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Application of 3D Printing Technology in Minimally Invasive Pelvic Surgery

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Abstract
Background. Due to the technological progress in traumatology, there are more opportunities to apply MIPO (minimally invasive plate osteosynthesis) techniques for treating pelvic ring injuries. However, such problems as implant malposition due to complicated intraoperative visualization and the risks of postoperative complications remain relevant.
The aim of the study — to evaluate the effectiveness of 3D printing technology during preoperative planning and intraoperative navigation in minimally invasive surgery for pelvic injuries.
Methods. This study presents the experience of surgical treatment of 53 patients with various pelvic injuries using 3D technologies. The patients are divided into 3 groups depending on the location of injury: Group 1 — with isolated posterior pelvic ring injuries; Group 2 — with anterior and posterior pelvic ring injuries; Group 3 — with combined pelvic and acetabular injuries. The proposed technique involves the use of software to generate a digital model, 3D printing, conducting preoperative elaborate preparation on the plastic model, its sterilization and application as a navigation device during the operation for accurate positioning of metal fixators in intended directions.
Results. Five patients have dropped out of the study (3 foreigners, 1 patient was transferred to the psychosomatic department of related medical facility, 1 patient died as a result of pulmonary embolism at 1.5 months post-op). At the time of writing, 48 patients remained in the study: radiographic signs of fracture union were noted in 43 (90%) cases, in the remaining 5 (10%) cases, the follow-up period was less than the average fusion period (3 months). Among 43 patients with confirmed fracture union, the functional result 8 months after surgery according to the Majeed scale in Group 1 was 92 points, in Group 2 — 89 points, in Group 3 — 74 points. In 2 patients, after fracture union, screw migration associated with osteoporotic changes was observed in the posterior pelvis. No other complications were noted.
Conclusions. Accurate reduction and stable minimally invasive fixation of pelvic ring injuries, combined with 3D technologies, are of great importance for early rehabilitation of patients, especially given the morpho-anatomical variability of the pelvic bones. This approach reduces the incidence of implant malposition and helps to minimize long-term consequences of the injury. The conducted retrospective study demonstrated the relevance, safety, and reliability of 3D printing technology in enhancing the diagnosis and treatment of patients with pelvic bone injuries

Keywords: minimally invasive osteosynthesis of pelvic bones, 3D technologies, minimally invasive pelvic surgery.

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Использование 3D-технологий в мини-инвазивной хирургии травм костей таза

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Реферат
Актуальность. Благодаря технологическому прогрессу в травматологии появляется больше возможностей для применения мини-инвазивных методов лечения травм тазового кольца. Однако остается актуальной проблема мальпозиции имплантатов ввиду затрудненной интраоперационной визуализации и рисков послеоперационных осложнений.
Цель исследования — оценка эффективности использования 3D-печати на этапах предоперационной подготовки и интраоперационной навигации в мини-инвазивной хирургии травм костей таза.
Материал и методы. В настоящем исследовании представлен опыт хирургического лечения 53 пациентов с различными травмами костей таза с использованием аддитивных технологий. Пациенты поделены на 3 группы в зависимости от локализации повреждения: группа 1 — с изолированной травмой заднего полукольца; группа 2 — с травмой заднего и переднего полукольца; группа 3 — с травмой заднего, переднего полукольца и вертлужной впадины. Предложенная методика предполагает использование программного обеспечения для формирования цифровой модели, 3D-печать на принтере, проведение предоперационной расширенной подготовки на пластиковой модели, стерилизацию модели и использование ее для навигации во время проведения операции для точности позиционирования металлофиксаторов в заданных направлениях.
Результаты. Из исследования выбыло 5 пациентов (3 иностранца, 1 пациент переведен в психосоматическое отделение смежного лечебного учреждения, 1 пациент скончался в результате тромбоэмболии легочной артерии через 1,5 мес. после операции). На момент написания статьи в исследовании осталось 48 пациентов: рентгенологические признаки консолидации переломов отмечены в 43 (90%) случаях, в остальных 5 (10%) случаях срок наблюдения был меньше среднего срока сращения (3 мес.). Функциональный результат через 8 мес. после операции у 43 пациентов с подтвержденной консолидацией по шкале Majeed в 1-й группе составил 92 балла, во 2-й группе — 89 баллов, 3-й — 74 балла. У 2 пациентов из 2-й группы после консолидации переломов наблюдалась миграция винта в задних отделах таза, связанная с остеопоротическими изменениями. Иных осложнений отмечено не было.
Заключение. Адекватная репозиция и надежная мини-инвазивная фиксация травм тазового кольца в сочетании с 3D-технологиями в хирургии таза при морфо-анатомической вариативности строения костей таза имеет большое значение для раннего функционального восстановления пациентов, снижает частоту мальпозиции имплантатов и уменьшает риск отдаленных последствий травмы. Проведенное ретроспективное исследование продемонстрировало актуальность, безопасность и надежность технологии 3D-печати для улучшения диагностики и результатов лечения пациентов с травмами костей таза.

Ключевые слова: мини-инвазивный остеосинтез костей таза, 3D-технологии, мини-инвазивная хирургия таза.

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INTRODUCTION

In recent years, trauma and orthopedic surgery have undergone significant changes due to the introduction of innovative technologies, such as C-arm fluoroscopy, computer navigation systems, intraoperative cone-beam computed tomography (CBCT), and additive technologies (AT).

AT is a manufacturing process that has been increasingly used in biomedical engineering since the late 1980s. The ability to produce improved, complex, and patient-specific biomedical products allows this technology to spread rapidly across various fields of healthcare [1]. The technology itself is based on the sequential layering of material to create three-dimensional objects, being the foundation of 3D printing.

One of the areas where AT shows great potential is in preoperative planning, particularly for identifying the optimal trajectories for implant placement in minimally invasive surgery for pelvic injuries. These procedures – including sacroiliac joint (SIJ) fixation, pubic symphysis disruption repair, and osteosynthesis of sacral, pubic, and ischial fractures – rely on stable pelvic bone fixation using screws, nails, or transpedicular systems inserted through small skin incisions or punctures [2, 3]. The complexity of such procedures lies in the absence of traditional intraoperative *ad oculos* and palpatory control, compounded by the intricate anatomical geometry of the pelvic bones and the proximity of numerous vascular and neural structures. Injury to these structures may lead to hematomas, thrombosis, a significant reduction in quality of life, and the development of chronic pain syndrome.

The choice of implant type and size is determined by the nature and location of the pelvic injury. To ensure accurate positioning and prevent implant malposition, various intraoperative methods are used to identify and assess the viability of bony corridors. Traditional techniques for controlling surgical accuracy and implant localization include the use of a C-arm, the surgeon's tactual sense, and, where available, intraoperative CBCT. These methods enable sufficient visualization of the relevant anatomical structures. Minimally invasive fixation techniques, including percutaneous approaches, reduce soft tissue trauma; however, the risk of vascular and nerve injury remains relatively high [4, 5, 6]. The reported rates of sacroiliac screw malposition under fluoroscopy range from 2 to 15% [7, 8], while nerve injury rates vary between 0.5 and 7.7% [9]. Recently, there has been a growing interest in the use of AT in pelvic surgery. However, clinical experience with this technology and the number of related publications remain limited.

The aim of the study – to evaluate the effectiveness of 3D printing technology during preoperative planning and intraoperative navigation in minimally invasive surgery for pelvic injuries.

METHODS

Study design

Study design: retrospective single-center.

At the Department of Traumatology of the Botkin Hospital (Moscow Department of Health), 53 surgeries were performed between November 2022 and July 2024 on patients with various pelvic bone injuries (a total of 78 fractures and 25 joint injuries).

Inclusion criteria:

– age over 18 years;

– closed uni- or bilateral sacral fractures in zones I and II according to the Denis classification, pubic bone fractures in all three zones according to the Nakatani classification, type B fractures of the posterior column of the acetabulum according to the Judet-Letournel classification, sacroiliac and pubic symphysis disruptions [8, 10, 11].

Exclusion criteria:

– open pelvic bone injuries;

– pelvic injuries requiring open reduction and internal fixation (ORIF);

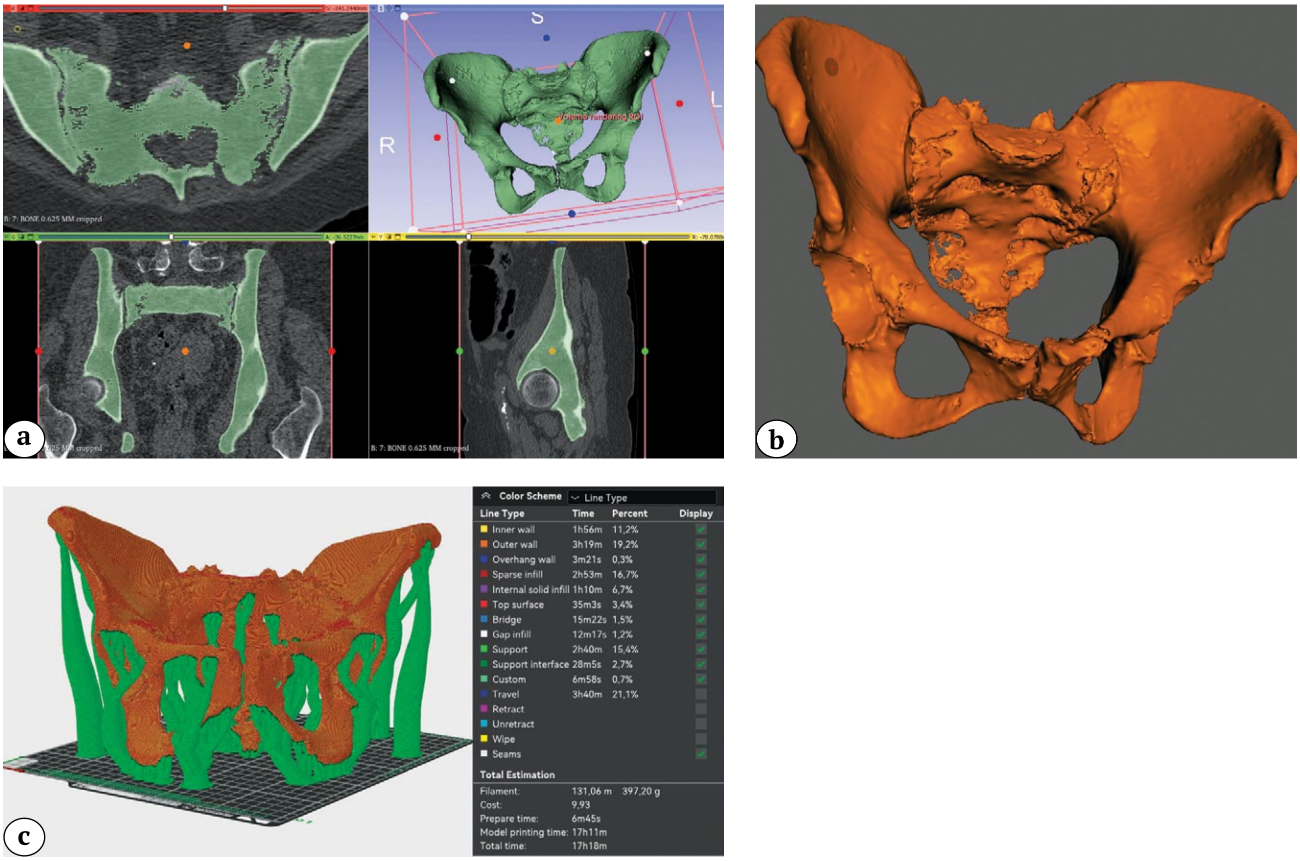
– polytrauma requiring surgical treatment of pelvic fractures within the first 24-48 hours after injury.

3D model generation technology

An intraoperative navigation technique based on 3D printing using an FDM printer and specialized 3D Slicer software [12], Autodesk Meshmixer, Bambu Studio Bambu Lab was employed. This study presents the experience of using 3D technologies for preoperative planning and intraoperative interaction between the surgeon and a volumetric polymer 3D model of the pelvic bones with various types of pelvic ring injuries, tailored to the specific clinical case and individual morpho-anatomical characteristics.

The method for creating a volumetric polymer model followed the protocol outlined below (Figure 1).

1. Performing a CT scan of the pelvis in a patient with a pelvic ring injury.
2. Segmenting the acquired DICOM files to isolate pelvic bone structures in 3D Slicer software and generating an initial digital model, which is then converted to STL format.
3. Stepwise post-processing of the STL file in Autodesk Meshmixer to obtain the final digital model and exporting it in STL format.
4. Preparing and adapting the final digital pelvic model for 3D printing in Bambu Studio Bambu Lab software.
5. Printing on an FDM printer using PLA (polylactic acid) or PETG (polyethylene terephthalate glycol) plastic. The average printing time for a full-scale 1:1 pelvic model was 16-19 hours.



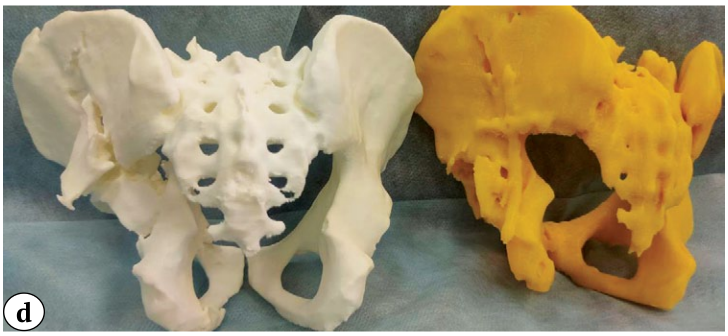


Figure 1. Stages of 3D model creation:
a — segmentation of DICOM files with isolation of pelvic bone structures in 3D Slicer software;
b — post-processing of the obtained digital model in Autodesk Meshmixer software;
c — preparation for 3D printing;
d — printed on an FDM printer model from PLA plastic (polylactide)

Preoperative planning using 3D models

The next step involved analyzing the resulting physical 3D model, discussing the clinical case to determine the surgical strategy, selecting the appropriate types and sizes of implants, assessing the associated risks of minimally invasive surgical treatment, and evaluating the accessibility and positioning of optimal safe bone corridors under visual control and using a C-arm (Figure 2).

The obtained results were documented photographically (Figure 3).

The physical 3D model was then sterilized using low-temperature plasma to allow intraoperative interaction with it (Figure 4).

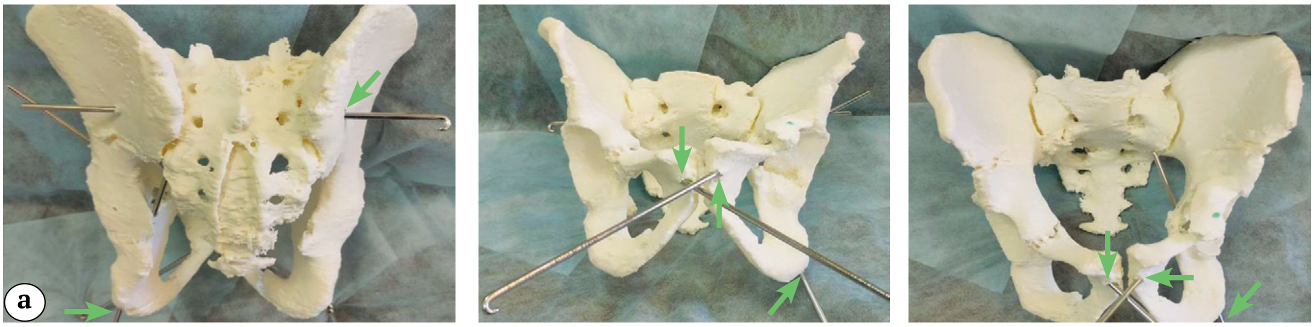
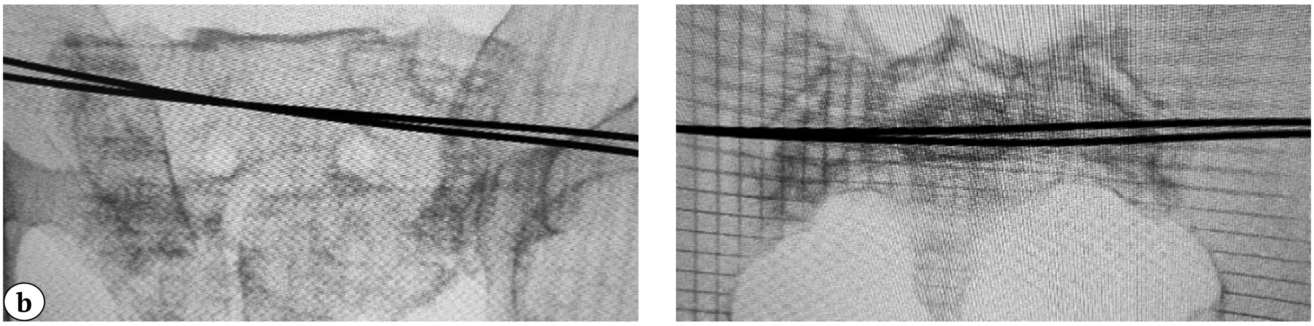


Figure 2. Evaluation of accessibility and positioning of optimal safe bone corridors:
a — visual control (green arrows indicate access points to safe bone spaces);
b — X-ray control after surgery using the obtained 3D model

Figure 3. Photograph of 3D model of the pelvic bones with wires (a) introduced in the S1 body and X-ray images of their position (b)



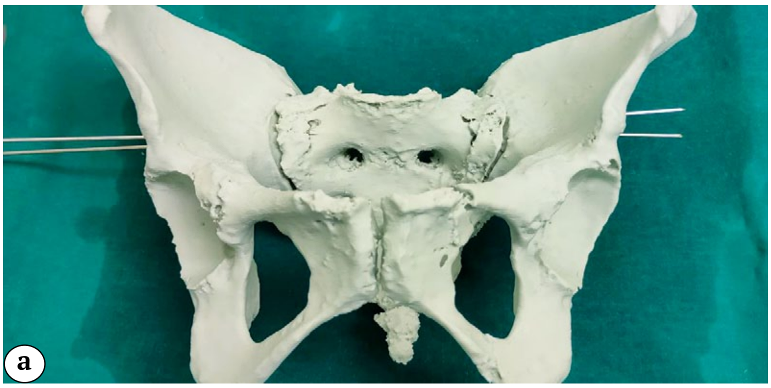
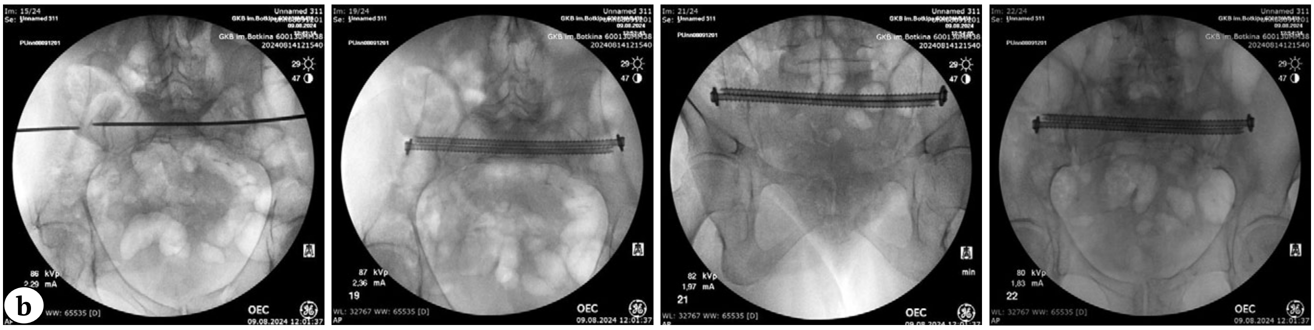


Figure 4 (a). Process and result of using 3D model:
a — model prepared for sterilization;



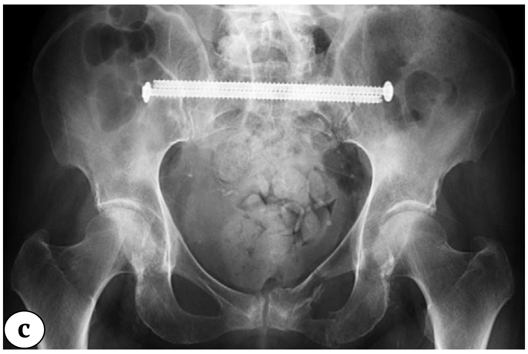


Figure 4 (b, c). Process and result of using the 3D model:
b — radiographic control during surgery;
c — postoperative X-ray

Selection of patients suitable for minimally invasive surgery for pelvic bone injuries

According to the Damage Control Orthopaedics (DCO) algorithm [13], the initial stage of treatment for patients with signs of pelvic ring instability involved stabilization with external fixators. In patients without obvious signs of instability, pelvic immobilization was performed using a pelvic band or was not required at all. After patient stabilization, creation of a patient-specific 1:1 scale plastic 3D pelvic model, surgical planning, and implant selection, the second stage was performed, which included definitive internal fixation using cannulated screws for the posterior pelvic ring and screws or nails for the anterior ring.

In patients with multiple or combined injuries, trauma severity was assessed using the Injury Severity Score (ISS). Pelvic fractures were classified according to the AO/OTA, Denis, and Nakatani classifications.

Indications for minimally invasive surgical treatment included:

1) vertically and horizontally unstable pelvic injuries with a time from trauma not exceeding 3 weeks;

2) pelvic injuries resulting from both frontal and sagittal compression;

3) pubic bone fractures in all Nakatani zones in combination with posterior pelvic ring injuries;

4) simple posterior column fractures of the acetabulum (type B according to the Judet-Letournel classification);

5) pubic symphysis diastasis with a residual gap of no more than 1.5 cm after stabilization with an external fixator;

6) sacroiliac joint disruptions, both uni- and bilateral;

7) sacral fractures in Denis zones I and II, H-shaped sacral fractures (61 C3.3 or 54 C2 (Spine) according to the AO/OTA classification) without neurological deficits.

Percutaneous low-trauma pelvic fixation technique was especially relevant for patients with moderate to severe post-traumatic anemia; with visceral obesity and local soft tissue detachment confirmed by ultrasound; with comorbidities such as *diabetes mellitus*, cardiovascular or renal insufficiency, and cancer; and for patients who remained on vasopressor support during the post-traumatic period.

Contraindications to minimally invasive surgery included:

1) local soft tissue damage or infection in the areas of the proposed surgical approach;

2) trauma older than 3 weeks;

3) narrow intramedullary canal of the pubic bone (less than 3 mm);

4) acetabular fractures requiring open reduction and internal fixation (ORIF);

5) sacral fractures in Denis zone III.

Based on the 3D models, a detailed evaluation was carried out, including sacral anatomy, sacral dysmorphism, sacralization or lumbarization of the sacrum, slope angles, and the curvature of the pubic bones.

Depending on the extent of pelvic injury, patients were divided into three groups: Group 1 — isolated injury of the posterior pelvic ring; Group 2 — injuries of both the posterior and anterior pelvic rings; Group 3 — injuries of the posterior and anterior rings combined with acetabular fractures (Table 1).

Statistical analysis

Descriptive statistical methods were used. The results are presented as median (Me), minimum and maximum values, and interquartile range [IQR].

Surgical technique and intraoperative navigation

The patient was positioned supine on a radiolucent operating table. A urinary catheter was inserted prior to the procedure to prevent iatrogenic injury. A pre-sterilized 3D-printed pelvic model with marked trajectories and implant entry points was prepared, along with printed fluoroscopic images showing the placement of previously inserted fixators or guiding wires in various projections.

Fluoroscopic control of the guiding wires and implants, and their comparison with the 3D model was performed throughout the procedure in standard views: inlet, outlet, anteroposterior, lateral, obturator, and iliac (according to Judet).

Through small skin incisions of 1.0-1.5 cm, guiding wires were introduced into various pelvic bone structures. Navigation was performed by comparing the wire positions and angles with the 3D model and by assessing the spatial orientation of the surgeon's hands (Figure 5).

Adjustments to wire placement were made as necessary, followed by repeated comparison with the 3D model. Then, in accordance with the preoperative plan, definitive hardware fixation was carried out: cannulated screws (6.5 or 7.3 mm, fully or partially threaded, with/without washers), a locking nail in the pubic bones, and 3.5 mm stainless steel cortical screws. Implant orientation in the patient's pelvic bones was compared with the pre-set implants in the plastic model. Final fluoroscopic control was performed, followed by suturing and application of aseptic dressings. If previously used, the external fixator was removed at this stage.

Table 1

Distribution of patients by injury location

Parameter		Value
Total number of patients, n		53
Injury location, n (%)	Posterior pelvic ring (Group 1)	17 (32%)
	Posterior and anterior pelvic rings (Group 2)	34 (64%)
	Posterior and anterior pelvic rings and the acetabulum (Group 3)	2 (4%)
Total number of fractures, n		78
Fracture location, n (%)	Posterior pelvic ring	45 (58%)
	Posterior and anterior pelvic rings	31 (40%)
	Posterior and anterior pelvic rings and the acetabulum	2 (2%)
Total number of joint injuries, n		25
Joint injury location, n (%)	Pubic symphysis	7 (28%)
	Sacroiliac joint	18 (72%)

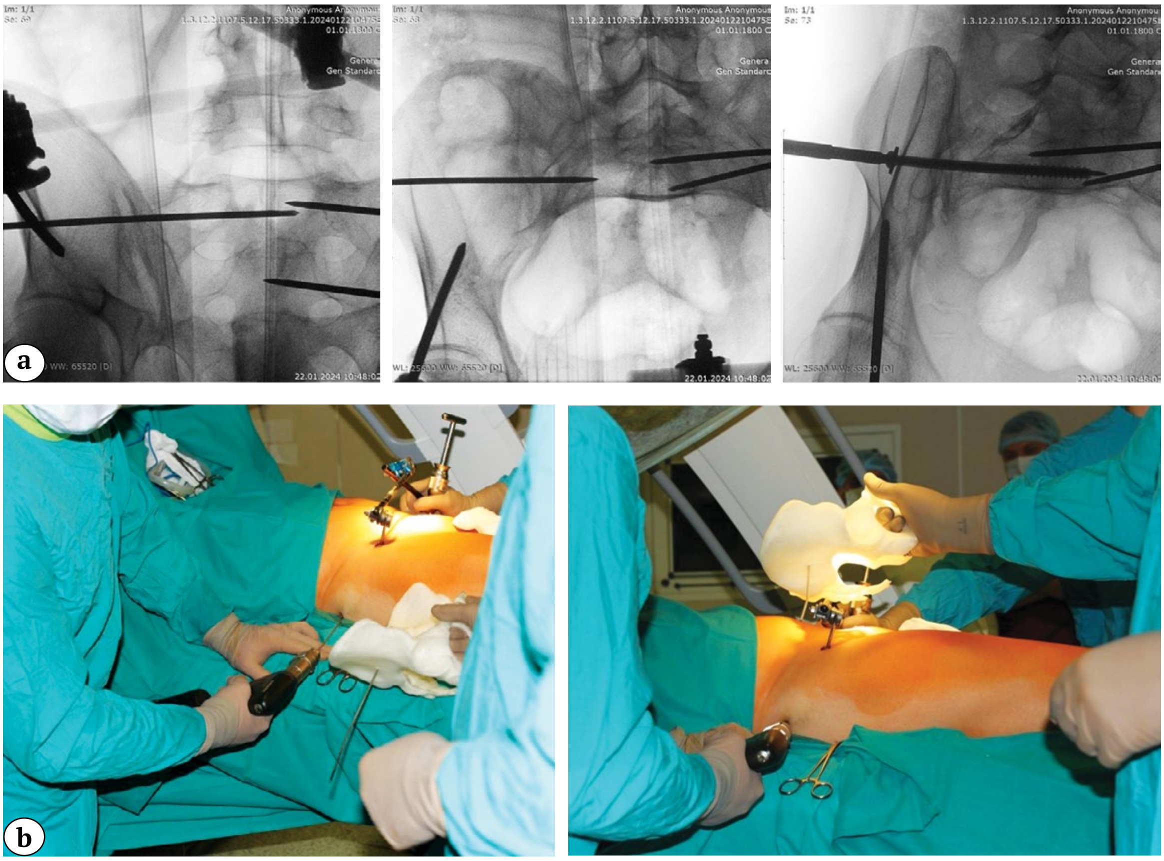


Figure 5. Intraoperative navigation: a — X-ray control; b — using a 3D model during surgery

Postoperative care

Patients with stable hemodynamics were mobilized on the first postoperative day. Those with multiple or combined injuries were allowed to roll over their side and sit up to prevent hypostatic complications. Sutures were removed on postoperative days 14-16.

All patients underwent radiographic and CT control within the first 24-48 hours after operation. In selected cases, digital models were reconstructed from CT data and used to create new physical models. Follow-up radiological assessments were performed at 1, 2, 3, 6, and 8 months postoperatively.

RESULTS

The first stage of treatment, fixation using tubular external fixator, was performed in 44 (83%) patients with the signs of pelvic ring instability. The characteristics of the surgical treatment are presented in Table 2.

Table 2

Surgical treatment characteristics in patient groups, n = 53

Parameter	Value
Time to the second stage, days, Me [IQR]	4.00 [2.00-6.00]
Group 1	2.00 [2.00-4.00]
Group 2	4.00 [2.00-6.00]
Group 3	12.00 [10.00-14.00]
Duration of operation, min, Me [IQR]	45 [25-55]
Group 1	20 [20-25]
Group 2	50 [45-55]
Group 3	80 [80-85]
Blood loss, ml, Me [IQR]	20 [10-30]

No cases of malpositioning of implants were detected on postoperative pelvic bone CT scans. In all cases, the postoperative wounds healed by primary intention. Five patients were excluded from the study: three were foreign nationals, one was transferred to the psychosomatic department of an affiliated medical facility, and one patient died as a result of pulmonary embolism 1.5 months after the surgery.

The total number of patients remaining in the study was 48. At the time of writing, the radiological signs of fracture union were observed in 43 (90%) cases: 13 patients from Group 1, 29 patients from Group 2, and 1 patient from Group 3. In the remaining 5 (10%) cases, the follow-up period was shorter than the average time required for bone union (3 months) (Table 3). The long-term functional outcome at 8 months postoperatively, assessed using the Majeed scoring system, is presented in Table 4.

No neurological complications, inflammatory changes in the postoperative wound area, or secondary displacement of fragments were observed in any case. In 2 patients from Group 2, four months after sacral fracture osteosynthesis the bone union was confirmed by CT; however, screw migration was noted against the background of pronounced osteoporotic changes. This required surgical removal of the migrated implants. No other complications were recorded during the study period.

Table 3

Radiologically confirmed bone union, n = 48

Parameter	Group 1	Group 2	Group 3
Fracture location, n (%)	14 (29.1%)	33 (68.8%)	1 (2%)
Bone union, n (%)			
3 months	9 (18.8%)	17 (35.4%)	–
4 months	2 (4.2%)	6 (12.5%)	–
5 months	2 (4.2%)	3 (6.3%)	–
6 months	–	–	–
7 months	–	3 (6.3%)	–
8 months	–	–	1 (2%)
Insufficient follow-up period	1 (2%)	4 (8.3%)	–

Table 4

Functional outcome according to the Majeed scale, n = 43

Parameter	Group 1	Group 2	Group 3
Fracture location, n (%)	13 (30.2%)	29 (67.4%)	1 (2%)
Majeed scale, points, Me [IQR]	92 [81-96]	89 [74-94]	74

DISCUSSION

At the present time, orthopedic trauma surgeons increasingly prefer minimally invasive methods of internal fixation for unstable pelvic injuries. Traditional techniques of internal fixation involve extensive and traumatic surgical approaches, which are associated with a significant blood loss, a high risk of neurovascular injury, and the development of infectious complications. Consequently, there is an ongoing search for less aggressive osteosynthesis techniques for pelvic ring injuries [3, 4, 14, 15, 16, 17]. Percutaneous screw implantation in the pelvic bones is a technically demanding procedure that requires the surgeon to have a thorough understanding of potential implant trajectories and their radiological visualization [18]. Not only the variability of pelvic bone anatomy but also factors such as obesity play a significant role, as the latter complicates intraoperative radiological navigation, thereby increasing the risk of iatrogenic nerve injuries. Malpositioning of screws in the sacral area by as little as 4° may result in damage to neural and vascular structures, with reported rates of such complications reaching up to 7.7% [19]. Although the incidence of these complications can be reduced through the use of digital intraoperative navigation systems during implant placement, this method still does not guarantee 100% accuracy in screw positioning [19, 20]. Furthermore, digital navigation systems such as the StealthStation Spine Referencing Set (Medtronic Sofamor Danek, Memphis, TN, USA) and 3D C-arm fluoroscopy with compatible software are high-cost tools that are not available in every hospital, and the final outcomes are closely linked to the surgeon's proficiency and experience with this technology [21, 22]. As an alternative method for screw placement, the use of a three-dimensional patient-specific guide for wire insertion into the posterior pelvic ring can be considered [23]. However, this technique requires precise, individualized manual modeling of the guides, as well as a more aggressive surgical approach to secure the guide tool onto the pelvic bones. The uniqueness of pelvic injury mechanisms, the combination of various injury patterns, the existence of numerous diverse classification systems, and the lack of a standardized surgical treatment algorithm complicate communication among clinicians and hinder decision-making regarding surgical tactics during treatment planning for such injuries.

3D printing technology has become widely adopted across various fields of medicine. Clinical applications of 3D printing have been described, and unified reference guides for its use in trauma surgery are being developed [24, 25]. In the present study, digital DICOM data from patients' CT scans were converted into STL files, which served as blueprints for subsequent full-scale 3D printing of physical models using various polymers. This approach provided excellent visualization and tactile perception of the sustained injuries in their actual size and scale. The resulting 3D model creates the conditions for personalized, precise, and rational surgical planning. Surgeons gain complete visualization of all elements of pelvic injuries prior to surgery, serving as a basis for developing an optimal surgical strategy that minimizes surgical injury. Rehearsing osteosynthesis on plastic pelvic models improves the accuracy of fracture reduction and the stability of the achieved fixation [26]. The implementation of 3D-printing-assisted surgery in the clinical management of pelvic trauma represents a safe and valuable adjunct that contributes to optimal perioperative outcomes and reduces the rate of complications [27].

The present study describes the surgical management of patients with various types of pelvic ring injuries using intraoperative navigation based on 3D models or 3D-printing assistance. The opportunity to perform preoperative osteosynthesis simulation enabled the optimization of implant selection, and the development of a fracture and joint injury reduction algorithm. The method allowed for the analysis of available bony corridors for implant placement at the preoperative stage without the risk of iatrogenic complications. The data obtained through preoperative analysis contributed to reducing radiation exposure for both patients and medical staff, shortening operative time, and ensuring accurate implant positioning. Operating surgeons reported a significant increase in the efficiency and convenience of percutaneous pelvic fracture fixation procedures when using 3D models as navigation aids. They noted that additive technologies facilitate precise implant placement despite the morpho-anatomical variability of the pelvic bones. Moreover, the 3D anatomical models improve communication between the physician and the patient, helping to explain the severity and nature of the injury, the specific features of the upcoming surgical intervention, and potential risks, which, in turn, enhances patient compliance in the post-traumatic and postoperative periods [27]. Another important advantage of additive technologies is the reduction of the learning curve duration in the training of young surgeons [26].

The radiological and functional outcomes assessed using the Majeed scoring system demonstrated excellent and good treatment results, which corresponded to an advanced level of care for pelvic bone injuries [28, 29].

It is important to acknowledge the limitations of the 3D printing approach, including the requirement for personnel with expertise in additive technologies, specialized software, dedicated 3D printers, and a sufficient supply of consumable materials. Factors such as the time needed to generate the digital model – segmentation (10-40 minutes), post-processing (10-15 minutes), slicing and print preparation (10-15 minutes) – as well as the actual 3D printing time for a full-scale pelvic model (13-19 hours) must also be taken into account. Furthermore, the learning curve associated with the implementation of 3D printing in a medical facility may affect both the quality of the printed models and the time required for their production.

This study was conducted on a small patient cohort with a relatively short follow-up period; therefore, further accumulation of clinical experience and analysis of the obtained results is required.

CONCLUSIONS

Accurate reduction and stable minimally invasive fixation of pelvic ring injuries, combined with 3D technologies, are of great importance for early rehabilitation of patients, especially given the morpho-anatomical variability of the pelvic bones. This approach reduces the incidence of implant malpositioning and helps to minimize long-term consequences of the injury. The conducted retrospective study demonstrated the relevance, safety, and reliability of 3D printing technology in enhancing the diagnosis and treatment of patients with pelvic bone injuries.

DISCLAIMERS

Author contribution

All authors made equal contributions to the study and the publication.

All authors have read and approved the final version of the manuscript of the article. All authors agree to bear responsibility for all aspects of the study to ensure proper consideration and resolution of all possible issues related to the correctness and reliability of any part of the work.

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