateral limb of rats after 3 months of observation. This highlights the importance of comprehensive examination of patients with bone deformities to develop preventive measures aimed at preserving the function of the joints in both limbs.

An interesting aspect is the development of degenerative changes initially in the articular cartilage of the talus in the talocrural joint of rats. This may be linked to the greater load on the bones of the foot during walking and their function of absorbing the load, in contrast to the long bones, where the load transmitted is already of lesser force by the time of the first contact with the surface. This is confirmed by biomechanical studies on post-mortem limb specimens, which showed that ≈ 83% of the load is borne by the articular cartilage of the talus in this joint [34].

When evaluating the risk of osteoarthritis development in the talocrural joint, it is important to take into account the age of patients with extra-articular femoral deformity and the duration of the deformity. In our experimental study, we used rats aged 6 months because, according to leading experimental researchers' recommendations [27], degenerative changes do not develop in younger animals under osteoarthritis modeling. Therefore, it is likely that in younger patients, changes in the talocrural joint will be less pronounced and will not interfere with normal physical activity.

A limitation of this study is the examination of structural changes in the articular cartilage using sagittal sections taken through the central axis of the rat limb, whereas the load on the medial part of the cartilage may have been higher due to the varus deformity. At the same time, the degenerative changes observed even under these conditions suggest that the deformity affects even the less-loaded areas of the joint.

Conclusion

The modeled extra-articular femoral deformity in rats induces degenerative changes in the articular cartilage of the talus from the first month, and from the third month, in the tibia in the talocrural joint. In the contralateral limb, degenerative changes in the articular cartilage were observed after 3 months, but they were less pronounced.

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

Future Research Prospects. Further experimental modeling of valgus deformity in the mid-third of the femur followed by studies on the articular cartilage structure in the knee and talocrural joints.

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References

1. Weiss, R. J., Montgomery, S. M., Al Dabbagh, Z., & Jansson, K. Å. (2009). National data of 6409 Swedish inpatients with femoral shaft fractures: Stable incidence between 1998 and 2004. *Injury, 40*(3), 304–308. https://doi.org/10.1016/j.injury.2008.07.017
2. Arneson, T. J., Melton, L. J., Lewallen, D. G., & O'Fallon, W. M. (1988). Epidemiology of diaphyseal and distal femoral fractures in Rochester, Minnesota, 1965–1984. *Clinical orthopaedics and related research,* 234, 188–194. https://doi.org/10.1097/00003086-198809000-00033
3. Böstman, O., Varjonen, L., Vainionpä, S., Majolä, A., & Rokkanen, P. (1989). Incidence of local complications after intramedullary nailing and after plate fixation of femoral shaft fractures. *Journal of trauma - injury, infection and critical care, 29*(5), 639–645. https://doi.org/10.1097/00005373-198905000-00019
4. Ricci, W. M., Bellabarba, C., Evanoff, B., Herscovici, D., DiPasquale, T., & Sanders, R. (2001). Retrograde versus antegrade nailing of femoral shaft fractures. *Journal of orthopaedic trauma, 15*(3), 161–169. https://doi.org/10.1097/00005131-200103000-00003
5. Ricci, W. M., Bellabarba, C., Lewis, R., Evanoff, B., Herscovici, D., DiPasquale, T., & Sanders, R. (2001). Angular malalignment after intramedullary nailing of femoral shaft fractures. *Journal of orthopaedic trauma, 15*(2), 90–95. https://doi.org/10.1097/00005131-200102000-00003
6. Jensen, S. S., Jensen, N. M., Gundtoft, P. H., Kold, S., Zura, R., & Viberg, B. (2022). Risk factors for nonunion following surgically managed, traumatic, diaphyseal fractures: a systematic review and meta-analysis. *EFORT open reviews, 7*(7), 516–525. https://doi.org/10.1530/EOR-21-0137
7. Vergano, L. B., Coviello, G., & Monesi, M. (2020). Rotational malalignment in femoral nailing: Prevention, diagnosis and surgical correction. *Acta biomedica, 91*(Suppl 14), 1–11. https://doi.org/10.23750/abm.v91i14-S.10725
8. Eckhoff, D. G. (1994). Effect of limb malrotation on malalignment and osteoarthritis. *Orthopedic clinics of North America, 25*(3), 405–414. https://doi.org/10.1016/s0030-5898(20)31925-8
9. Castano Betancourt, M. C., Maia, C. R., Munhoz, M., Morais, C. L., & Machado, E. G. (2022). A review of Risk Factors for Post-traumatic hip and knee osteoarthritis following musculoskeletal injuries other than anterior cruciate ligament rupture. *Orthopedic reviews, 14*(4), 2022. https://doi.org/10.52965/001c.38747
10. Phillips, J. R. A., Trezies, A. J. H., & Davis, T. R. C. (2011). Long-term follow-up of femoral shaft fracture: Relevance of malunion and malalignment for the development of knee arthritis. *Injury, 42*(2), 156–161. https://doi.org/10.1016/j.injury.2010.06.024
11. Ricci, W. M., Gallagher, B., & Haidukewych, G. J. (2009). Intramedullary nailing of femoral shaft fractures: Current concepts. *Journal of the American academy of orthopaedic surgeons, 17*(5), 296–305. https://doi.org/10.5435/00124635-200905000-00004
12. Claireaux, H. A., Searle, H. K. C., Parsons, N. R., & Grif-

fin, X. L. (2022). Interventions for treating fractures of the distal femur in adults. *Cochrane database of systematic reviews, 2022*(10). https://doi.org/10.1002/14651858.CD010606.pub3

13. Gugala, Z., Qaisi, Y. T., Hipp, J. A., & Lindsey, R. W. (2011). Long-term functional implications of the iatrogenic rotational malalignment of healed diaphyseal femur fractures following intramedullary nailing. *Clinical biomechanics, 26*(3), 274–277. https://doi.org/10.1016/j.clinbiomech.2010.11.005
14. Dagneaux, L., Allal, R., Pithioux, M., Chabrand, P., Ollivier, M., & Argenson, J.-N. (2018). Femoral malrotation from diaphyseal fractures results in changes in patellofemoral alignment and higher patellofemoral stress from a finite element model study. *The knee, 25*(5), 807–813. https://doi.org/10.1016/j.knee.2018.06.008
15. Karaman, O., Ayhan, E., Kesmezacar, H., Seker, A., Unlu, M. C., & Aydingoz, O. (2014). Rotational malalignment after closed intramedullary nailing of femoral shaft fractures and its influence on daily life. *European journal of orthopaedic surgery and traumatology, 24*(7), 1243–1247. https://doi.org/10.1007/s00590-013-1289-8
16. Jaarsma, R. L., Ongkiehong, B. F., Grüneberg, C., Verdonschot, N., Duysens, J., & Van Kampen, A. (2004). Compensation for rotational malalignment after intramedullary nailing for femoral shaft fractures: An analysis by plantar pressure measurements during gait. *Injury, 35*(12), 1270–1278. https://doi.org/10.1016/j.injury.2004.01.016
17. Cunningham, B. P., Cole, P. A., & Ortega, G. (2020). *Malunions of the Femoral Shaft. In Malunions: Diagnosis, Evaluation and Management* (261–282). Springer, New York, NY. https://doi.org/10.1007/978-1-0716-1124-1_10
18. Kim, J. S., Amendola, A., Barg, A., Baumhauer, J., Brodsky, J. W., Cushman, D. M., Gonzalez, T. A., Janisse, D., Jurynec, M. J., Lawrence Marsh, J., Sofka, C. M., Clanton, T. O., & Anderson, D. D. (2022). Summary report of the arthritis foundation and the american orthopaedic foot & ankle society's symposium on targets for osteoarthritis research: part 1: epidemiology, pathophysiology, and current imaging approaches. *Foot and ankle orthopaedics, 7*(4). https://doi.org/10.1177/24730114221127011
19. Delco, M. L., Kennedy, J. G., Bonassar, L. J., & Fortier, L. A. (2017). Post-traumatic osteoarthritis of the ankle: A distinct clinical entity requiring new research approaches. *Journal of orthopaedic research, 35*(3), 440–453. https://doi.org/10.1002/jor.23462
20. Godoy-Santos, A. L., Fonseca, L. F., de Cesar Netto, C., Giordano, V., Valderrabano, V., & Rammelt, S. (2021). Ankle osteoarthritis. *Revista Brasileira de ortopedia, 56*(6), 689–696. https://doi.org/10.1055/s-0040-1709733
21. Liang, D., Sun, J., Wei, F., Zhang, J., Li, P., Xu, Y., Shang, X., Deng, J., Zhao, T., & Wei, L. (2017). Establishment of rat ankle post-traumatic osteoarthritis model induced by malleolus fracture. *BMC musculoskeletal disorders, 18*(1). https://doi.org/10.1186/s12891-017-1821-9
22. Guo, J. B., Liang, T., Che, Y. J., Yang, H. L., & Luo, Z. P. (2020). Structure and mechanical properties of high-weight-bearing and low-weight-bearing areas of hip cartilage at the micro- And nano-levels. *BMC musculoskeletal disorders, 21*(1). https://doi.org/10.1186/s12891-020-03468-y
23. Santos, S., Emery, N., Neu, C. P., & Pierce, D. M. (2019). Propagation of microcracks in collagen networks of cartilage under mechanical loads. *Osteoarthritis and cartilage, 27*(9), 1392–1402. https://doi.org/10.1016/j.joca.2019.04.017
24. European convention for the protection of vertebrate animalsused for experimental and other scientific purposes: Strasbourg,18 March 1986. (2000).
25. Law of Ukraine No. 3447-IV, article 26. On the protection of animals from cruel treatment. Kyiv, 21 February, 2006. (In Ukrainian)
26. Romanenko, K. K., Ashukina, N. O., Goridova, L. D., & Prozorovsky, D. V. (2014). Method for modeling fractures of long bones of limbs (92613). https://base.nipo.gov.ua/search-bulletin/search.php?action=viewdetails&dbname=invdu&IdClaim=203923
27. Gerwin, N., Bendele, A., Glasson, S., & Carlson, C. (2010). The OARSI histopathology initiative — recommendations for histological assessments of osteoarthritis in the rat. *Osteoarthritis and cartilage*, 18, S24–S34. https://doi.org/10.1016/j.joca.2010.05.030
28. Romanenko, K., Ashukina, N., Batura, I., & Prozorovsky, D. (2017). Morphology of the articular cartilage of the knee joint in rats with extraarticular femoral bone deformity. *Orthopaedics, traumatology and prosthetics, 0*(1), 63–71. https://doi.org/10.15674/0030-59872017163-71
29. Yao, Q., Wu, X., Tao, C., Gong, W., Chen, M., Qu, M., Zhong, Y., He, T., Chen, S., & Xiao, G. (2023). Osteoarthritis: Pathogenic signaling pathways and therapeutic targets. *Signal transduction and targeted therapy, 8*(1). https://doi.org/10.1038/s41392-023-01330-w
30. Chang, S. H., Yasui, T., Taketomi, S., Matsumoto, T., Kim-Kaneyama, J. R., Omiya, T., Hosaka, Y., Inui, H., Omata, Y., Yamagami, R., Mori, D., Yano, F., Chung, U., Tanaka, S., & Saito, T. (2016). Comparison of mouse and human ankles and establishment of mouse ankle osteoarthritis models by surgically-induced instability. *Osteoarthritis and cartilage, 24*(4), 688–697. https://doi.org/10.1016/j.joca.2015.11.008
31. Korzh, M., Romanenko, K., Karpinsky, M., Prozorovsky, D., & Yaresko, O. (2015). Mathematic modeling of the influence of femur malalignment on the bearing of lower extremity joints. *Orthopaedics, traumatology and prosthetics, 0*(4), 25. https://doi.org/10.15674/0030-59872015425-30
32. Tong, L., Yu, H., Huang, X., Shen, J., Xiao, G., Chen, L., Wang, H., Xing, L., & Chen, D. (2022). Current understanding of osteoarthritis pathogenesis and relevant new approaches. *Bone research, 10*(1), 1–17. https://doi.org/10.1038/s41413-022-00226-9
33. Herrera-Pérez, M., Valderrabano, V., Godoy-Santos, A. L., de César Netto, C., González-Martín, D., & Tejero, S. (2022). Ankle osteoarthritis: comprehensive review and treatment algorithm proposal. *EFORT open reviews, 7*(7), 448–459. https://doi.org/10.1530/EOR-21-0117
34. Calhoun, J. H., Li, F., Ledbetter, B. R., & Viegas, S. F. (1994). A comprehensive study of pressure distribution in the ankle joint with inversion and eversion. *Foot & ankle international, 15*(3), 125–133. https://doi.org/10.1177/107110079401500307

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DEGENERATIVE CHANGES IN RAT ANKLE CARTILAGE INDUCED BY VARUS EXTRA-ARTICULAR FEMORAL DEFORMATION

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Determination of the safety and effectiveness of carboxyterapy in *in vivo* models of osteoarthritis and tendon inflammation

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Local administration of carbon dioxide (carboxytherapy) is regarded as a promising approach for modulating inflammation, improving microcirculation, and stimulating reparative processes. However, traditional subcutaneous CO_2 delivery techniques are associated with variability of local effects, risk of mechanical tissue irritation, and insufficient standardization of administration parameters, which limits reproducibility of experimental findings. These limitations highlight the need to develop optimized CO_2 delivery techniques with controlled administration and improved safety. Objective. To evaluate the efficacy and safety of subcutaneous administration of a CO_2–NaHCO3 gas-buffer mixture in preclinical models of acute inflammation and monoiodoacetate (MIA)-induced osteoarthritis. Methods. The study was conducted in rats using formalin- and carrageenan-induced models of acute inflammation and a monoiodoacetic acid–induced osteoarthritis model. Animals received subcutaneous injections of a CO_2 + $NaHCO_3$ mixture (1:1) in small volumes; comparisons were performed against the classical subcutaneous CO_2 administration protocol described by Raymundo et al. Results. In acute inflammation models, administration of the $CO_2/NaHCO_3$ mixture significantly reduced edema severity ($p < 0.001$). In the MIA-induced osteoarthritis model, treatment resulted in a statistically significant decrease in TNF-α and IL-6 levels and an increase in TGF-β1 concentration (all $p < 0.001$), indicating anti-inflammatory activity and modulatory effects on systemic inflammatory markers. Conclusions. The subcutaneous administration technique of the CO_2 + $NaHCO_3$ mixture investigated in this study demonstrated anti-inflammatory activity and a favorable safety profile in preclinical models, supporting the rationale for further research into its potential application for degenerative-inflammatory disorders of the musculoskeletal system.

Локальне застосування вуглекислого газу (карбокситерапія) розглядається як перспективний підхід до модуляції запалення, покращення мікроциркуляції та стимуляції репаративних процесів. Разом із тим традиційні методики підшкірного введення CO_2 характеризуються варіабельністю локальної дії, ризиком механічного подразнення тканин і недостатньою стандартизованістю параметрів введення, що ускладнює відтворюваність експериментальних даних. Це зумовлює потребу в розробленні оптимізованих технік локального застосування CO_2 із контрольованою доставкою та підвищеною безпечністю. Мета. Оцінити ефективність і безпеку підшкірного введення газо-буферної суміші CO_2 і $NaHCO_3$ у доклінічних моделях гострого запалення й остеоартриту, індукованого монойодоцтовою кислотою (МЙОК). Методи. Дослідження проведено на щурах із використанням формалін- і карагенін-індукованих моделей гострого запалення й остеоартриту, викликаного МЙОК. Тваринам підшкірно вводили суміш CO_2 + $NaHCO_3$ (1:1) у малих об'ємах; порівняння проводили з протоколом підшкірного введення чистого CO_2 за методом Raymundo. Результати. У моделях гострого запалення введення суміші CO_2 + $NaHCO_3$ достовірно зменшувало виразність набряку ($p < 0,001$). У моделі МЙОК-індукованого остеоартриту відзначено статистично значуще зниження рівнів TNF-α та IL-6 і підвищення концентрації TGF-β1 (усі $p < 0,001$), що свідчить про протизапальний ефект і модулювальний вплив суміші на системні маркери запалення. Висновки. Методика підшкірного введення суміші CO_2 + $NaHCO_3$, досліджена в роботі, проявила протизапальний ефект і задовільний профіль безпеки в доклінічних моделях, що обґрунтовує подальше її вивчення для можливого застосування за дегенеративно-запальних уражень опорно-рухової системи. Ключові слова. Карбокситерапія, CO2, запалення, остеоартрит, цитокіни, щури, дегенеративні захворювання суглобів, дегенеративно-запальні стани.

Keywords. Carboxytherapy; CO_2, inflammation, osteoarthritis, cytokines, rats, degenerative joint diseases, degenerative-inflammatory conditions

Introduction

Carbon dioxide therapy, also known as carboxytherapy, involves using carbon dioxide (CO_2) for medical treatments and has gained considerable interest from both researchers and healthcare professionals in recent years, especially in fields like vascular medicine, dermatology, regenerative therapy, and aesthetic medicine. This interest is due to CO_2's ability to influence microcirculation, cell metabolism, and tissue oxygenation, which collectively promote reparative processes. The effects of CO_2 therapy on tissue healing, including improved vascularization, oxygenation, and activation of cell proliferation, have been experimentally confirmed multiple times, particularly in skin wound healing models [1]. Recent preclinical studies have shown that local percutaneous and transcutaneous CO_2 application can stimulate osteogenesis and bone tissue remodeling. Specifically, percutaneous CO_2 administration has been shown to accelerate new bone formation in distraction osteogenesis models [2], while transcutaneous or topical application promotes fracture healing and bone defect repair [3, 4], enhancing vascularization and mineralization of the regenerating tissue [5]. These findings support the rationale for studying the local application of CO_2 in models of degenerative-inflammatory joint diseases, particularly osteoarthritis.

The biophysiological mechanisms of CO_2 action are partly associated with the "Bohr effect": an increase in the partial pressure of the gas in local tissues leads to a decrease in pH, which shifts the oxygen-hemoglobin dissociation curve toward oxygen release, thus improving tissue oxygenation [6]. In preclinical models, particularly in experiments on laboratory animals, local transcutaneous CO_2 administration is associated with the activation of angiogenic signaling pathways, manifested by increased expression of VEGF (vascular endothelial growth factor) and, partially, modulation of eNOS (endothelial nitric oxide synthase) activity. These changes may create favorable conditions for the restoration and regeneration of damaged tissues [3]. Clinical studies in humans have shown CO_2 therapy improves the healing of chronic wounds and microcirculation, although direct evidence of NO signaling activation in human tissues still requires further research [7, 8].

The practical application of CO_2 encompasses a wide range of methods from balneotherapy and inhalations (according to the literature) to transdermal hydrogels, carboxytherapy (CO_2 injections), and other local delivery forms [8, 9]. Each of these methods has its own characteristics in terms of localization of action, dose control, tissue permeability, and safety [7, 8]. At the preclinical level (animal models), transdermal CO_2 application (with hydrogels or in combination with other techniques) has been shown to accelerate bone growth through the stimulation of angiogenesis [3, 4], increased blood flow, and VEGF expression, as well as potentially influencing other signaling pathways [9]. In earlier clinical studies in humans, transdermal CO_2 therapy demonstrated safety and the ability to increase local blood flow near fractures [10], although direct evidence regarding bone regeneration in humans or effects on inflammatory mechanisms in such situations is still limited. Therefore, CO_2 therapy remains a promising research approach in orthopedics and potentially rheumatology, requiring further controlled studies.

Despite promising results from preclinical studies, there is still no unified methodology for the local application of CO_2 in scientific literature. Research on the effectiveness of various delivery methods (transdermal, injection, hydrogel, etc.), dosing parameters, and exposure regimes remains limited [4]. This complicates the standardization of approaches and hinders the translation of prior results into clinical practice. Therefore, it is particularly important to study dose-response relationships, safety, effectiveness, and the potential for combined action of CO_2 with other pharmacological agents.

In our study, we focused on the subcutaneous route of CO_2 administration as an approach that provides direct influence on local microcirculation and allows for precise control over the volume and localization of exposure. We developed and tested a standardized technique for subcutaneous administration of a CO_2 + $NaHCO_3$ mixture in rats, investigating its impact on the expression of key inflammatory and regenerative markers, morphological indicators, and pain behavioral indices in inflammation and osteoarthritis models.

Objective: To assess the effectiveness and safety of subcutaneous administration of a gas-buffer mixture of CO_2 + $NaHCO_3$ in preclinical models of acute inflammation and osteoarthritis induced by mono-iodoacetic acid.

Materials and Methods

All studies were conducted at the vivarium of Poltava State Medical University and performed in accordance with the basic principles of the European Council Convention on the Protection of Vertebrate Animals Used for Experimental and Scientific Purposes and Directive 2010/63/EU. The study was approved by the ethical committees of Poltava State

Medical University (Protocol No. 225, 21.03.2024) and Uzhhorod National University (Protocol No. 9/2, 07.06.2023). Animals were kept under standardized conditions: temperature (22 ± 2) °C, relative humidity 40–60%, light/dark cycle 12/12 hours, standard diet, and free access to drinking water. All procedures were performed with adherence to principles of humane treatment and minimizing animal suffering, in accordance with ARRIVE guidelines.

The study used outbred white rats weighing 180–230 g at the start of the experiment. The animals were randomized using a simple randomization method into groups of eight animals (n = 8) for each experimental and control condition. Allocation of rats and subsequent outcome assessment were performed in a blinded manner with respect to treatment.

The animals were divided into the following groups:

I — intact;

II — pathological control (formalin-, carrageenan-, or MIA [monoiodoacetic acid]–induced model, depending on the experiment);

III — pathology + CO_2 (0.5 ml, subcutaneously).

Models of inflammation and osteoarthritis

Formalin-induced model of aseptic inflammation

Aseptic inflammation was induced by subplantar injection of 2.5 % formalin solution (0.1 ml) under the aponeurosis of the plantar surface of the rat hind paw, according to the methodological recommendations edited by O. V. Stefanov [11]. Edema dynamics were assessed by changes in limb circumference measured before induction and at 1, 2, 3, 4, 5, and 24 hours after formalin administration using a plethysmometer (Table 1).

Carrageenan-induced acute inflammation

Acute inflammation was modeled by subaponeurotic injection of 1 % carrageenan solution (0.1 ml) into the right hind limb. This model is based on the classical protocol of Winter, Risley, and Nuss and its modifications [12, 13].

Limb volume was measured before induction and at 1, 2, 3, and 5 hours after carrageenan administration (Table 2). After 5 hours, euthanasia was performed under thiopental anesthesia (50 mg/kg) for blood collection and biochemical analysis.

Monoiodoacetic acid–induced osteoarthritis (MIA-OA)

Osteoarthritis was induced by intra-articular injection of 0.05 ml (0.005 ml) of a 3 % MIA solution, prepared ex tempore by dissolving 3 mg of MIA in 0.1 ml of 0.9 % NaCl solution, followed by sterile withdrawal of the required volume. The applied regimen corresponds to adapted protocols for MIA-induced osteoarthritis in rats [14, 15].

Biochemical parameters were assessed on day 14 and/or day 28 of the experiment. Serum levels of the pro-inflammatory cytokine TNF-α and the anti-inflammatory cytokine TGF-β1 were determined (Table 3). In addition, the level of IL-6 was measured as a marker of the systemic inflammatory response (Table 4).

Animal euthanasia was performed under thiopental anesthesia (50 mg/kg) in accordance with bioethical requirements.

Table 1

The size of the circumference of the rats' hind limb over time in the formalin-induced inflammation model (ml; M ± SD, n = 8)

Animal group	Before the pathology	1 hour	2 hours	3 hours	4 hours	5 hours	24 hours
Intact	0.451 ± 0.009	0.451 ± 0.009	0.451 ± 0.009	0.451 ± 0.009	0.451 ± 0.009	0.451 ± 0.009	0.451 ± 0.009
Control pathology	0.454 ± 0.011	0.489 ± 0.010	0.539 ± 0.013	0.615 ± 0.013	0.701 ± 0.017	0.770 ± 0.016	0.651 ± 0.012
Pathology + CO_2	0.422 ± 0.006	0.485 ± 0.008	0.509 ± 0.009	0.559 ± 0.004*	0.621 ± 0.009	0.690 ± 0.013**	0.594 ± 0.012

Notes: The data are presented as M ± SD; n = 8. $p < 0.05$; * $p < 0.01$; ** $p < 0.001$ — significant difference compared to the control pathology group (formalin).

Table 2

Change in the limb circumference in rats with carrageenan-induced inflammation (ml; M ± SD, n = 8)

Animal group	Before the pathology	1 hour	2 hours	3 hours	5 hours
Intact	0.427 ± 0.029	0.427 ± 0.029	0.427 ± 0.029	0.427 ± 0.029	0.427 ± 0.029
Control pathology	0.410 ± 0.028	0.529 ± 0.022	0.609 ± 0.022	0.740 ± 0.025	0.695 ± 0.037
Pathology + CO_2	0.406 ± 0.019	0.463 ± 0.027*	0.514 ± 0.023*	0.659 ± 0.031*	0.613 ± 0.026*

Notes: The data are presented as M ± SD; n = 8 in each group. * $p < 0.001$ — significant difference compared to the pathology group (carrageenan).

Table 3

Levels of TNF-α and TGF-β1 in the serum of rats with MIA-induced osteoarthritis (14th and 28th day of observation)

Animal group	14 days TNF-α, pg/ml	28 days TNF-α, pg/ml	14 days TGF-β1, pg/ml	28 days TGF-β1, pg/ml
Intact	6.87 ± 0.44	6.87 ± 0.44	567.12 ± 19.40	567.12 ± 19.40
Intact + saline solution	6.85 ± 0.33	6.85 ± 0.32	572.15 ± 21.25	572.15 ± 21.25
Pathology (MIA)	29.97 ± 0.50	29.59 ± 0.10	840.56 ± 7.87	831.89 ± 6.19
MIA + CO_2 0.5 ml	28.09 ± 0.66*	26.42 ± 0.35*	1133.62 ± 13.59*	1192.39 ± 20.42*

Notes: The data are presented as M ± SD; n = 5 in each group. * $p < 0.001$ — significant difference compared to the pathology group (MIA).

Table 4

IL-6 level in the serum of rats with MIA-induced osteoarthritis (14th and 28th day of observation)

Animal group	14 днів IL-6, пг/мл	28 днів IL-6, пг/мл
Intact	1.33 ± 0.09	1.33 ± 0.09
Intact + saline solution	1.29 ± 0.07	1.29 ± 0.07
Pathology (MIA)	14.58 ± 0.27	14.29 ± 0.34
MIA + CO_2 0.5 ml	12.58 ± 0.18*	12.06 ± 0.28*

Notes: The data are presented as M ± SD; n = 5 in each group. * $p < 0.001$ — significant difference compared to the pathology group (MIA).

To prepare the CO_2 + $NaHCO_3$ mixture, medical-grade purified carbon dioxide (Aquario BLUE, 2 L, or equivalent), a CO_2 delivery system (Eheim CO_2 SET) with a sterile 0.22 µm filter, sterile syringes, 30G micro-needles (0.3 × 13 mm), and sterile $NaHCO_3$ solution (0.9–1.5 %) in 0.9 % NaCl were used. First, 0.5 ml of $NaHCO_3$ solution was drawn into the syringe, after which 0.5 ml of CO_2, pre-equilibrated to 22–24 °C, was aspirated through a three-way stopcock. This produced a gas-buffer mixture at a 1:1 volumetric ratio with short-term pH stability of 7.0–7.3 for ≤ 1 minute after preparation. The mixture was used immediately. Subcutaneous injection was performed into the periarticular area over the medial condyle of the knee joint using a 30G needle at an angle of 20°–30°, at a dose of 0.5–1.0 ml (3–5 ml/kg). The injection was administered slowly, without additional pressure, after checking the mixture for the absence of bubbles and excessive pressure. The administration frequency was once daily (for the formalin and carrageenan models) or once every 3 days (for the MIA-OA model) for 14 or 28 days, depending on the protocol. After administration, animals were observed for at least 30 minutes for immediate reactions.

For methodological control, in selected series the Raymundo subcutaneous CO_2 injection technique was used: a standardized flow of 80 ml/min for 10 seconds into a single site through a 30G needle inserted at a 90° angle to the skin [16]. This allowed comparison of morphofunctional and safety aspects between the conventional protocol and the optimized method of administering the CO_2 + $NaHCO_3$ mixture.

The analysis was performed using Jamovi (version 2.3.21). Quantitative data are presented as M ± SD (except where mean ± SEM is indicated). Normality was checked using the Shapiro–Wilk test; homogeneity of variances was checked using Levene's test. For data with normal distribution, one-way ANOVA (or two-way ANOVA for time series: group × time) with Tukey's post-hoc test was used; in case of violation of homogeneity, Welch's test was applied; for non-normal data, the Kruskal-Wallis test with Bonferroni correction was used. The significance level was set at $p < 0.05$.

Results and Discussion

The comparative analysis of subcutaneous CO_2 injection techniques revealed significant differences in the safety profile and local effects. The classical Raymundo method involved rapid injection of pure CO_2 under pressure. This regime was accompanied by pronounced mechanical tissue stretching and transient hypercapnia [16], which reflects the specific response to the rapid subcutaneous injection of gas. Additionally, classical protocols are associated with reactive hyperemia, changes in microcirculation, and local vascular reactions, which have been confirmed by other experimental studies [8, 17].

Morphofunctional criteria for evaluating the local tissue response to CO_2, described in the literature, include the degree of local edema, erythema, microcirculatory changes, temperature reactions, and histological condition of the dermis and subcutaneous tissue [18]. These parameters are used to assess the safety profile and identify potential adverse reactions, including transient disruption of tissue homeostasis.

At the same time, new data demonstrate that the decrease in local pH induced by CO_2 can activate dermal fibroblasts and enhance the synthesis of extracellular matrix components through CREB-dependent induction of TGF-β1 [19]. This creates experimental groundwork for the development of softer and safer local CO_2 injection regimes aimed at reducing mechanical load on tissues and minimizing nociceptive activation.

The CO_2 + $NaHCO_3$ (1:1) therapeutic system we proposed, injected at an angle of 20°–30°, ensured a more uniform distribution of the gas phase in the subcutaneous tissue and avoided macroscopic and histological signs of mechanical damage even with repeated injections (every 3 days for 14–28 days), which indicates a better safety profile compared to traditional pure CO_2 injection protocols.

Considering the described mechanical and biochemical features of traditional gas injection techniques, an important task was to create a protocol that provides lower tissue stress, better tolerability, and the possibility of repeated use. Our data indicate that reducing the gas phase volume and adding a buffering component ($NaHCO_3$) significantly reduces local mechanical and chemical stress. This leads to less activation of nociceptors and minimizes the risk of microtrauma, making the proposed therapeutic system suitable for long-term experimental protocols, especially when modeling chronic degenerative-inflammatory conditions such as osteoarthritis.

Systemic Anti-Inflammatory and Reparative Effects of CO_2 + $NaHCO_3$ in the Osteoarthritis Model

In the MIA-induced osteoarthritis model, subcutaneous injection of the CO_2 + $NaHCO_3$ gas-buffer mixture was accompanied by significant systemic changes in blood serum and joint tissues. The levels of pro-inflammatory cytokines TNF-α and IL-6 were statistically significantly lower compared to the pathology group (all $p < 0.001$). Simultaneously, there was a significant increase in the concentration of TGF-β1 ($p < 0.001$), which may indicate the activation of anti-inflammatory and reparative mechanisms in the joint tissues.

CO_2 Effects in Acute Inflammation Models

In formalin- and carrageenan-induced acute inflammation models, subcutaneous CO_2 injection also led to a statistically significant reduction in the severity of the inflammatory response compared to the pathology control ($p < 0.001$), which was consistent with a decrease in edema and inhibition of acute-phase reactions.

Safety and Tolerability

The proposed protocol for subcutaneous injection of the CO_2 + $NaHCO_3$ therapeutic system (1.0 ml at a 1:1 ratio, according to the prescribed schedule) did not cause necrosis, hematomas, or visible macroscopic signs of tissue damage even with repeated applications. Clinical and laboratory indicators (complete blood count, liver, and kidney function) remained within normal limits, indicating apyrexia, no allergic reactions, good tolerability, and absence of pronounced systemic toxicity in the context of this experiment.

The obtained results align with the hypothesis that one of the key mechanisms of local CO_2 action is the induction of mild hypercapnia in tissues, which leads to a local shift in the oxygen-hemoglobin dissociation curve (Bohr effect). This enhances oxygen delivery to the affected area and creates a favorable environment for repair, angiogenesis, and tissue metabolism [8]. Unlike classical protocols for subcutaneous CO_2 injection [16], which are accompanied by tissue stretching, pain, and the release of neuropeptides, modern approaches — specifically the therapeutic system CO_2 + $NaHCO_3$ proposed in this study — are based on controlled, gentle gas delivery in a buffered liquid. This reduces local stress reactions and barotrauma, promoting safer and more effective biological effects [2, 4].

Thus, the proposed technique for subcutaneous injection of the CO_2 + $NaHCO_3$ therapeutic system in a 1:1 ratio, in small volumes, aligns with modern approaches to preclinical CO_2 therapy, demonstrating advantages in terms of biosafety, controlled delivery, and potential for further research. The injection can be performed without specialized equipment, using standard medical tools (syringe, micro-needle), which ensures simplicity, reproducibility, and safety of the method.

Conclusions

Carbon dioxide therapy with the CO_2 + $NaHCO_3$ mixture in an optimized format, involving subcutaneous injection in small volumes, demonstrates a pronounced anti-inflammatory and regenerative effect in inflammation and osteoarthritis models, particularly through the reduction of TNF-α, IL-6 levels, and improvement in joint morphology.

The proposed therapeutic system CO_2 + $NaHCO_3$ is characterized by good local tolerability, absence of macroscopic damage or side effects even with repeated use. It can potentially be combined with anti-inflammatory agents to enhance therapeutic efficacy.

The findings establish a scientific foundation for future investigations into the mechanisms of action of the CO_2 + $NaHCO_3$ mixture, assessment of its long-term effects, and exploration of its potential for clinical application.

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

Future Research Perspectives. Future research perspectives include studying the dose-dependent effects of the CO_2 + $NaHCO_3$ therapeutic system (volume, frequency, gas/liquid ratio), monitoring local changes in pO_2/pCO_2/pH in tissues, investigating the role of VEGF, eNOS, TGF-β, and osteogenic markers, conducting toxicological safety assessments, testing effects on cell cultures (endothelial cells, osteoblasts, chondrocytes), and evaluating its efficacy in larger preclinical models.

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References

1. Prazeres, J., Lima, A., & Ribeiro, G. (2025). Effects of carbon dioxide therapy on skin wound healing. *Biomedicines, 13*(1), 228. https://doi.org/10.3390/biomedicines13010228
2. Kumabe, Y., Fukui, T., Takahara, S., Kuroiwa, Y., Arakura, M., Oe, K., Oda, T., Sawauchi, K., Matsushita, T., Matsumoto, T., Hayashi, S., Kuroda, R., & Niikura, T. (2020). Percutaneous CO_2 treatment accelerates bone generation during distraction osteogenesis in rabbits. *Clinical orthopaedics and related research, 478*(8), 1922–1935. https://doi.org/10.1097/CORR.0000000000001288
3. Sawauchi, K., Fukui, T., Oe, K., Oda, T., Yoshikawa, R., Takase, K., Inoue, S., Nishida, R., Kuroda, R., & Niikura, T. (2024). Transcutaneous CO2 application combined with low-intensity pulsed ultrasound accelerates bone fracture healing in rats. *BMC Musculoskeletal disorders, 25*(1), 863. https://doi.org/10.1186/s12891-024-07976-z
4. Kuroiwa, Y., Fukui, T., Takahara, S., Lee, S. Y., Oe, K., Arakura, M., Kumabe, Y., Oda, T., Matsumoto, T., Matsushita, T., Akisue, T., Sakai, Y., Kuroda, R., & Niikura, T. (2019). Topical cutaneous application of CO2 accelerates bone healing in a rat femoral defect model. *BMC Musculoskeletal disorders, 20*(1), 237. https://doi.org/10.1186/s12891-019-2601-5
5. Oda, T., Iwakura, T., Fukui, T., Oe, K., Mifune, Y., Hayashi, S., Matsumoto, T., Matsushita, T., Kawamoto, T., Sakai, Y., Akisue, T., Kuroda, R., & Niikura, T. (2020). Effects of the duration of transcutaneous CO_2 application on the facilitatory effect in rat fracture repair. *Journal of orthopaedic science, 25*(5), 886–891. https://doi.org/10.1016/j.jos.2019.09.017
6. Matsumoto, T., Tanaka, M., Ikeji, T., Maeshige, N., Sakai, Y., Akisue, T., Kondo, H., Ishihara, A., & Fujino, H. (2019). Application of transcutaneous carbon dioxide improves capillary regression of skeletal muscle in hyperglycemia. *Journal of physiological sciences, 69*(2), 317–326. https://doi.org/10.1007/s12576-018-0648-y
7. Bulum, T., Poljičanin, T., Badanjak, A., Držič, J., & Metelko, Ž. (2025). Effect of transcutaneous application of carbon dioxide on wound healing, wound recurrence rate and diabetic polyneuropathy in patients with neuropathic, ischemic and neuroischemic diabetes-related foot ulcers. *Life, 15*(4), 618. https://doi.org/10.3390/life15040618
8. Sakai, Y., Miwa, M., Oe, K., Ueha, T., Koh, A., Niikura, T., et al. (2011). A novel system for transcutaneous application of carbon dioxide causing an “artificial Bohr effect” in the human body. *PLoS one, 6*(9), e24137. https://doi.org/10.1371/journal.pone.0024137
9. Koga, T., Niikura, T., Lee, S. Y., Okumachi, E., Ueha, T., Iwakura, T., et al. (2014). Topical cutaneous CO2 application by means of a novel hydrogel accelerates fracture repair in rats. *Journal of bone and joint surgery (American Volume), 96*(24), 2077–2084. https://doi.org/10.2106/JBJS.M.01498
10. Niikura, T., Iwakura, T., Omori, T., Lee, S. Y., Sakai, Y., Akisue, T., Oe, K., Fukui, T., Matsushita, T., Matsumoto, T., & Kuroda, R. (2019). Topical cutaneous application of carbon dioxide via a hydrogel for improved fracture repair: Results of phase I clinical safety trial. *BMC Musculoskeletal disorders, 20*(1), 563. https://doi.org/10.1186/s12891-019-2911-7
11. Stefanov, O. V. (2001). Preclinical studies of medicinal products: methodological recommendations. Kyiv: Avicenna. (in Ukrainian)
12. Klimenko, N. A., Tatarko, S. V., Shevchenko, A. N., & Gubina-Vakulik, G. I. (2007). Justification of the model of chronic (secondary chronic) inflammation. *Eksperimental and Clinic Medicine*, 2, 24–28. (in Ukrainian)
13. Necas, J., & Bartosikova, L. (2013). Carrageenan: a review. *Veterinar medicine, 58*(4), 187–205. (in Ukrainian)
14. Udo, M., Muneta, T., Tsuji, K., Ozeki, N., Nakagawa, Y., Ohara, T., Saito, R., Yanagisawa, K., & Sekiya, I. (2016). Monoiodoacetic acid induces cartilage degeneration and synovitis in rats in a dose- and time- dependent Manner. *Osteoarthritis and cartilage*, 24, S405–S406. https://doi.org/10.1016/j.joca.2016.01.733
15. Riewruja, K., Makarczyk, M., Alexander, P. G., Gao, Q., Goodman, S. B., Bunnell, B. A., Gold, M. S., & Lin, H. (2022). Experimental models to study osteoarthritis pain and develop therapeutics. *Osteoarthritis and cartilage open, 4*(4), 100306. https://doi.org/10.1016/j.ocarto.2022.100306
16. Raymundo, E. C., Hochman, B., Nishioka, M. A., Gonçalves de Freitas, J. O., Maximino, J. R., Chadi, G., & Ferreira, L. M. (2014). Effects of subcutaneous carbon dioxide on calcitonin gene-related peptide and substance P secretion in rat skin. *Acta Cirurgica Brasileira, 29*(4), 224–230. https://doi.org/10.1590/S0102-86502014000400002
17. Brandi, C., Grimaldi, L., Nisi, G., Brafa, A., Campa, A., Calabrò, M., Campana, M., & D'Aniello, C. (2010). The role of carbon dioxide therapy in the treatment of chronic wounds. *In vivo, 24*(2), 223–226.
18. Macura, M., Ban Frangez, H., Cankar, K., Finžgar, M., & Frangez, I. (2020). The effect of transcutaneous application of gaseous CO2 on diabetic chronic wound healing-A double-blind randomized clinical trial. *International wound journal, 17*(6), 1607–1614. https://doi.org/10.1111/iwj.13436
19. Takano, K., Kasamatsu, S., Aoki, M., & Takahashi, Y. (2023). Reduction of extracellular pH induced by carbon dioxide enhances extracellular matrix production via CREB-dependent upregulation of TGF-β1 in human dermal fibroblasts. *Experimental dermatology, 32*(10), 1651–1662. https://doi.org/10.1111/exd.14867

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DETERMINATION OF THE SAFETY AND EFFECTIVENESS OF CARBOXYTHERAPY IN IN VIVO MODELS OF OSTEOARTHRITIS AND TENDON INFLAMMATION

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Research into the effectiveness of using a tourniquet to stop bleeding "SICH-Tourniquet"

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The experience of combat medics in the conditions of full-scale Russian aggression against Ukraine has demonstrated a huge amount of massive bleeding in the event of combat trauma. The operation of tourniquets is a fundamental element of modern tactical medicine. Objective. To assess the effectiveness of the tourniquet for stopping bleeding «SICH-Tourniquet» and to build a mathematical model that would allow predicting the pressure under the tourniquet based on individual anthropometric and hemodynamic parameters of a person. Materials. The study involved 130 volunteers aged 10 to 73 years, including 20 children. The gender distribution was as follows: 55 (42.3 %) men and 55 (42.3 %) women, as well as 20 children (10–17 years; 7 girls, 13 boys) Results. Observation included measurement of hemodynamic parameters, assessment of application time, pain syndrome, capillary test, effectiveness of dry and wet tourniquet, as well as durability during repeated use. It was found that the tourniquet provides complete occlusion of arterial blood flow in both the upper and lower extremities, without significant difference from its position. Correlation and regression analysis allowed us to identify key factors that influence effective compression pressure. For the upper extremities, the following statistically significant predictors were: gender, arm circumference, and body mass index. For the lower extremities, the following had the greatest influence: age, hip circumference, and diastolic pressure. Conclusions. Simplified models suitable for predicting pressure in field conditions were created. «SICH-Tourniquet» demonstrated high efficiency, reliability and safety, particularly in the pediatric group. The resulting mathematical models can be used to optimize individual compression selection in tactical and emergency medical care.

Досвід бойових медиків в умовах повномасштабної агресії росії проти України продемонстрував величезну кількість масивних кровотеч у разі бойової травми. Експлуатація турнікетів є основоположним елементом сучасної тактичної медицини. Мета. Оцінити ефективність джгута для зупинки кровотечі «СІЧ-Турнікет» та побудувати математичну модель, яка дозволяла би прогнозувати тиск під турнікетом на основі індивідуальних антропометричних і гемодинамічних параметрів людини. Методи. У дослідженні взяли участь 130 добровольців віком від 10 до 73 років, включаючи 20 дітей. За гендерним типом розподіл виглядав таким чином: 55 (42,3 %) чоловіків та 55 (42,3 %) жінок, а також 20 дітей віком (10–17 років; 7 дівчаток, 13 хлопчиків). Результати. Спостереження включало вимірювання гемодинамічних показників, оцінювання часу накладання, больового синдрому, капілярного тесту, ефективності сухого та мокрого турнікета, а також довговічності за багаторазового використання. Виявлено, що турнікет забезпечує повну оклюзію артеріального кровотоку як на верхній, так і на нижній кінцівці, без значущої різниці від її положення. Кореляційний та регресійний аналіз дозволив визначити ключові чинники, які впливають на ефективний компресійний тиск. Для верхньої кінцівки статистично значущими предикторами стали: стать, окружність руки й індекс маси тіла. Для нижньої кінцівки найбільший вплив мали: вік, окружність стегна та діастолічний тиск. Висновки. Створені спрощені моделі придатні для прогнозування тиску в польових умовах. «СІЧ-Турнікет» продемонстрував високу ефективність, надійність і безпеку, зокрема у педіатричній групі. Отримані математичні моделі можуть бути використані для оптимізації індивідуального вибору компресії в разі тактичної та екстреної медичної допомоги. Ключові слова. Джгут, зупинка кровотечі, математична модель, турнікет.

Keywords. Tourniquet, bleeding control, mathematical model, tourniquet

Introduction

The experience of combat medics during Russia's full-scale aggression against Ukraine has highlighted the significant prevalence of massive hemorrhages resulting from combat injuries. Injuries to the limbs, torso, or neck vessels can lead to critical blood loss within minutes, making timely intervention crucial. In many cases, even the best medical care will be ineffective if bleeding is not immediately controlled at the scene.

Tourniquets are categorized by their mechanism of action into pneumatic (gas cushion) and non-pneumatic (mechanical/band) types [1]. According to FDA classification, both pneumatic (21 CFR 878.5910) and non-pneumatic (21 CFR 878.5900) tourniquets fall under Class I. Among modern mechanical tourniquets, notable examples include the Combat Application Tourniquet (CAT) and its domestic counterpart, the "SICH-Tourniquet", which is widely used in emergency combat and crisis situations.

The use of tourniquets is a foundational element of modern tactical medicine. The Tactical Combat Casualty Care (TCCC) protocol emphasizes that the first critically important step in trauma care is controlling massive hemorrhage, which aligns with the MARCH algorithm (Massive hemorrhage, Airway, Respiration, Circulation, Hypothermia). This algorithm is widely used to prioritize care in tactical settings [2].

Classic studies on combat mortality (including those by R. F. Bellamy) have underscored the leading role of hemorrhage on the battlefield, highlighting the importance of timely tourniquet application for controlling massive bleeding [3]. As a result, contemporary military medicine places significant focus on tactical interventions for massive hemorrhages.

Objective: To assess the effectiveness of the "SICH-Tourniquet" for hemorrhage control and to develop a mathematical model that can predict the pressure exerted by the tourniquet based on individual parameters such as anthropometric measurements, blood pressure, age, and gender.

Materials and Methods

The study involved 130 volunteers aged between 10 and 73 years, who were either hospitalized or received outpatient care at the State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine from February to May 2025. Participants had no acute somatic disorders. Methodological support was provided by faculty members of the Medical Faculty at V. N. Karazin Kharkiv National University.

The gender distribution of participants was as follows: 55 males (42.3 %) and 55 females (42.3 %), as well as 20 children (ages 10–17; 7 girls and 13 boys). All participants provided informed consent and were insured by the Ukrainian insurance company "VELTA" (Lomonosova St. 4, Office 46, Kyiv, Ukraine, under insurance agreement No. 03KV/25 dated 06/02/2025). The study was conducted in accordance with the ethical principles outlined in the Helsinki Declaration of Human Rights, the Constitution of Ukraine, and relevant health care legislation, including all ethical guidelines for clinical research (Protocol No. 249 dated 21.02.2025, State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine).

For the modeling of tourniquet application, the "SICH-Tourniquet" was used, provided by the sponsor of the study, the limited liability company "SICH-UKRAINE."

Before the experiment, each participant was instructed and shown the technique of applying the tourniquet once. The participant performed the initial tight tightening of the strap manually by pulling on its free end, and then applied compression using the tourniquet's windlass, holding the tourniquet in place for 100 seconds.

The effectiveness of the tourniquet was tested by applying it sequentially to the middle of the upper arm (upper limb — UL) and the middle of the thigh (lower limb — LL). The same person performed all measurements. The cessation of blood flow was recorded by a single individual using Doppler ultrasound on the "GE Healthcare Logiq P9 XD clear" device. During this stage, two separate tourniquets were used: one applied to the middle of the upper arm, and the second to the middle of the thigh. The tourniquet was applied twice to the upper arm: once on the arm in the extended position and once on the arm bent at a 90° angle at the elbow joint. Similarly, the tourniquet was applied twice to the middle of the thigh: once on the leg in the extended position and once on the leg bent at a 90° angle at the knee joint.

The next stage of the study involved using a wet tourniquet. Before use, the tourniquet was submerged in water for 10 minutes, after which it was applied sequentially to the arm and leg in the extended position. The cessation of blood flow was also recorded using Doppler ultrasound. To determine the reliability and durability of the tourniquet under conditions of repeated use, the same tourniquet was applied to the middle of the upper arm of each participant.

The final stage involved self-application of the tourniquet and performing the actions mentioned above. The period between applications was no shorter than 5 minutes.

During the observation, the following parameters were collected:

– Anthropometric: age, gender, body mass index (BMI), circumference of the upper and lower limbs;

– Hemodynamic: systolic and diastolic blood pressure (SBP, DBP), heart rate (HR). Blood pressure was measured using the automatic PARAMED Flagman sphygmomanometer with a measurement accuracy of ±3 mmHg.

– Local hemodynamic: blood flow velocity before compression in the brachial artery, popliteal artery (*a. poplitea*), and posterior tibial artery (*a. tibialis posterior*); pressure in the sphygmomanometer and under the tourniquet cuff (sensor);

– Mechanical impact indicators: the number of windlass turns of the tourniquet until complete cessation of blood flow;

– Physiological reactions: capillary refill time (capillary test);

– Subjective assessment: pain score on the visual analog scale (VAS) and comfort level during the procedure.

After preliminary data processing, descriptive statistics were performed, correlation analysis was conducted, and a regression model was developed to predict the pressure under the tourniquet. Statistical analysis was carried out using licensed software SPSS 26 (Statistical Package for the Social Sciences) and R.

The study was conducted in the premises of the State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Medical Sciences of Ukraine under standard medical facility conditions with controlled microclimate parameters (temperature 20–24 °C, humidity 40–60 %), in accordance with the requirements for clinical trials.

Results

After data collection, the general functional state indicators of the study participants were determined (Table 1).

The average age was (46.0 ± 18.9) years, with women being significantly ($p < 0.001$) older at 52.4 ± 18.4 years compared to men (37.7 ± 15.5) years. The average BMI was 28.2 ± 7.4, with a statistically significant ($p < 0.001$) predominance in women.

The circumference of the upper limb was on average (31.8 ± 6.0) mm, with no significant difference between genders ($p = 0.958$). However, the circumference of the lower limb was significantly ($p = 0.039$) larger in women (52.8 ± 9.3 mm) compared to men (49.6 ± 7.8 mm). Women also showed a significantly ($p = 0.001$) higher systolic blood pressure of (129.5 ± 17.7) mmHg compared to men (119.3 ± 17.5 mmHg). No significant differences were found in DBP or HR.

SBP averaged (125.0 ± 18.3) mmHg, DBP was (79.5 ± 10.9) mmHg, and HR was (79.9 ± 13.2) beats per minute.

Hemodynamic parameters of arterial blood flow in patients before tourniquet application are shown in Table 2.

Table 1

General characteristics of study participants

Characteristics	Study group	Gender		
		male (n = 57)	female (n = 73)	difference (t, p, 95 % CI)
Age	46.0 ± 18.6 10.0 ÷ 75.0	37.7 ± 15.5 10.0 ÷ 67.0	52.4 ± 18.4 13.0 ÷ 75.0	t = –4.834; p < 0.001 [–20.7; 8.7]
BMI	28.2 ± 7.4 12.4 ÷ 46.6	25.6 ± 6.4 12.4 ÷ 45.8	30.2 ± 7.5 18.0 ÷ 46.6	t = –3.670; p < 0.001 [–7.0; –2.1]
Circumference of the upper limb	31.8 ± 6.0 15.7 ÷ 50.0	31.7 ± 6.3 15.7 ÷ 50.0	31.8 ± 5.8 22.5 ÷ 45.0	t = –0.053; p = 0.958 [–2.2; 2.0]
Circumference of the lower limb	51.4 ± 8.8 28.5 ÷ 89.0	49.6 ± 7.8 28.5 ÷ 68.0	52.8 ± 9.3 38.0 ÷ 89.0	t = –2.090; p = 0.039 [–6.2; –0.2]
SBP	125.0 ± 18.3 90.0 ÷ 170.0	119.3 ± 17.5 90.0 ÷ 160.0	129.5 ± 17.7 90.0 ÷ 170.0	t = –3.264; p = 0.001 [–16.3; –4.0]
DBP	79.5 ± 10.9 58.0 ÷ 110.0	77.5 ± 11.5 60.0 ÷ 110.0	81.0 ± 10.3 58.0 ÷ 100.0	t = –1.846; p = 0.067 [–7.3; 0.3]
HR	79.9 ± 13.2 54.0 ÷ 138.0	81.2 ± 14.1 60.0 ÷ 138.0	78.8 ± 12.4 54.0 ÷ 110.0	t = 1.013; p = 0.313 [–2.3; 7.0]

Upon analysis, no significant differences were found in the hemodynamic parameters of arterial blood flow across all patients, except for the posterior tibial artery (*a. tibialis posterior*), where blood flow velocity in men (50.3 ± 3.3 cm/s) was significantly ($p = 0.045$) higher than in women (48.6 ± 5.7 cm/s). However, it is worth noting that the range of blood flow velocity values in men overlapped with that in women, which may indicate the statistical significance could be coincidental.

The time taken to apply the tourniquet after training the participants was on average (26.3 ± 9.8) seconds, with a range from 10 to 88 seconds.

To ensure occlusion, it took (2.0 ± 0.3) turns of the windlass to apply the dry tourniquet and (2.3 ± 0.5) turns for the wet one, with the latter being statistically significantly greater ($t = -7.433$; $p < 0.001$).

No correlation was found between the circumference of the limb (arm) and the time taken to apply the tourniquet ($r = -0.133$; $p = 0.132$).

Applying the tourniquet to the arm or leg in an extended position versus when the joint was bent at a 90° angle did not show statistically significant hemodynamic differences depending on the position of the limb.

One of the indicators of the quality of the tourniquets is the degree of pain syndrome caused by limb compression, as well as the capillary refill index (Table 3).

A significant variation in the pain syndrome assessment was found during tourniquet application — ranging from 3 (mild) to 10 (intolerable), with the average score being (6.2 ± 1.7) points, indicating moderate intensity pain. The comfort level of the participants was relatively high, averaging (4.9 ± 0.3) points. The capillary refill time also varied, ranging from 3 to 8 seconds, which could be influenced by the condition of the vascular wall and blood parameters of the participants.

The study of the reliability and durability of the tourniquet with repeated use showed that the same tourniquet, applied consecutively on all participants, did not lose functionality or fixation reliability.

A separate experiment was conducted using a wet tourniquet — it was submerged in water, after which it was applied in the standard manner, and observations were made for 30 seconds. It was found that all physiological occlusion indicators were achieved, and the effectiveness of its use remained at the level of the dry tourniquet.

The study included participants from various age groups, including minors (children aged 10–17 years). No side effects related to the use of the tourniquet were noted. This supports the conclusion that it is safe and effective for use in pediatric practice.

No skin damage was observed following the use of the tourniquet in any case.

A mathematical model was developed to predict the pressure under the tourniquet based on an individual's parameters. In the first stage of the study, metric data for age and BMI were used to more accurately assess the prediction.

Assessment of Tourniquet Application on the Upper Limb

As noted, the effectiveness of the tourniquet is based on providing the required pressure under the cuff. To identify the factors influencing the magnitude of the pressure, a Pearson correlation analysis was performed. The results are presented in Table 4.

The circumference of the upper limb and BMI were found to be the most informative variables. The blood flow velocity in the brachial artery showed a weak negative correlation, but it was decided to include this parameter in the regression model. The cuff pressure of the sphygmomanometer has a nearly linear relationship with the dependent variable, so it will be excluded from further analysis. In addition to

Table 2

Hemodynamic parameters of blood flow in the arteries of the upper and lower limbs before applying the tourniquet

Blood flow velocity indicator, cm/s	Study group	Gender		
		male (n = 57)	female (n = 73)	difference (t, p, 95 % CI)
Brachial artery	68.7 ± 6.5 52.5 ÷ 78.9	69.6 ± 6.0 55.3 ÷ 78.9	68.0 ± 6.7 52.5 ÷ 78.9	t = 1.415; p = 0.160 [–0.6; 3.9]
Femoral artery	85.6 ± 6.2 70.5 ÷ 100.0	85.7 ± 5.9 75.3 ÷ 100.0	85.5 ± 6.5 70.5 ÷ 98.8	t = .218; p = 0.828 [–1.9; 2.4]
a. poplitea	69.0 ± 4.6 55.0 ÷ 79.5	69.2 ± 5.0 55.0 ÷ 75.6	68.8 ± 4.4 55.7 ÷ 79.5	t = .519; p = 0.605 [–1.2; 2.1]
a. tibialis posterior	49.3 ± 4.8 30.0 ÷ 57.0	50.3 ± 3.3 43.0 ÷ 55.0	48.6 ± 5.7 30.0 ÷ 57.0	t = 2.021; p = 0.045 [0.0; 3.4]

the above data, the "gender" variable was included in the regression model.

According to the regression analysis, the quality of the model was evaluated, and it was found that it explains 36 % of the variation in the pressure under the cuff ($R^2 = 0.360$), which is a moderate level for clinical research. The model is statistically significant ($F = 8.494$, $p < 0.001$). The predictors are presented in Table 5.

The constructed regression model revealed a statistically significant impact of gender, upper limb circumference, and BMI on the pressure level under the tourniquet. The most pronounced effects were observed for the upper limb circumference (β = 0.304; p = 0.009) and gender (β = –0.223; p = 0.013). A simplified model can be obtained by excluding the insignificant predictors (Table 6).

In the simplified regression model, built to predict the pressure under the tourniquet, the statistically significant predictors were gender (β = –0.196; p = 0.018), upper limb circumference (β = 0.295; p = 0.009), and BMI (β = 0.303; p = 0.012). Heart rate showed a tendency to affect the pressure (p = 0.072), but it did not reach statistical significance. The model is statistically significant (F = 16.705; p = 0.001) and explains 34.8% of the variation in the pressure level under the tourniquet, confirming its suitability for practical application in individualized control of compressive load.

The prediction equation is as follows:

$$\text{Pressure} = 34.05 - 0.910 \cdot \text{Gender} + 0.114 \cdot \text{Upper Limb Circumference} + 0.095 \cdot \text{BMI} + 0.024 \cdot \text{Heart Rate}. \quad (1)$$

The result of the predictive equation is presented graphically (Fig. 1).

In the graph showing the relationship between the predicted and actual values of the pressure under

Table 3

Assessment of tourniquet comfort and safety

Indicator	Value
VAS, points	6.2 ± 1.7 3 ÷ 10
Capillary test, sec	4.9 ± 1.0 3 ÷ 8
Comfort score, points	4.9 ± 0.3 4 ÷ 5

Table 4

Results of correlation analysis of the relationship between the pressure under the tourniquet cuff and other patient parameters

Characteristics	r	p-value	Interpretation
Age	0.248	0.004	Moderate positive correlation, significant
Circumference of the upper limb	0.518	0.001	Strong positive correlation, highly significant
BMI	0.476	0.001	Average positive, substantial
SBP	0.323	0.000	Moderate positive
DBP	0.280	0.001	Moderate positive
HR	0.214	0.015	Weak, but significant
Blood flow velocity in brachial artery (cm/s)	–0.212	0.016	Weak negative
Cuff pressure (Sphygmomanometer)	0.941	0.001	Very strong correlation (linear, associated)

Table 5

Significance and evaluation of predictors in the regression model

Regression model elements	B	β	t	p–value	Interpretation
(Constant)	33.449	—	—	—	—
Gender	–1.034	–0.223	–2.527	0.013	Women had lower pressure by approximately 1 mm Hg
Age	0.001	0.012	0.100	0.920	—
Circumference of the upper limb	0.118	0.304	2.648	0.009	As the circumference of the upper limb increases, the required pressure of the tourniquet also increases
BMI	0.081	0.258	1.970	0.051	Close to significance
SBD	0.033	0.258	1.420	0.158	—
DBP	–0.044	–0.207	–1.236	0.219	—
HR	0.024	0.135	1.766	0.080	Close to significance
Blood flow velocity in brachial artery	0.006	0.017	0.196	0.845	—

Table 6

Simplified regression model elements

Predictor	B	β	t	p–value	Interpretation
Constant	34.050	—	22.002	0.000	—
Gender	–0.910	–0.196	–2.397	0.018	In women, the pressure is, on average, lower by ~0.9 mm Hg.
Circumference of the upper limb	0.114	0.295	2.637	0.009	An increase in circumference by 1 cm → pressure +0.11 mm Hg.
BMI	0.095	0.303	2.536	0.012	Higher BMI → higher pressure (by ~0.1 mm per 1 kg/m²).
HR	0.024	0.136	1.815	0.072	At the threshold of significance, may have an effect

Table 7

Result of correlation of predictors on pressure of the tourniquet applied to the lower limb

Predictor	r	p–value	Interpretation
Gender	–0.022	0.801	—
Age	0.549	0.001	Moderate positive correlation, increases with age
Circumference of the lower limb	0.517	0.001	Moderate positive correlation with lower limb circumference
BMI	0.500	0.001	Moderate positive correlation with BMI
SBP	0.416	0.001	Moderate positive correlation with SBP
DBP	0.453	0.001	Moderate positive correlation with DBP
HR	0.106	0.232	Moderate positive correlation with HR
Blood flow velocity in the arteries:			Weak correlation with HR
– femoral;	0.155	0.079	
– popliteal	0.060	0.496	
– posterior tibial	0.119	0.178	
Pressure in the lower limb	0.990	—	Very weak correlation with blood flow velocity in the arteries

the tourniquet (Fig. 1a), the points are grouped along the diagonal, indicating a high degree of agreement between the model and the empirical data. Deviations from the ideal line (y = x) are minor, without systematic bias, confirming the high quality of the prediction. A visual assessment of the residuals plot (Fig. 1b) revealed no structural patterns. The dispersion of the residuals around zero is random, which supports the correctness of the model specification and the absence of significant deviations from the assumption of normality of errors.

BMI demonstrated a high positive correlation with the upper limb circumference ($r = 0.721$; $p < 0.001$), indicating a close connection between the overall mass-height characteristic and the local anatomical parameter. Therefore, the circumference of the arm can be considered a practical guideline for determining the individual sufficient level of compressive pressure.

Assessment of the Effectiveness of Tourniquet Application on the Lower Limb

To control the pressure, the presence of blood flow in the femoral, popliteal, and posterior tibial arteries was used. The predictors of influence are presented in Table 7.

According to the results of the paired correlation analysis, it was found that the pressure under the tourniquet on the lower limb significantly correlates with age ($r = 0.549$; $p < 0.001$), lower limb circumference ($r = 0.517$; $p < 0.001$), BMI ($r = 0.500$; $p < 0.001$), SBP ($r = 0.416$; $p < 0.001$), and DBP ($r = 0.453$; $p < 0.001$). The highest level of correlation was recorded with the pressure from the sphygmomanometer ($r = 0.990$), indicating almost perfect agreement between the results of sphygmomanometry and the measurements registered under the cuff.

Other predictors, such as gender, heart rate, and blood flow velocity in the main arteries (*popliteal, tibialis posterior*), did not show a statistically significant relationship with compressive pressure. The full regression model, which takes into account all significant predictors, is presented in Table 8.

The model is statistically significant ($F = 19.463$; $p < 0.001$) and explains 44.0 % of the variation in the pressure measured by the sensor on the lower limb ($R^2 = 0.440$). Standardized coefficients indicate that the most significant impact on the model comes from

Table 8

Full regression model

Predictor	B	β	t	p–value	Interpretation
(Constant)	33.395		17.892	0.001	—
Age	0.062	0.398	3.948	0.001	With increasing age, the effective pressure increases
Circumference of the lower limb	0.114	0.343	3.769	0.000	A larger circumference of the lower limb is associated with an increase in the measurement
BMI	0.020	0.052	0.470	0.639	Insignificant indicators
SBP	–0.047	–0.298	–1.834	0.069	
DBP	0.083	0.314	2.107	0.037	Higher diastolic blood pressure (DBP) is also associated with an increase in the result

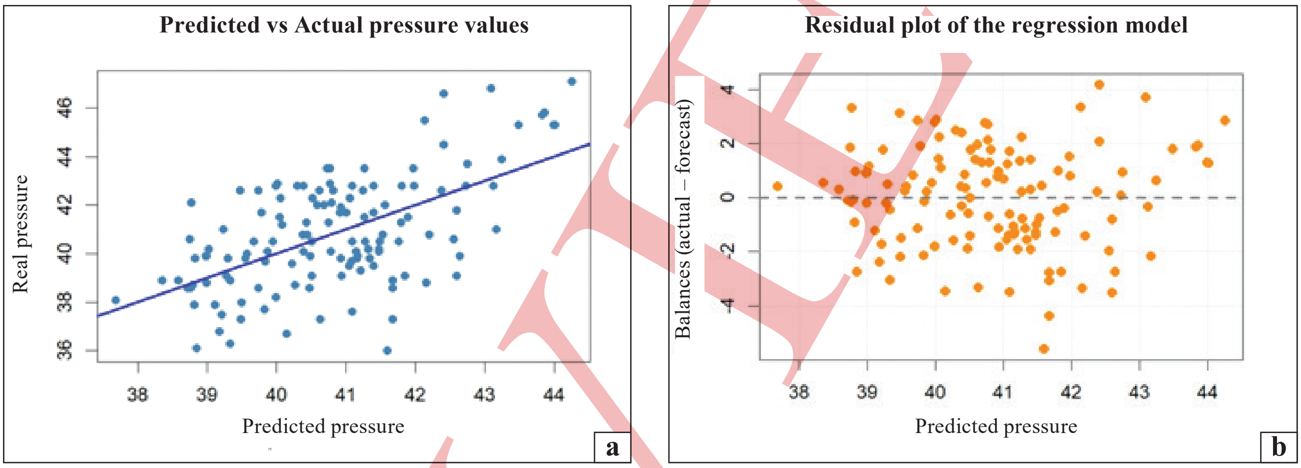

Figure 1. Graphical representation of the regression equation results: a) distribution of actual pressure under the cuff relative to the predicted line; b) evaluation of the regression equation residuals.

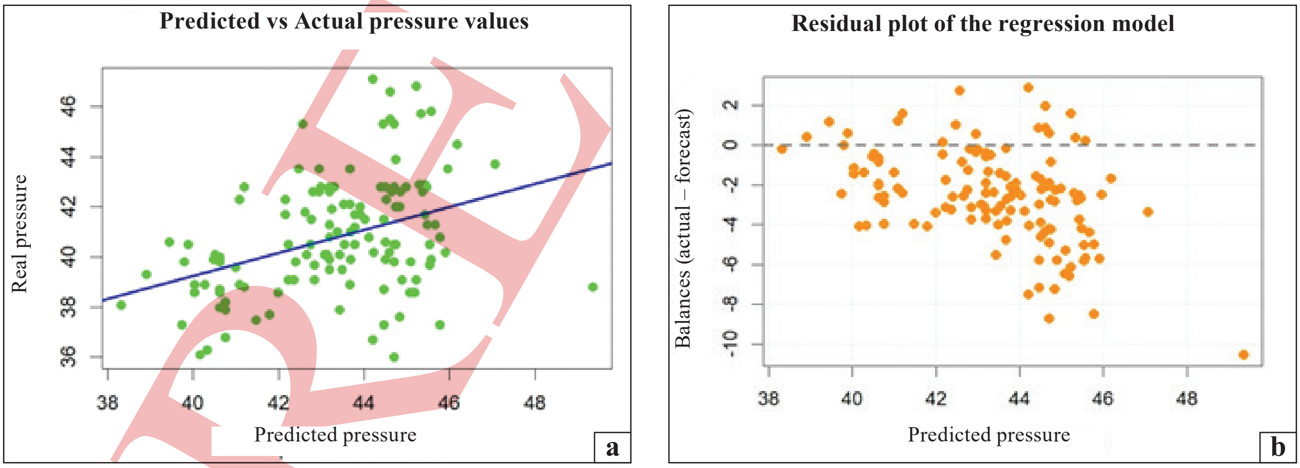

Figure 2. Graphical representation of the regression equation results: a) distribution of actual pressure under the cuff relative to the predicted line; b) evaluation of the regression equation residuals.

age (β = 0.398), lower limb circumference (β = 0.343), and DBP (β = 0.314).

Considering the high level of correlation between age and blood pressure (r ≈ 0.7), it was decided that it would be appropriate to use an ordinal age index as an integrated predictor, reflecting age-related changes in vascular reactivity. In the simplified regression model, which included only the age code and lower limb circumference, the coefficient of determination was R^2 = 0.44, confirming sufficient predictive ability for practical application. For model simplification, age was encoded according to the following principle:

1) 10–18; 2) 19–35; 3) 36–60; 4) 61+.

Table 9 shows predictors for the simplified predictive model.

Thus, the regression equation for the pressure level on the lower limb is as follows:

$$\text{Pressure} = 33.626 + 0.119 \cdot \text{lower limb circumference} + 1.278 \cdot \text{AgeCode}. \quad (2)$$

The graphical representation of the results of the regression equation is shown in Fig. 2.

In the graph showing the relationship between the predicted and actual values of the pressure under the tourniquet (Fig. 2a), the points are grouped along the diagonal, indicating a high degree of agreement between the model and the empirical data. Deviations from the ideal line (y = x) are minor, without systematic bias, confirming the high quality of the prediction. The residuals plot (Fig. 2b) shows a generally uniform distribution around the zero axis, but with a predominance of negative residual values. This asymmetry suggests that the model tends to slightly overestimate the predicted values in most cases. Nevertheless, there are no clear signs of non-linearity or heteroscedasticity.

One of the quality indicators for tourniquets, as mentioned earlier, is the degree of pain syndrome caused by limb compression, as well as the capillary index. Therefore, a correlation analysis was conducted between the pain level on the Visual Analog Scale (VAS), the capillary test, and the pressure under the tourniquet cuff and the limb circumference (Table 10).

The results of the correlation analysis indicate a statistically significant, but moderate, negative relationship between the pressure under the cuff and the subjective pain score on the VAS scale, both on the upper ($r = -0.297$; $p = 0.001$) and lower limbs ($r = -0.335$; $p < 0.001$). Thus, it is noted that as compressive pressure increases, the intensity of the pain sensation also increases.

A similar trend was observed for the upper limb circumference: individuals with smaller circumferences had a higher level of discomfort ($r = -0.287$; $p = 0.001$), which confirms the need for individualized compression based on anthropometric features.

Regarding the capillary response: a significant positive correlation was found only with the pressure under the tourniquet on the lower limb ($r = 0.234$; $p = 0.007$), which may indicate impaired microcirculation under increased compression. At the same time, no significant correlation with capillary response was found for other variables.

Discussion

According to the analysis of combat fatalities, early application of tourniquets is critical for survival in cases of severe limb injuries. In a comprehensive analysis of 4,596 combat fatalities from 2001 to 2011, conducted by B. J. Eastridge et al., hemorrhage dominated among potentially survivable deaths (90.9 %); fatal bleeding was predominantly located in the torso (67.3 %), followed by the junctional areas (19.2 %) and limbs (13.5 %) [4]. In the system-level analysis of the use of tourniquets, prehospital transfusion and reduced transport times were associated with 44.2 % of the total share of preventable deaths in the period from 2001 to 2017 [5].

The Committee on Tactical Combat Casualty Care (CoTCCC) recommends tourniquets as an effective

Table 9

Simplified regression model for predicting pressure under the tourniquet cuff on the lower limb

	B	β	t	p-value
(Constant)	33.626	—	29.008	0.001
Circumference of the lower limb	0.119	0.359	5.062	0.001
Age code	1.278	0.444	6.259	0.001

Table 10

Results of the correlation analysis of the relationship between pain level according to the VAS, capillary test, limb circumference, and pressure under the tourniquet cuff

Predictor	VAS		Capillary test	
	r	p–value	r	p–value
Pressure under the tourniquet cuff on the upper limb	–0.297	0.001	0.051	0.563
Circumference of the upper limb	–0.287	0.001	0.234	0.007
Pressure under the tourniquet cuff on the lower limb	–0.335	0.000	0.234	0.007
Circumference of the lower limb	–0.021	0.813	0.115	0.194

means for controlling bleeding from the limbs within tactical medicine protocols [6].

However, it should be noted that improper application or incorrect replacement of the tourniquet in combat conditions can lead to re-bleeding, which can be potentially fatal without proper control and staff training [7].

It is also important to note that this study included individuals aged 10 to 75 years, including adolescents (10–17), which provides grounds to consider the effectiveness of the device in pediatric practice. Modern principles for the application of tourniquets emphasize the importance of testing them in various populations, including pediatric patients. Studies demonstrate the effectiveness of tourniquets across a wide age range, requiring consideration of anatomical features for the development and evaluation of new models of tourniquets. In pediatrics, the Pediatric Trauma Society's position supports the use of tourniquets for life-saving indications; a meta-analysis of civilian data shows a reduction in mortality (OR ≈ 0.48) without increasing the risk of amputations or compartment syndrome [8].

An additional study, in which the same "SICH-Tourniquet" was applied to stop bleeding for 130 individuals consecutively, demonstrated the high wear resistance of the design without a loss of efficiency or mechanical damage, confirming the product's suitability for mass use in combat or emergency situations.

According to cohort studies [9] and a systematic review and meta-analysis, the benefits of tourniquets outweigh the potential risks: although isolated cases of nerve damage or tissue ischemia have been recorded, the incidence of serious negative consequences is low, especially when compared to lives saved. Specifically, a meta-analysis of the use of tourniquets in civilian patients with traumatic limb vascular injuries showed that their application in the prehospital stage nearly halved the risk of death from traumatic hemorrhage (OR = 0.48; 95 % CI 0.27–0.86), while not increasing the risk of limb amputation (OR = 0.85; 95 % CI 0.43–1.68) or compartment syndrome (OR = 0.94; 95 % CI 0.37–2.35) [10]. It should be noted, however, that according to the GRADE methodology, the quality of evidence was rated as "very low" due to the methodological limitations of the included studies.

Conclusions

It has been established that the pain syndrome during the application of the tourniquet is of moderate intensity. The comfort rating of the participants was quite high. The capillary test also showed high variability, which likely depended on the condition of the vascular wall and blood parameters of the participants. The subjective and physiological responses to compression showed statistically significant but weak correlations with pressure levels. This likely reflects individual variations in pain sensitivity and peripheral circulation status, which cannot be predicted solely based on compression parameters.

No difference was observed in the arterial blood flow indicators in patients of either gender, except for the data on *a. tibialis posterior*. The time required to apply the tourniquet after training of the participants was on average (26.3 ± 9.8) s, ranging from 10 to 88 s. To achieve occlusion, an average of (2.0 ± 0.3) turns were required for the dry tourniquet and (2.3 ± 0.5) turns for the wet one. No correlation was found between limb circumference and tourniquet application time.

Application of the tourniquet on the arm in the extended position and in the elbow joint flexed at 90°, as well as on the extended or flexed leg at the knee joint, showed no statistically significant hemodynamic differences depending on the position of the limb. The experiment with the wet tourniquet demonstrated the achievement of all physiological indicators of occlusion.

Based on the conducted research, there are grounds to consider the "SICH" tourniquet safe and effective for use in pediatric practice.

Considering the limited possibilities for operational measurement of parameters in field conditions, simplified yet sufficiently informative regression models have been developed, which take into account the minimum initial data. At the same time, given the specifics of the military population, where the predominant age range is 35–60 years, this factor can be considered conditionally stable.

The findings show that the "SICH-Tourniquet" for stopping hemorrhage fully meets its intended purpose, specifically for the complete temporary cessation of hemorrhage from the main vessels of the limbs.

Conflicts of Interest. The authors declare no conflict of interest..

Prospects for Further Research. Further studies will allow for the improvement of the tourniquet design and enhance the level of medical care provided.

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References

1. Office of the Federal Register. (2025.). Code of federal regulations (CFR) — TITLE 21 — Food and drugs. Washington (DC): U.S. Government Publishing Office
2. Strauss, R., Menchetti, I., Perrier, L., Blondal, E., Peng, H., Sullivan-Kwantes, W., Tien, H., Nathens, A., Beckett, A., Callum, J., & Da Luz, L. T. (2021). Evaluating the tactical combat casualty care principles in civilian and military settings: Systematic review, knowledge gap analysis and recommendations for future research. *Trauma surgery & acute care open, 6*(1), e000773. https://doi.org/10.1136/tsaco-2021-000773
3. Bellamy, R. F. (1984). The causes of death in conventional land warfare: Implications for combat casualty care research. *Military medicine, 149*(2), 55-62. https://doi.org/10.1093/milmed/149.2.55
4. Eastridge, B. J., Mabry, R. L., Seguin, P., Cantrell, J., Tops, T., Uribe, P., Mallett, O., Zubko, T., Oetjen-Gerdes, L., Rasmussen, T. E., Butler, F. K., Kotwal, R. S., Holcomb, J. B., Wade, C., Champion, H., Lawnick, M., Moores, L., & Blackbourne, L. H. (2012). Death on the battlefield (2001–2011). *Journal of trauma and acute care surgery, 73*(6), S431–S437. https://doi.org/10.1097/ta.0b013e3182755dcc
5. Howard, J. T., Kotwal, R. S., Stern, C. A., Janak, J. C., Mazuchowski, E. L., Butler, F. K., Stockinger, Z. T., Holcomb, B. R., Bono, R. C., & Smith, D. J. (2019). Use of combat casualty care data to assess the US military trauma system during the Afghanistan and Iraq conflicts, 2001–2017. *JAMA surgery, 154*(7), 600. https://doi.org/10.1001/jamasurg.2019.0151
6. Butler, F. K, Holcomb, J. B, …, & Shackelford, S. (2018). Advanced resuscitative care in tactical combat casualty care. *Journal of special operations medicine, 18*(4), 37–55. https://doi.org/10.1001/10.55460/YJB8-ZC0Y
7. Kragh, J. F., Walters, T. J., Baer, D. G., Fox, C. J., Wade, C. E., Salinas, J., & Holcomb, J. B. (2008). Practical use of emergency tourniquets to stop bleeding in major limb trauma. *Journal of trauma: injury, infection & critical care, 64*(2), S38–S50. https://doi.org/10.1097/ta.0b013e31816086b1
8. Cunningham, A., Auerbach, M., Cicero, M., & Jafri, M. (2018). Tourniquet usage in prehospital care and resuscitation of pediatric trauma patients — pediatric trauma society position statement. *Journal of trauma and acute care surgery, 85*(4), 665–667. https://doi.org/10.1097/ta.0000000000001839
9. Inaba, K., Siboni, S., Resnick, S., Zhu, J., Wong, M. D., Haltmeier, T., Benjamin, E., & Demetriades, D. (2015). Tourniquet use for civilian extremity trauma. *Journal of trauma and acute care surgery, 79*(2), 232–237. https://doi.org/10.1097/ta.0000000000000747.
10. Ko, Y., Tsai, T., Wu, C., Lin, K., Hsieh, M., Lu, T., Matsuyama, T., Chiang, W., & Ma, M. H. (2024). Effectiveness and safety of tourniquet utilization for civilian vascular extremity trauma in the pre-hospital settings: A systematic review and meta-analysis. *World journal of emergency surgery, 19*(1). https://doi.org/10.1186/s13017-024-00536-9.

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RESEARCH INTO THE EFFECTIVENESS OF USING A TOURNIQUET TO STOP BLEEDING "SICH-TOURNIQUET"

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