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ORIGINAL ARTICLE

Efficacy of 3D printing-assisted treatment for acetabular fractures

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ABSTRACT

Objectives: The aim of this study was to investigate the efficacy of three-dimensional (3D) printing-assisted treatment for acetabular fractures (AFs) and to compare with conventional surgical methods.

Patients and methods: Between May 2019 and May 2022, a total of 44 patients (33 males, 11 females; mean age: 40.6±11.8 years; range, 20 to 68 years) who were diagnosed with AFs based on clinical symptoms, X-ray and computed tomography (CT) and underwent open reduction and internal fixation in Hospital of Xinjiang Production and Construction Corps were retrospectively analyzed. The patients were divided into two groups based on whether 3D printing was applied as the experimental group (n=24) and control group (n=20). In the experimental group, pelvic and acetabular data were imported into a 3D printer, and an equal-scale highly simulated model was printed using photosensitive resin as the 3D printing material. The model was used to develop more specific personalized surgical plans, to determine the optimal sequence of surgical procedures for fracture reduction, and simulate surgery *in vitro*.

Results: In the experimental group, the mean surgical duration was shorter (123.57±22.05 *vs*. 163.57±26.20 min, p<0.001), the mean intraoperative bleeding loss was lower (557.14±174.15 *vs*. 885.71±203.27 mL, p<0.001), and the frequency of intraoperative fluoroscopy was lower (8.64±1.65 *vs*. 12.07±2.76, p<0.001) than in the control group. No statistically significant differences were found between the two groups in the Visual Analog Scale scores after surgery or the hip function score after treatment (p>0.05). No major postoperative complications were observed in any of the patients.

Conclusion: Compared to conventional surgical treatment, preoperative 3D printing-assisted treatment for adult patients with AFs can significantly reduce surgical duration, intraoperative bleeding loss and frequency of intraoperative C-arm fluoroscopy, reducing surgical difficulty and improving surgical safety.

Keywords: Acetabular fracture, computer simulation, internal fixation, pre-formed plate.

Acetabular fractures (AFs) are a very serious fracture type, accounting for 1 to 3% of whole-body fractures. For AFs with surgical indications, early surgery is crucial for achieving anatomical reduction and reconstructing hip function.[1-3] However, surgical difficulty and risk increase due to the deep position of the acetabulum, complex anatomical structure, irregular bone structure, susceptibility to damage to surrounding tissues, blood vessels and nerves intraoperatively, and multiple types of fractures.

The acetabulum is a critical load-bearing joint in the human body, and AFs are intraarticular fractures. According to the AO principles, AFs require anatomical reduction and rigid internal fixation.[4] The conventional surgical treatment for AFs distinguishes their types mainly based on preoperative X-ray and computed tomography (CT) scanning + three-dimensional (3D) imaging reconstruction, and preoperative incisions are mainly planned based on surgeons' experience. Although CT has greatly improved the understanding of AFs, it is unable to analyze the details of fractures from various perspectives.

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The 3D printing technique plays a key role in the formulation of surgical plans and is more intuitive than conventional imaging techniques; it is also beneficial for the implementation of surgery.[5] As 3D printing is widely applied in various fields of orthopedics, it has brought new developments to AF treatment. Additionally, it improves accuracy in the understanding of the AF and better guides its clinical classification by restoring the actual condition of the AF on the affected side in a 1:1 ratio. Moreover, through the mirror effect of the acetabulum on the healthy side, the reconstruction plate can be performed before surgery, saving the time required for intraoperative implant placement.[6] A recent study supported the feasibility of using 3D spinal implants.[7] A systematic review showed that 3D printing technology-assisted surgery reduced operative time, intraoperative blood loss, and bone healing time compared to conventional surgery, without causing significant complications.[8] Similarly, 3D printing was found to be effective and safe in the surgical treatment of anatomically complex fractures of the limb skeleton.[9]

There are many advantages to applying 3D printing in AF surgery, and using this technology may be helpful in understanding a patient's fracture and planning surgery. However, there is a limited number of studies in the literature comparing the efficacy of 3D printing-assisted preformed plates with conventional surgical methods in adult AF treatment and whether AF patients will, indeed, benefit from 3D printing technology still requires further validation.

In the present study, we aimed to investigate the efficacy of 3D printing-assisted treatment for AFs and to compare with conventional surgical methods in AF treatment among adults to provide new ideas for the treatment of AFs.

PATIENTS AND METHODS

This single-center, retrospective study was conducted between May 2019 and May 2022. Using a convenience sampling method, a total of 44 patients (33 males, 11 females; mean age: 40.6±11.8 years; range, 20 to 68 years) diagnosed with AFs based on clinical symptoms, X-ray and CT who underwent open reduction and internal fixation in Hospital of Xinjiang Production and Construction Corps, Department of Orthopaedic were included. The patients were divided into two groups based on whether 3D printing was applied as the experimental group (n=24) and control group (n=20).

Inclusion criteria were as follows: *(i)* patients with AFs aged 18 to 70 years who became injured within the past three weeks and had a body mass index (BMI) of <30 kg/m^2 and surgical indications; *(ii)* who had stable preoperative conditions, could tolerate surgery and had no surgical contraindications; *(iii)* who were informed along with their family about the treatment plan and were willing to pay for the cost of 3D printing; and *(iv)* who followed medical advice during treatment, cooperated with the postoperative follow-up and had relatively complete follow-up data. Exclusion criteria were as follows: *(i)* patients with AFs who were underage or required conservative treatment; *(ii)* had open fractures, pathological fractures or old AFs (>3 weeks); *(iii)* had life-threatening complications or severe medical diseases that were not effectively controlled; and iv) did not follow medical advice during treatment and had poor compliance during follow-up, resulting in incomplete or missing follow-up data.

Preoperative 3D printing and surgical plan design

The main function of 3D-printed models is to reconstruct patients' anatomical structures, allowing surgeons to gain a better understanding of fracture conditions and providing more detailed images. The pelvic thin-slice CT scanning data (Gemstone spectral CT scanner provided by the central hospital of our hospital, with a slice thickness of 1 mm) of the experimental group were transmitted to the ADW4.6 workstation for 3D reconstruction. The 3D-reconstructed data in Digital Imaging and Communications in Medicine (DICOM) format were imported into the Mimics version 21.0 software (Materialise, Leuven, Belgium) using the computer to generate 3D images of the pelvis, and the data were checked and corrected to remove artifacts (Figure 1). After removing the femoral head from the 3D images of the pelvis, individual fracture fragments were marked and a virtual reduction of the fractures was achieved through separation, rotation and translation on the computer to obtain the restored pelvic shape (Figure 2). The pelvic and acetabular data were imported into the Hongtai HT-480S light-cured resin-mould 3D printer (Hongtai Technology Co., Laguna, Philippines), and an equally proportional highly simulated model was printed using photosensitive resin as the 3D printing material. Through omni-directional observation of the displacement of the acetabular models, fractures could be better classified to develop more specific

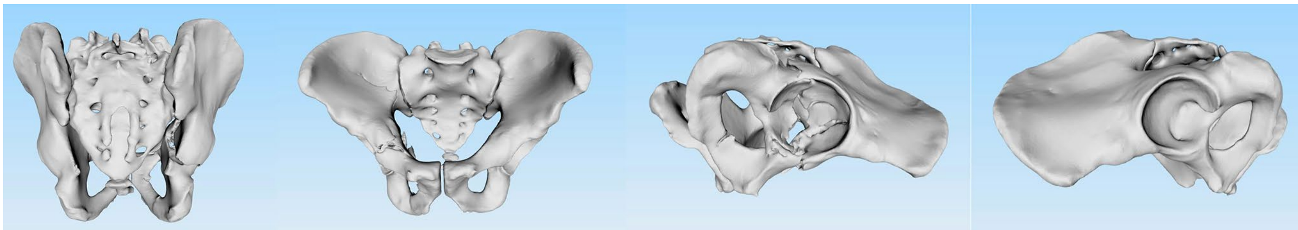

FIGURE 1. Omni-directional observation on degree of fracture displacement after modeling.

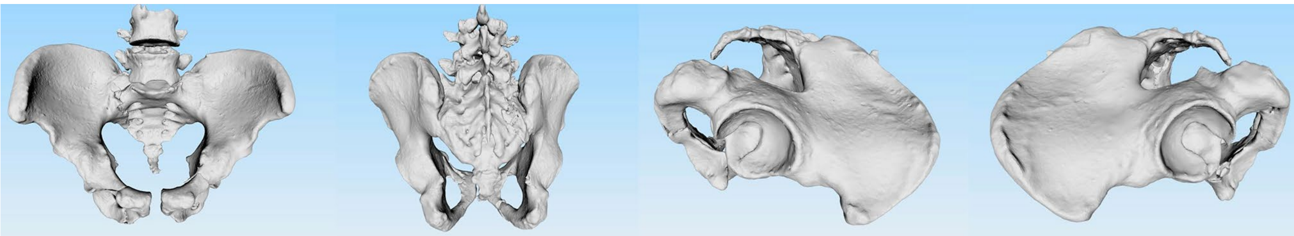

FIGURE 2. Image of 3D pelvis model after simulated restoration.

personalized surgical plans. Repeated practices of fracture reduction were conducted in the laboratory to determine the optimal sequence of surgical procedures for fracture reduction. Appropriate plates and screws were selected, and the plates were pre-bent to simulate surgery *in vitro*. In the control group, AFs were diagnosed and classified based on the pelvic X-ray, pelvic CT and 3D reconstruction data, and surgical plans were empirically designed.

Intraoperative processing

Under general anesthesia, the patients were placed in the supine position while using the ilioinguinal approach or the lateral rectus abdominis approach. After routine disinfection and towel laying, the skin, subcutaneous tissue and muscular layer were incised layer by layer until the extraperitoneal space was reached, followed by electrocoagulation and careful dissociation to establish a surgical window. Intraoperatively, the displaced fractures were visible through the surgical window. Afterwards, the blood clots on the fracture wounds were cleared, and the variable anastomosis between the obturator vessels and the inferior epigastric vessels (corona mortis) was disconnected and ligated according to the conditions. With satisfactory results from C-arm fluoroscopy, one to three titanium plates and multiple screws were used for fracture fixation. After obtaining satisfactory results from fluoroscopy again, the study explored *(i)* whether the femoral arteries, femoral veins, inferior epigastric arteries, corona mortis, femoral nerves and lateral femoral cutaneous nerves were damaged; *(ii)* whether the peritoneum was intact; and *(iii)* whether there were any abnormalities in hip mobility. After confirming the absence of abnormalities, the abdominal cavity was rinsed and closed. A drainage tube was indwelt after surgery. Cefuroxime sodium was administrated to prevent infection.

In the experimental group, surgical planning and virtual surgery were performed on the computer, and the plates were pre-bent in the laboratory; repeated practices were then conducted on the 3D pelvic and acetabular models before surgery. In the control group, preoperative planning was conducted empirically based on the imaging data from preoperative pelvic X-ray, pelvic CT and 3D reconstruction, and intraoperative fracture reduction and fixation was also performed empirically.

Postoperative processing

The patients in both groups received the same treatment after surgery. All patients were administered the same anti-infective, thromboprophylactic, and analgesic treatments postoperatively. The drainage tube was indwelt in the wounds for approximately one to two days postoperatively and withdrawn when the wound drainage fluid reached <30 mL within 24 h. Pelvic X-ray and CT were repeated to observe the reduction and fixation of fractures. The patients were encouraged to gradually increase the passive range of motion of the affected limb and transit to active motion, and continuous passive motion machine-assisted hip exercise was performed, if necessary. After discharge, the patients were advised to attend follow-up at 1, 3, 6, 12, and 18 months after surgery, using X-ray and pelvic CT if necessary, and follow-up data were recorded.

Data collection

Patient data including age, sex, and cause of injury, intraoperative data, imaging findings, preoperative and one-week postoperative Visual Analog Scale (VAS) scores, six-month postoperative hip function scores, and postoperative complications were collected.

The surgical duration (the time from skin incision to fracture fixation), intraoperative blood loss (intraoperative blood volume + postoperative drainage volume) and frequency of intraoperative C-arm fluoroscopy were recorded intraoperatively and compared between the experimental group and the control group.

After withdrawing the drainage tube from the wound postoperatively, pelvic X-ray was repeated and CT was performed, if necessary. The modified Matta criteria[10] for the quality of fracture reduction were used to evaluate AF reduction, with a maximum AF displacement <1 mm considered excellent (anatomical reduction), 1-3 mm considered good (satisfactory reduction) and >3 mm considered poor (unsatisfactory reduction).

The patients' pain levels were assessed using the VAS. The patients were asked to indicate the corresponding value of their pain on a graduated pain ruler. The lower the value was, the milder the pain, and vice versa. The score ranged from 0 to 10, with 0 for no pain, 1-3 for mild pain, 4-6 for moderate pain and 7-10 for severe pain.[11]

The Merle d'Aubigné-Postel scores[12] of the two groups at six months after surgery were recorded. The criteria were scored based on pain, walking and range of motion, with a score of 18 as excellent, 15-17 as good, 13-14 as fair and <13 as poor. The scoring rules are detailed in Table I.

Postoperative complications: The incidences of postoperative incisional infection, neurovascular injury, lower-limb deep vein thrombosis (DVT), heterotopic ossification, and post-traumatic arthritis in both groups were recorded.

TABLE I
Modified Merle d'Aubigné-Postel scoring scale for patients undergoing AF surgery

Item	Scoring rules	Points
Pain	No pain	6
	Mild pain	5
	Pain after walking but relievable	4
	Moderate pain but able to walk	3
	Severe pain and unable to walk	2
Walking	Normal walking	6
	Mild claudication without crutches	5
	Long-distance walking with crutches	4
	Walking requiring a help from others	3
	Severe restricted walking	2
	Unable to walk	1
Range of motion	95-100°	6
	80-94°	5
	70-79°	4
	60-69°	3
	50-59°	2
	<50°	1
Score	Excellent	18
	Good	15-17
	Fair	13-14
	Poor)	<13

AF: Acetabular fractures.

Statistical analysis

Statistical analysis was performed using the SPSS version 26.0 software (IBM Corp., Armonk, NY, USA). The Kolmogorov-Smirnov test was used for testing normality. Continuous data were expressed in mean ± standard deviation (SD) or median (Q1-Q3), while categorical data were expressed in number and frequency. The paired t-test was used for data in a paired design and the independent sample t-test for data in a group sequential design. Inter-group comparisons were conducted using the U test. Normally distributed data were analyzed using the χ^2 test, while non-normally distributed data were analyzed using the Fisher exact probability test. A two-tailed *p* value of <0.05 was considered statistically significant.

RESULTS

There was no significant difference in the age, sex or cause of injury between the groups (p>0.05; Table II).

Comparison of intraoperative data and maximum fracture displacement

In the experimental group, the mean surgical duration was shorter (123.57±22.05 *vs.* 163.57±26.20 min, p<0.001), the mean intraoperative bleeding loss was lower (557.14±174.15 *vs.* 885.71±203.27 mL, p<0.001), and the frequency of intraoperative fluoroscopy was lower (8.64±1.65 *vs.* 12.07±2.76, p<0.001) than in the control group. The maximum fracture displacement showed no statistically significant difference between the two groups (p=0.519; Table 3).

Comparison of pain and hip function

No statistically significant differences were found between the two groups in the VAS scores after surgery (p>0.05) or in the hip function score after treatment (p=0.526; Table 4).

Evaluation of postoperative complications

All patients received effective follow-up for 6 to 18 months, with a median follow-up time of

TABLE II
Comparison of general data

Item	Experimental group (n=24)		Control group (n=20)		t/χ^2	*p*
	n	Mean±SD	n	Mean±SD		
Age (year)		43.5±11.6		37.4±12.7	1.645	0.124
Sex					0.000	1.000
Male	18		15			
Female	6		5			
Cause of injury					0.029	0.865
Traffic accident	9		8			
Fall from a height	15		12			
Type of fracture					-	1.000*
Both-column fracture	8		7			
T-shaped fracture	5		5			
Anterior column + posterior semi-transverse fracture	4		3			
Transverse + posterior wall fracture	3		2			
Posterior column + posterior wall fracture	4		3			
Associated injuries					-	0.870*
Craniocerebral trauma	4		2			
Rib fractures	4		5			
Closed abdominal trauma	8		5			
Shock	4		5			
Limb fractures	4		3			
Duration from injury to surgery		9.22±3.81		8.83±3.72	0.311	0.737

SD: Standard deviation; * Fisher's exact probability test. The t/χ^2 values represent the value of the statistic for the t-test/χ^2 test.

TABLE III
Comparison of intraoperative data and maximum fracture displacement

	Experimental group (n=24)	Control group (n=20)		
Item	Mean±SD	Mean±SD	t	*p*
Intraoperative data				
Surgical duration (min)	123.57±22.05	163.57±26.20	–4.371	<0.001
Bleeding loss (mL)	557.14±174.15	885.71±203.27	–4.593	<0.001
Frequency of intraoperative fluoroscopy (n)	8.64±1.65	12.07±2.76	–3.994	<0.001
Maximum fracture displacement (mm)	1.33±0.81	1.56±1.03	–0.654	0.519

SD: Standard deviation; The t value represents the value of the statistic for the t-test.

TABLE IV
Comparison of pain and hip function

	Experimental group (n=24)	Control group (n=20)		
Item	Mean±SD	Mean±SD	t	*p*
Postoperative VAS score score (point)	2.14±0.86	2.21±0.89	–0.215	0.831
Hip function score (point)	16.14±1.41	15.79±1.52	0.643	0.526

SD: Standard deviation; VAS: Visual Analog Scale; The t value represents the value of the statistic for the t-test.

12.64 months. No major complications, such as incisional infection, neurovascular injury, lower-limb DVT, heterotopic ossification or post-traumatic arthritis, occurred in either group.

DISCUSSION

In the present study, we investigated the efficacy of 3D printing-assisted treatment for AFs and compared with conventional surgical methods in AF treatment among adults. Our study results demonstrated that adult patients with AFs who underwent preoperative 3D printing-assisted treatment experienced reduced surgical duration, intraoperative bleeding loss and frequency of intraoperative C-arm fluoroscopy compared to those who received conventional surgical treatment, providing a novel insight for the treatment of AFs.

Currently, 3D-printed models constructed based on CT scanning are widely applied in clinical practice. They can be used to observe fracture morphology from multiple angles and mark different fracture fragments using different colors, theoretically improving the accuracy of fracture classification. By searching for the optimal implant position in the 3D-printed pelvic and acetabular model, surgical plan design, plate pre-bending and even special customized implant plate preforming can be realized while simulating the direction, angle and length of screw placement to enable the difficulties of the surgery to be anticipated and the reduction effect of fractures and occurrence of long-term complications to be preliminarily evaluated.[13,14] Moreover, preoperative simulated surgery optimizes surgical processes and further enhances the surgeons' understanding of the patients' condition. Based on a meta-analysis of studies conducted in patients with traumatic fractures, 3D printing-assisted surgery significantly reduced operation time, intraoperative blood loss and the number of fluoroscopies.[15] For total hip arthroplasty, custom-made 3D printed acetabular implants showed a fixed and well-positioning in radiographic examination.[16] Previous evidence[17,18] suggests that 3D printing technology is reliable and accurate in the classification of AFs.

In the present study, 3D printing was applied in adult patients with AFs based on pelvic CT plain scanning and 3D reconstruction data, significantly reducing unnecessary intraoperative fracture reduction, plate pre-bending or pre-bending difficulty, and the duration of fracture fixation. It also improved fracture reduction quality and significantly reduced intraoperative bleeding loss and frequency of C-arm fluoroscopy, thereby protecting the health of patients and medical staff. In line with this finding, previous studies also demonstrated that the use of modern 3D printed acetabular models in fracture treatment can reduce intraoperative X-ray exposure, thereby benefiting patients and intraoperative staff.[19-21] Currently, only one study reported no significant difference in radiation exposure during surgery.[22]

Previous studies have shown that reduced operative time in AFs leads to improved outcomes in the short and long term.[23] In this study, the surgical duration, intraoperative bleeding loss, and frequency of intraoperative C-arm fluoroscopy in the control group increased significantly compared with the experimental group, and the difference was statistically significant. This can be attributed to the fact that the surgeons had an insufficient understanding of the spatial position of the patients' fracture displacement before surgery, which significantly prolonged the time required for intraoperative fracture reduction and fixation and led to multiple C-arm fluoroscopy during surgery, further prolonging the surgical duration. Additionally, it was difficult to stop bleeding from the medullary cavity of the fractured joint, and soft-tissue dissection also caused bleeding; hence, intraoperative bleeding loss increased accordingly. Our results are consistent with the data from the retrospective studies, where less blood loss was registered in the 3D printed group versus the conventional one.[24]

After surgery, both fracture reduction quality and the hip function score showed no statistically significant difference between the two groups; however, the score was slightly higher in the experimental group, which can be explained by the fact that the control group took more time and bled more when achieving the anatomical reduction of fractures. Hip function in the postoperative follow-up might have also benefited from the quality of fracture reduction. Ansari et al.[25] also found that the functional outcome in the conventional group and 3D printing group was similar at final follow-up.

Nonetheless, this study has some limitations. First, it has a small sample size and has a retrospective design, lacking long-term, large-sample randomized-controlled trails. Subgroup analyses could not be performed, such as differences in the probability of occurrence of heterotopic ossification by surgical approach. In addition, the 3D-printed pelvic and acetabular models are relatively expensive, and there is a certain selection bias in the grouping of patients, which was based on whether this technique was applied. Finally, the follow-up time is relatively short at only 6 to 18 months, making it difficult to accurately evaluate the occurrence of long-term complications such as post-traumatic arthritis and heterotopic ossification. Further multi-center, large-scale studies with longer follow-up can provide more powerful evidence in subsequent research.

In conclusion, compared to conventional surgical treatment, preoperative 3D printing-assisted treatment for adult patients with AFs may reduce surgical duration, intraoperative bleeding loss and frequency of intraoperative C-arm fluoroscopy, reducing surgical difficulty and improving surgical safety. However, more comprehensive studies with larger sample sizes and long-term follow-up which evaluate long-term outcomes after treatment are needed.

Ethics Committee Approval: The study protocol was approved by the Hospital of Xinjiang Production and Construction Corps Ethics Committee (date: 09.09.2022, no: 202206201). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Patient Consent for Publication: A written informed consent was obtained from each patient.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Conceived of the study: S.C.M., G.R.S.; Participated in its design and data analysis and statistics: B.B.L., C.W., Z.L.P. All authors helped to draft the manuscript, read and approved the final manuscript

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