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ORIGINAL PAPER

Conventional plate fixation method versus pre-operative virtual simulation and three-dimensional printing-assisted contoured plate fixation method in the treatment of anterior pelvic ring fracture

Chun-Chi Hung [1] · Yuan-Ta Li [1] · Yu-Ching Chou [2] · Jia-En Chen [3] · Chia-Chun Wu [1] · Hsain-Chung Shen [1] · Tsu-Te Yeh [1]

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Abstract

Purpose Treating pelvic fractures remains a challenging task for orthopaedic surgeons. We aimed to evaluate the feasibility, accuracy, and effectiveness of three-dimensional (3D) printing technology and computer-assisted virtual surgery for pre-operative planning in anterior ring fractures of the pelvis. We hypothesized that using 3D printing models would reduce operation time and significantly improve the surgical outcomes of pelvic fracture repair.

Methods We retrospectively reviewed the records of 30 patients with pelvic fractures treated by anterior pelvic fixation with locking plates (14 patients, conventional locking plate fixation; 16 patients, pre-operative virtual simulation with 3D, printing-assisted, pre-contoured, locking plate fixation). We compared operative time, instrumentation time, blood loss, and post-surgical residual displacements, as evaluated on X-ray films, among groups. Statistical analyses evaluated significant differences between the groups for each of these variables.

Results The patients treated with the virtual simulation and 3D printing-assisted technique had significantly shorter internal fixation times, shorter surgery duration, and less blood loss (− 57 minutes, − 70 minutes, and − 274 ml, respectively; $P < 0.05$) than patients in the conventional surgery group. However, the post-operative radiological result was similar between groups ($P > 0.05$). The complication rate was less in the 3D printing group (1/16 patients) than in the conventional surgery group (3/14 patients).

Conclusion The 3D simulation and printing technique is an effective and reliable method for treating anterior pelvic ring fractures. With precise pre-operative planning and accurate execution of the procedures, this time-saving approach can provide a more personalized treatment plan, allowing for a safer orthopaedic surgery.

Keywords Pre-operative virtual simulation · Three-dimensional printing · Pelvic fracture · Plate fixation

Introduction

The treatment of pelvic fractures remains one of the most challenging tasks for orthopaedic surgeons because of the complex anatomy, morphological variations, and limited surgical access to the fracture sites. Currently, two-dimensional (2D) and three-dimensional (3D) computed tomography (CT) images are used in conjunction with plain X-rays to identify the main fracture components and their spatial relationship with one another. However, because these images are viewed on a 2D screen, they provide limited insight into the true physical configuration of the fracture and optimal surgical management that should be used. The 3D printing technique has been adopted in clinical orthopaedics recently. It allows rapid construction of accurate, full-scale individual fracture models so that surgeons can observe, take measurements, and even practice surgery on the models.

Although posterior pelvic ring fixation is more important for pelvic fracture management, anterior ring fixation is necessary to restore pelvic congruity and stability under some circumstances [1, 2]. Given the morphological variations among individuals and varied pelvic fracture

✉ Tsu-Te Yeh
tsutey@gmail.com

1 Department of Orthopaedic Surgery, Tri-Service General Hospital and National Defense Medical Center, 325 Cheng-Kung Road, Section 2, Taipei 114, Taiwan, Republic of China

2 School of Public Health, National Defense Medical Center, Taipei, Taiwan, Republic of China

3 National Defense Medical Center, Graduate Institute of Aerospace and Undersea Medicine, Taipei, Taiwan, Republic of China

patterns, creating a universal contoured fixation plate suitable for every patient and achieving optimal anatomical contouring intra-operatively are difficult [3]. The impreciseness of plate contouring intra-operatively results in sub-optimal fracture reduction. A 3D model of the fracture pattern can be generated to prepare a pre-bend fixation plate adapted to the complex orthopaedics [4, 5]. Determining screw lengths during surgery may not be accurate enough and could result in complications and prolong operation time. Studies have shown that surgery combined with 3D printing technology allows surgeons to prepare for surgical pelvic reconstruction economically and effectively [6]. We believed it might be possible to use a 3D printing technique in treating pelvic anterior ring fractures, thereby reducing surgery duration, blood loss, and operative complications and achieving an overall better surgical result.

This study describes a method in which a 3D printing technique was used in patients with anterior pelvic ring fractures, and fixation plates were shaped pre-operatively based on a 3D-printed model. We hypothesized that the 3D printing technique would reduce operation time and significantly improve the surgical outcomes of pelvic fracture repair. The aim of the study was to evaluate the feasibility and effectiveness of 3D printing technology for pre-operative planning in anterior ring fractures of the pelvis. We retrospectively compared 3D printing techniques with conventional surgical treatment with respect to surgical outcomes. To the best of our knowledge, our study is the first to perform this comparison.

Patients and methods

This study retrospectively assessed 51 patients with traumatic pelvic ring fractures that underwent surgery at the Tri-Service General Hospital in Taiwan from November 2012 to September 2017. The inclusion criterion was undergoing open reduction for anterior pelvic ring and internal fixation with locking plates. The exclusion criteria were (1) fractures on tumourous bone, (2) fractures complicated by extra-pelvic bleeding, (3) fractures fixed with other implants, and (4) fractures with concomitant traumatic brain injury. Based on these inclusion and exclusion criteria, a total of 30 consecutive patients were included. All patients underwent CT (3-mm axial slices) and diagnostic radiography, and fracture types were classified according to the Tile classification [3]. These 30 patients were divided into two groups: conventional surgery group (group 1) and 3D printing group (group 2; Table 1). The study was approved by the XX Medical Center Institutional Review Board. All patients provided written informed consent. All procedures were in accordance with the Declaration of Helsinki.

Table 1 Demographic data

	Group 1 ($n = 14$) Conventional treatment	Group 2 ($n = 16$) 3D printing	P value[a]
Age (year), M ± SD	35.64 ± 17.37	35.44 ± 13.52	0.971
Sex, n (%)			1.000
Men	8 (57.10)	10 (62.50)	
Women	6 (42.90)	6 (37.50)	
BMI (kg/m^2)	21.72 ± 3.74	23.40 ± 4.52	0.281
Tile classification, n (%)			0.717[b]
A (stable)	1 (7.10)	1 (6.30)	
B (partial stable)	8 (57.10)	6 (37.50)	
C (unstable)	5 (35.70)	9 (56.30)	
Duration from injury to surgery (days), M ± SD	10.21 ± 7.57	9.13 ± 4.30	0.640
Plate configuration, n (%)			0.128[b]
L	1 (7.10)	3 (18.80)	
L, (S)	2 (14.30)	2 (12.50)	
R	5 (35.70)	4 (25.00)	
R, (S)	1 (7.10)	1 (6.30)	
R, L	0 (0)	5 (31.30)	
R, L, (S)	1 (7.10)	1 (6.30)	
R, S	1 (7.10)	0 (0)	
S	3 (21.40)	0 (0)	
Number of plates, n (%)			1.000
1	9 (64.30)	10 (62.50)	
2	5 (35.70)	6 (37.50)	

Plate configuration: L: left anterior column plate; L, (S): left anterior column plate and spanning the pubic symphysis to contralateral side; R: right side anterior column plate; R,(S): right side anterior column plate and spanning the pubic symphysis to contralateral side; R, L: bilateral anterior column plates; R, L, (S): bilateral anterior column plates spanning the pubic symphysis to contralateral side with some holes overlapping; R, S: one right side anterior column plate and one symphyseal plate; S: symphyseal plate

M ± *SD* mean ± standard deviation, *BMI* body mass index

[a] *t* test or chi-square

[b] Fisher's exact test

Surgical technique

All operations were performed with the patient under general anesthesia by one surgeon. Patients were positioned on the radio-transparent operation table in the supine position. An ilioinguinal approach or combination with the modified Stoppa approach were used.

In group 1, a thin metal template was used to determine plate shape and length. The reconstruction plate was contoured according to the template to fit the cranial surface of the superior pubic ramus and iliac bone. A commercial in situ plate bending instrument (DePuy Synthes, Switzerland) was used for plate minor adjustment.

In group 2, CT scans were converted to DICOM images and imported into the medical imaging processing software (MIMICS, version 19, Belgium). A 3D image was created using MIMICS on a personal computer (Fig. 1a). Using the splitting process, bilateral femurs were erased and the pelvis isolated (Fig. 1b). The reduction methods for fractured bones included segmentation, split, mirror, and reposition techniques in the software depending on the fracture patterns (Fig. 1c, d). The reduced pelvis model was then exported in an STL format for 3D printing. The patient-specific pelvis model (1:1 model) was manufactured by a fused deposition modeling apparatus (UP BOX+, Tiertime, China) (Fig. 2). The required plate length and position, as well as screw number, location, and length, were determined by this life-size 3D-printed model. The straight reconstruction plate (Civic, Taiwan) was contoured pre-operatively according to the patient-specific pelvis model (Fig. 3). We minimized the surgical skin incisions with two separate 5-cm incisions over the suprapubic and iliac crest regions and minimized soft tissue dissection (Fig. 4). After adequate fracture site reduction, the pre-contoured anatomic plate was applied for fixation in an appropriate position. In some patients, plate lengths spanned the symphysis pubis and were attached to the contralateral superior pubic ramus if needed (Fig. 5). All of the previous procedures were performed by the two orthopedic physicians. One physician possessed a 3D-printing engineering license; thus, there was no need for an additional engineer or extra cost.

The post-operative rehabilitation protocol was based on the fracture type of each patient. Generally, mobilization during the first week post-surgery without weight-bearing was suggested. Protected partial weight-bearing was allowed after six weeks, and full weight-bearing was permitted after two months.

Outcome measures

We obtained plain radiograms of the patients' pelvis immediately post-surgery; they were followed up every three months within one year and twice a year in the next one year to evaluate the condition of the reduction, implant placement, and fracture healing. A radiological analysis was performed using the standard anteroposterior, inlet, and outlet view plain radiograms of the pelvis. All radiological assessments were performed by a physician who did not participate in the treatment. The radiological results were graded according to the maximal residual displacement of the fracture site after operation. The results were graded as good, (0–2 mm), fair (2–4 mm), and poor (> 4 mm). The outcome measures were total operation time, instrumentation time, blood loss amount, complications, and reduction achieved from the surgery. The operation time was recorded from the initial skin incision to the complete wound closure based on the medical record. Intra-operative blood loss was quantified by measuring the amount of irrigation fluid and weighing surgical sponges used for blood and fluid collection during surgery. Complications included infections, neurovascular injuries, erosion of soft tissues overlying the implant, screw loosening, implant brakeage or loosening, and nonunion.

The chi-squared test was used to compare total surgical duration, instrumentation time, and blood loss volume between the two groups. Fisher's exact test was used to compare

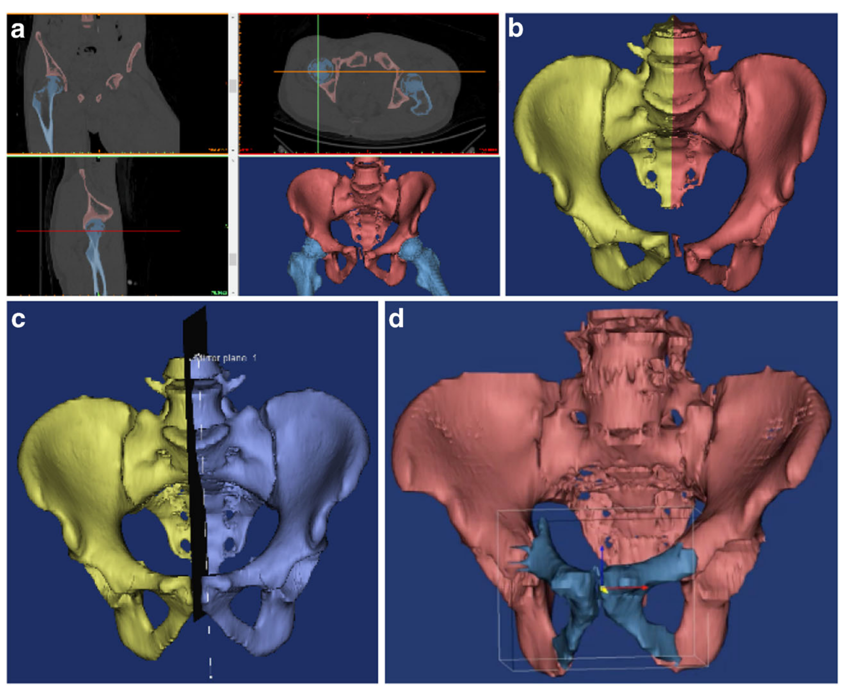

Fig. 1 Steps in simulation for manufacturing bone model included segmentation (**a**), split (**b**), mirror (**c**), and reposition (**d**) techniques

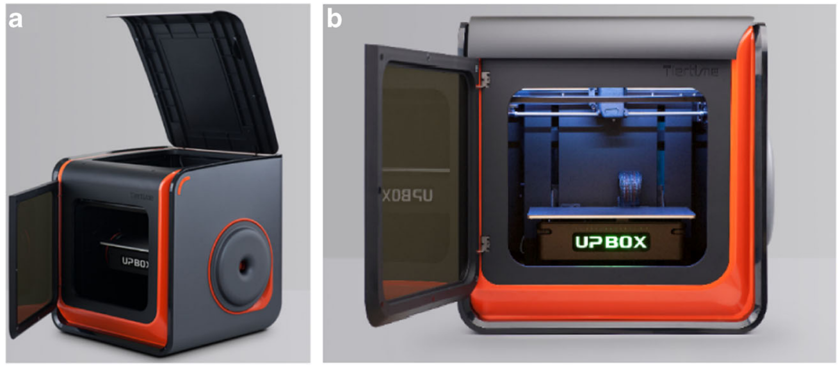

Fig. 2 3D model printer (UP BOX+, Tiertime) a. side view, b. front view

the radiological results and complications between the two groups. A $P < 0.05$ was considered statistically significant. The Statistical Package for the Social Sciences software (version 22.0, USA) was used for all statistical analyses.

Results

Clinical data

In group 1, the mean age of the 14 patients was 35.64 ± 17.37 years, and the mean body mass index (BMI) was 21.72 ± 3.74 kg/m^2. There were one Tile type A, eight type B, and five type C fractures. In group 2, the mean age of the 16 patients was 35.44 ± 13.52 years. Of these 16 patients, and the mean BMI was 23.40 ± 4.52 kg/m^2. There were one Tile type A, six type B, and nine type C fractures. Table 1 summarizes patient characteristics, and the demographics between both groups were comparable (all $P > 0.05$). The mean follow-up duration of the patients was 24.3 months (range, 5–63 months), and no patients were lost to follow-up.

Fig. 3 Patient-specific 3D-printed model and pre-contoured plate based on this model. Plate length and screw length could be estimated pre-operatively

Peri-operative clinical parameters

In group 2, the preoperative virtual simulation time was 46.56 ± 22.78 minutes. Printing time for the life-size 3D model was 929.06 ± 206.38 minutes. The time required for pre-operatively contouring the plate was 62.50 ± 21.45 minutes.

The mean surgical duration in group 1 was 276.21 ± 89.53 minutes, but it was 206.13 ± 70.32 minutes in group 2; the difference was statistically significant ($P < 0.05$). The mean instrumentation time in group 1 was 102.86 ± 25.85 minutes and 45.63 ± 15.26 minutes in group 2, which was a significant difference ($P < 0.001$). The mean blood loss in group 1 was 549.29 ± 404.43 ml, and 275.00 ± 196.64 ml in group 2, which was a significant difference ($P < 0.05$; Table 2).

Post-operative fracture displacement

In group 1, good, fair, and poor grades were observed in eight, four, and two cases, respectively. In group 2, good, fair, and poor grades were observed in 13, three and zero cases, respectively. The post-operative radiological results between groups were similar ($P = 0.237$).

Fig. 4 Surgical incision. The lateral window of the ilioinguinal approach combined with a modified Stoppa approach was used

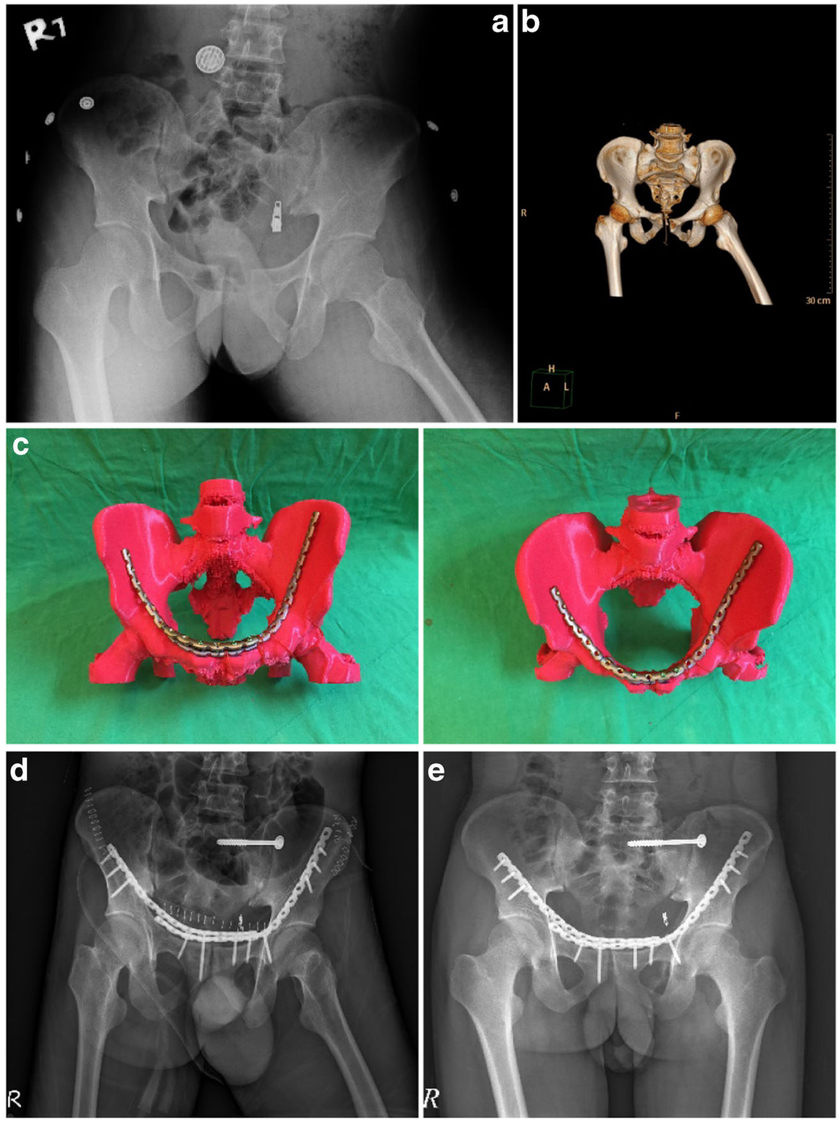

Fig. 5 A 23-year-old man with both anterior and posterior ring fractures of the pelvis underwent 3D printing technology assisted surgery. **a** Pre-operative plan radiography of pelvis. **b** Pre-operative 3D reconstruction CT showed bilateral pubic rami fractures and diastasis of the pubic symphysis. **c** 3D printed model and pre-contoured plate. **d** Post-operative radiography of pelvis. **e** Three months post-op follow-up radiography of pelvis

Post-operative complications

Three patients that experienced complications occurred in group 1, including bladder rupture with vesico-cutaneous fistula formation, implant loosening, and implant failure. Only one patient (1/16) had a complication (bladder rupture) in group 2 and underwent immediate intra-operative repair. No neurovascular injury or surgical wound infections were found peri-operatively. Nonunion or delayed union was not observed on follow-up radiograms.

Discussion

Recent advances in imaging techniques including CT allow surgeons to accurately identify fracture morphology, but a complete understanding of fracture patterns remains difficult. The recently adopted 3D printing method allows rapid and accurate construction of a full-scale individual model, which can facilitate visualization of the fracture pattern and complex pelvic anatomy prior to surgery. Surgeons can manipulate the segmented bones or fragments in a virtual simulation and therefore determine the best sequential reduction procedures. They can choose the appropriate surgical incision and approach. The fixation implant can be pre-contoured according to the 3D patient-specific pelvis model, and the screw length could be estimated pre-operatively, which decreases the risks of implant-related complications. Moreover, the pre-contoured plate can serve as an anatomic plate for efficient fracture reduction during pelvic surgery. This is the same concept as the indirect reduction technique for proximal humeral fracture fixation using anatomic locking plates [7]. These 3D printing techniques have been successfully used in orthopaedic surgeries [6, 8–13] and improved the surgeon's efficiency, shorten surgical duration, and reduce iatrogenic complications [14].

Table 2 Patient outcome parameters

	Group 1 ($n = 14$)	Group 2 ($n = 16$)	P value[a]
Software time (min), M ± SD	–	46.56 ± 22.78	–
3D printing time (min), M ± SD	–	929.06 ± 206.38	–
Pre-contour time (min), M ± SD	–	62.50 ± 21.45	–
Operation time (min), M ± SD	276.21 ± 89.53	206.13 ± 70.32	0.023
Instrumentation (min), M ± SD	102.86 ± 25.85	45.63 ± 15.26	< 0.001
Blood loss (ml), M ± SD	549.29 ± 404.43	275.00 ± 196.64	0.023
Post-operative X-ray film			0.237[b]
Good (< 2 mm)	8 (57.10)	13 (81.30)	
Fair (2–4 mm)	4 (28.60)	3 (18.80)	
Poor (> 4 mm)	2 (14.30)	0 (0)	
Complication			
No	11 (78.60)	15 (93.80)	
Yes	3 (21.40)	1 (6.30)	

M ± SD mean ± standard deviation

[a] Chi-squared test

[b] Fisher's exact test

Conventional surgical methods require complete exposure of the fracture and contouring of the implant intra-operatively. This increases surgical invasiveness, which may be associated with unnecessary tissue damage and increased haemorrhage [15], and increases operative time, especially when the plate position needs to span the pubic symphysis. Compared with the conventional ilioinguinal approach, our pre-contoured plate could be applied with minimally invasiveness, bypassing the need for massive soft tissue dissection and detachment. Therefore, it could decrease lateral femoral cutaneous nerve injuries intra-operatively.

In this study, the surgical duration in group 2 was significantly less than that in group 1. This mainly resulted from the pre-bending of the fixation plate, which significantly decreased the instrumentation time ($P < 0.05$), taking 57 min less in group 2. Earlier studies without comparative analyses reported reduced surgical duration with appropriate pre-operative planning and utilization of pre-contoured plates [16, 17]. Given that 3D technique can be used to classify the fractures and to understand the morphology pre-operatively, the surgeon could make smaller incisions and perform fracture reduction more easily. Consequently, we were able to decrease the physical and psychological demands on the surgeons, as well as preclude the drawbacks associated with prolonged general anaesthesia and reduce fluoroscopy requirements [17].

In our study, the virtual simulation of a bone fracture reduction could be carried out within 20 and 90 minutes in some simple and complex fracture cases, respectively. The pre-operative 3D simulation and printing technique often required less than 24 hours to complete. However, this delay is not a concern for pelvic fractures in which surgery is recommended at least five to ten days post-injury. We recognized that the pre-contouring process saved an average of 70 minutes of operating room time and cost US$20 in plastic consumables. These results demonstrate that the proposed technique is economical and efficient for complex pelvic surgeries.

In our study, the blood loss in group 2 was significantly less than that in group 1 ($P < 0.005$), which was the result from efficient fracture reduction and surgery. Shen et al. reported less blood loss using virtually derived pre-contoured plates, with an average blood loss of 566 ml [13]. Shortening the operation time and smaller incisions help decrease intra-operative blood loss, thus improving haemodynamic stability.

Earlier studies have demonstrated improved fracture reduction using pre-contoured plates or virtual planning in pelvic fracture surgery [13, 16]. Herein, post-operative X-ray results between both groups were not statistically significant ($P = 0.237$). However, good reduction rates were achieved more frequently in group 2 than in group 1 (13 patients [81.3%] and eight patients [57.1%], respectively). Furthermore, two of the 14 patients in group 1 had poor grading compared to zero of the 16 patients in group 2. This seems that the 3D printing technique facilitates fracture reduction in pelvic surgery. It is likely that the result was not statistically significant because of the small number of enrolled cases or the lack of variety of fracture patterns. Despite the lack of statistically significant results, a trend toward better fracture reduction performance was noted in group 2. Although the same level of fracture reduction was achieved in group 2, the shorter surgical duration in this group was statistically significant. Therefore, we believe that the 3D printing technique is an efficacious method for pelvic fracture treatment. CT is considered a far better choice for assessments of fracture displacement than plain radiography [18]. Further studies should evaluate the influence of the 3D printing technique on fracture reduction using CT.

The numbers and rate of complications in the group 2 were less than those in group 1 (1/16 and 3/14 patients, respectively). We believe that shorter surgical and anaesthesia duration, decreased blood loss, decreased destruction of soft tissues, and precise implant fixations are helpful in decreasing complications. With the aid of the printed models, plates can be chosen and contoured accurately for optimal compactness with the bone surface. This ensures the accuracy and mechanical strength of the reduction, minimizes dissection of surrounding soft tissue, and protects blood supply surrounding the bony fragments, which can help improve fracture healing and reduce the risks of post-operative malunion or nonunion.

Some limitations could be noted in this study, including the retrospective design and comparatively small sample size. It was not a randomized-controlled blinded study and focused on the peri-operative results rather than long-term clinical outcomes. In addition, it did not address the functional outcomes between groups; therefore, only techniques and initial experiences could be described well in the present study. A larger patient population is needed to further assess its clinical application. Further studies should seek to prospectively assess the influence of the 3D printing-assisted, pre-contoured plate fixation method on treatment outcomes.

Overall, the 3D simulation and printing technique is an effective and reliable method for the treatment of anterior pelvic ring fractures. This technique, combined with computer-assisted virtual surgical procedures, permits economical and efficient surgical simulations of complex pelvic fractures, provides a more personalized treatment plan, and increases safety.

Compliance with ethical standards

Conflict of interest The authors declare they have no conflicts of interest.

Research involving human participants and/or animals

Ethical approval The study was approved by the National Defense Medical Center Institutional Review Board. All procedures were in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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