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Traditional versus mirror three-dimensional printing technology for isolated acetabular fractures: a retrospective study with a median follow-up of 25 months

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Abstract

Objective: To assess the outcomes of traditional three-dimensional (3D) printing technology (TPT) versus mirror 3D printing technology (MTT) in treating isolated acetabular fractures (IAFs).

Methods: Consecutive patients with an IAF treated by either TPT or MTT at our tertiary medical centre from 2012 to 2018 were retrospectively reviewed. Follow-up was performed 1, 3, 6, and 12 months postoperatively and annually thereafter. The primary outcome was the Harris hip score (HHS), and the secondary outcomes were major intraoperative variables and key orthopaedic complications.

Results: One hundred fourteen eligible patients (114 hips) with an IAF (TPT, n = 56; MTT, n = 58) were evaluated. The median follow-up was 25 months (range, 21–28 months). At the last follow-up, the mean HHS was 82.46 ±14.70 for TPT and 86.30 ± 13.26 for MTT with a statistically significant difference. Significant differences were also detected in the major intraoperative variables (operation time, intraoperative blood loss, number of fluoroscopic screenings, and anatomical reduction number) and the major orthopaedic complications (loosening, implant failure, and heterotopic ossification).

Conclusion: Compared with TPT, MTT tends to produce accurate IAF reduction and may result in better intraoperative variables and a lower rate of major orthopaedic complications.

Keywords

Acetabular fracture, three-dimensional, traditional, mirror, outcome, Harris hip score

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Introduction

Traditional three-dimensional (3D) printing technology (TPT) can simulate the surrounding structure of the real site of acetabular fractures (AFs), creating favourable conditions for surgeons, simplifying complex AFs, and providing a solid foundation for personalised management of complex AFs.[1,2] Although TPT can help surgeons comprehend the spatial structure of complex AFs, it is limited by its absence of exposure to potentially helpful details (e.g., linear displacement of each fragment relative to its anatomic position), which will directly result in lack of the 3D configuration of complex AF components.[1,3,4] With the increasing application of TPT in the surgical treatment of various types of AFs, most research teams have reached a consensus that compared with conventional surgical methods, TPT-assisted treatment allows surgeons to more easily obtain the spatial advantages of AFs, provides a more intuitive overview of the detailed arrangement of AFs, and results in more precise reduction, thus allowing surgeons to accurately determine the length and width of the plate and the length of the screw required for fracture repair.[1,5,6] Despite these advantages of TPT, it is not always easy to achieve anatomical reduction of the articular surface of complex AFs because of the limitations in accuracy of the current printing technology and printed materials, lack of a detailed understanding of true anatomical relationships, presence of 3D anisotropy, and the complex anatomical structure of the pelvis.[2,7]

These factors markedly increase the risk of an inappropriate pre-bent shape of the reconstructed plate, resulting in an inaccurate length of the screws fixed on the model and ultimate failure to achieve the desired effect.[8–10] In this review, we introduce the use of mirror 3D printing model technology (MTT), which involves printing a 3D model of the unaffected acetabulum to reflect the true anatomical relationship, to assess the clinical outcomes of TPT versus MTT for the management of isolated AFs (IAFs).

Materials and methods

Study population

This study was approved in January 2019 by the Institutional Review Board of Jinshan Hospital, Fudan University (Shanghai, China; IRB-190322), and all patients provided written informed consent to undergo treatment. The present study was reported according to the relevant EQUATOR Network guideline (https://www.equator-network.org/). From January 2012 to August 2018, 153 consecutive patients with an IAF who underwent treatment with a reconstruction plate using TPT or MTT were retrospectively identified from our medical centre. The inclusion criteria were a freshly closed IAF, complete computed tomography (CT) images, normal anatomy of the non-fractured contralateral acetabulum, and a bone mineral density (BMD) T-score of less than −2.5 at the lumbar vertebra or femoral neck. The key exclusion criteria were lack of follow-up data, previous acetabular surgery, open fractures, pelvic deformity, severe soft tissue injuries, nerve injury of the affected limb, dyskinesia prior to fracture, pathological fractures, clinically noteworthy cardiovascular disease or heart surgery (e.g., stent implantation) requiring medication for maintenance, active bleeding or conditions related to high-risk bleeding, arterial dissection, coagulation disorders (e.g., aplastic anaemia, haemophilia, diffuse intravascular coagulation, or thromboembolic events within 6 months), infectious diseases (e.g., acute respiratory distress syndrome), a concurrent tumour or previous chemoradiotherapy for any tumour, psychosis, and an American Society of Anesthesiologists (ASA) score of IV or V. Follow-up was performed 1, 3, 6, and 12 months after surgery and yearly thereafter. The primary outcome was the Harris hip score (HHS), and the secondary outcomes were major intraoperative variables and key orthopaedic complications.

All surgical procedures were performed by high-volume orthopaedic surgeons (X. K., W.Y., B.L., and X.C.Z.). In the TPT group, a 3D-printed model of the affected acetabulum was generated. In the MTT group, two 3D-printed models of the patient's bilateral acetabulum were generated (Figure 1(a) and (b)). Based on mirror image technology, we pre-set the bone marking line and the shape and position of the plate on the contralateral acetabulum (Figure 1(b)). The exposure of the affected acetabulum and the installation of the internal fixation plate and screws were consistent with our previous report.[11] Figure 1 (c) and (d) shows the postoperative effects based on mirror image technology. Postoperative management was also consistent with our previous report.[11]

Definition of study variables

The major intraoperative variables were the operation time, intraoperative blood loss, number of fluoroscopic screenings, and reduction grades. Reduction was judged using Matta's criteria.[12] The major orthopaedic complications included loosening, failure, refracture, lower limb shortening (>1.5 cm), grade ≥III heterotopic ossification, peripheral nerve injury, and osteoarthritis. Intraoperative blood loss was estimated according to a previous report.[13]

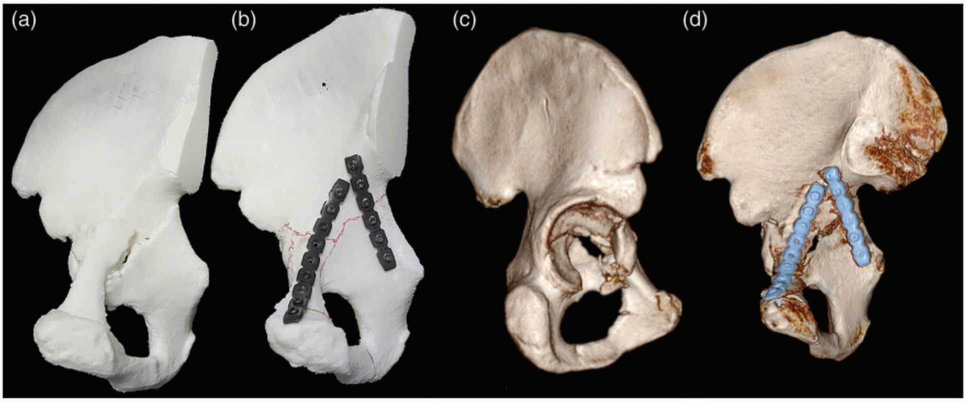

Figure 1. Comparison of preoperative and postoperative plate positions. (a) Preoperative fracture morphology on the affected side. (b) Preoperative mirror image simulating plate position. The shape and orientation of the fracture line are indicated by scribing on the mirror model according to the three-dimensionally printed mirror model technology. (c) Preoperative computed tomography reconstruction of fracture morphology. (d) Postoperative computed tomography image reconstruction.

IAF, loosening, lower limb shortening (>1.5 cm), grade ≥III heterotopic ossification, peripheral nerve injury, and osteoarthritis were evaluated based our previous criteria.[11] Failure was defined as removal of the reconstruction plate.[2]

Statistical analysis

Categorical data (sex, comorbidities, mechanism of injury, American Society of Anesthesiologists score, fracture type, surgery position, approach, fracture reduction quality, and key orthopaedic complications) were compared using the chi-square test. Continuous data (age, body mass index, BMD, time to surgery, HHS, follow-up time, intraoperative blood loss, and number of fluoroscopic screenings) were compared using Student's t-test for normally distributed variables and the Mann–Whitney U test for non-normally distributed variables. The level of statistical significance was set at $p = 0.05$. All analyses were implemented using IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA).

Results

In total, 114 patients with an IAF who underwent management with TPT or MTT were evaluated (TPT, n = 56; MTT, n = 58) (Figure 2). The patients' mean age was 53.42 ± 9.48 years in the TPT group and 52.82 ± 8.73 years in the MTT group. The mean body mass index was 27.23 ± 8.61 kg/m^2 in the TPT group and 27.42 ± 7.69 kg/m^2 in the MTT group. The mean BMD was −2.73 ± 0.56 in the TPT group and −2.75 ± 0.68 in the MTT group. The mean HHS prior to surgery was 56.47 ± 16.12 in the TPT group and 56.71 ± 15.79 in the MTT group. The median follow-up period was 25 months (range, 21–28 months). The baseline data are shown in Table 1.

Primary outcome

Table 2 shows the primary outcome. At each follow-up, a significant difference was observed between the two groups. The HHS score reached a maximum value of 85.18 ± 11.66 at 12 months after surgery in the TPT group and 88.25 ± 14.39 at 15

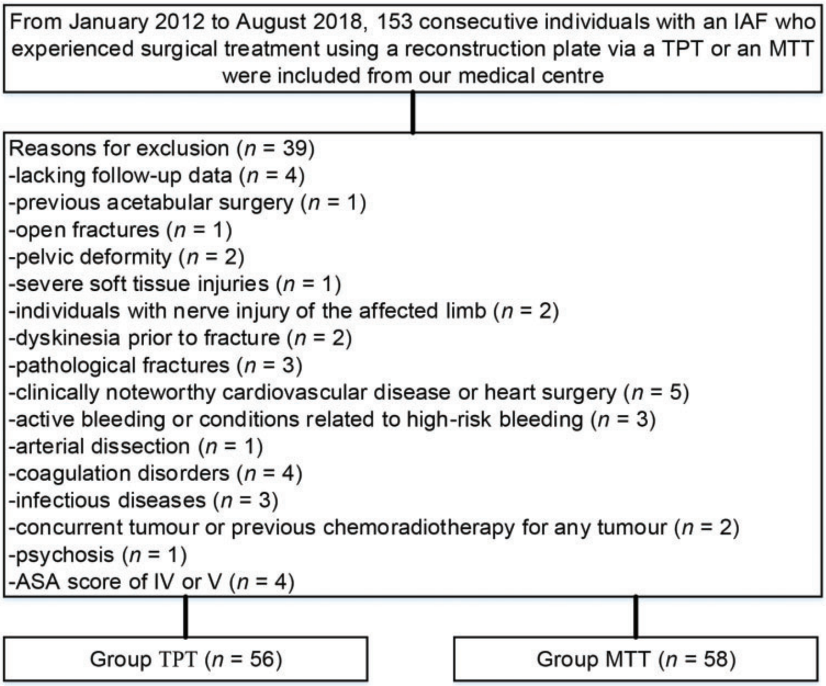

Figure 2. Flow diagram exhibiting methods to assess the outcomes of traditional three-dimensional (3D) printing technology (TPT) versus mirror 3D printing technology (MTT) in managing isolated acetabular fractures (IAFs). ASA, American Society of Anesthesiologists.

months after surgery in the MTT group. At 12 months after surgery, the HHS was 85.18 ± 11.66 in the TPT group and 87.26 ± 12.35 in the MTT group ($p = 0.028$). At the last follow-up, the HHS was 82.46 ± 14.70 in the TPT group and 86.30 ± 13.26 in the MTT group ($p = 0.013$).

Secondary outcomes

Table 3 shows the secondary outcomes. Statistically significant differences were observed in the following major intraoperative variables between the TPT and MTT groups: operation time (124.26 ± 38.71 vs. 82.21 ± 20.53 minutes, respectively; $p < 0.001$), intraoperative blood loss (587.1 ± 101.76 vs. 412.3 ± 70.21 mL, respectively; $p < 0.001$), number of fluoroscopic screenings (7.12 ± 4.71 vs. 4.12 ± 1.26, respectively; $p = 0.012$), and anatomical reduction number (35 [62.5%] vs. 48 [81.0%], respectively; $p = 0.016$). Significant differences were also detected in the rates of the following major orthopaedic complications between the TPT and MTT groups: loosening (30.4% vs. 13.8%, respectively; $p = 0.033$), implant failure (19.6% vs. 5.2%, respectively; $p = 0.019$), and grade ≥III heterotopic ossification (26.8% vs. 5.2%, respectively; $p = 0.002$). No significant differences were observed in refracture, lower limb shortening (>1.5 cm), peripheral nerve injury, or osteoarthritis.

Discussion

The results of this review involving patients with an IAF who underwent treatment with

Table 1. Baseline data.

Variable	TPT (n = 56)	MTT (n = 58)	*p*-value
Sex, female/male	26/30	25/33	0.721
Age years	53.42 ± 9.48	52.82 ± 8.73	0.143
BMI, kg/m^2	27.23 ± 8.61	27.42 ± 7.69	0.276
BMD	−2.73 ± 0.56	−2.75 ± 0.68	0.248
Side, left/right	24/32	21/37	0.468
Comorbidities			0.833
Hypertension	16 (28.6)	19 (32.8)	
Diabetes	26 (46.4)	24 (41.4)	
Cerebrovascular accident	5 (8.9)	3 (5.2)	
Cardiopathy	8 (14.3)	7 (12.1)	
Mechanism of injury			0.457
Traffic	25 (44.6)	23 (39.7)	
Falling	20 (35.7)	27 (46.6)	
Tamp	11 (19.6)	8 (13.8)	
ASA score			0.408
I	8 (14.3)	14 (24.1)	
II	29 (51.8)	26 (44.8)	
III	19 (33.9)	18 (31.0)	
Fracture types			0.709
Associated both column	19 (33.9)	17 (29.3)	
Transverse + posterior wall	14 (25.0)	18 (31.0)	
Anterior column + posterior hemi-transverse	12 (21.4)	15 (25.9)	
Posterior column + posterior wall	11 (19.6)	8 (13.8)	
Approach			0.561
Korcher–Langenbeck	24 (42.9)	28 (48.3)	
Modified Stoppa	32 (57.1)	30 (51.7)	
Time to surgery, days	7.00 ± 6.00	7.00 ± 5.00	0.105
HHS prior to surgery	56.47 ± 16.12	56.71 ± 15.79	0.113

Data are presented as mean ± standard deviation, n, or n (%).
TPT, traditional three-dimensional printing technology; MTT, mirror three-dimensional printing technology; HHS, Harris hip score; ASA, American Society of Anesthesiologists; BMI, body mass index; BMD, bone mineral density.

TPT or MTT show that MTT may have noteworthy advantages over TPT in terms of intraoperative variables and major orthopaedic complications. Although distinctions between TPT and MTT were reviewed in our previous report,[11] these advantages have not been fully translated into surgical technical advantages. Furthermore, although we found significant differences in the HHS in the current study, the clinical importance of the observed differences may not be great.

The current findings are in accordance with those of previous studies,[11,14–17] showing that MTT significantly shortens the operative time, reduces blood loss and the number of intraoperative fluoroscopy screenings, and can achieve anatomic reduction, thus significantly reducing the incidence of postoperative complications. Li et al.[18] reported 16 cases of IAFs and showed that MTT has distinct advantages over traditional surgery and can provide surgeons with exceedingly intuitive fracture

Table 2. Follow-up functional outcomes.

HHS, month(s) postoperatively	TPT (n = 56)	MTT (n = 58)	*p*-value
1	78.33 ± 7.82	80.15 ± 9.52	0.029*
3	80.73 ± 8.37	82.42 ± 7.47	0.032*
6	82.86 ± 9.32	85.59 ± 9.73	0.021*
12	85.18 ± 11.66	87.26 ± 12.35	0.028*
13	83.27 ± 12.32	86.75 ± 13.26	0.022*
15	81.32 ± 12.94	88.25 ± 14.39	0.014*
18	83.52 ± 14.64	86.49 ± 12.15	0.023*
24	82.17 ± 12.53	88.03 ± 10.82	0.017*
Final follow-up	82.46 ± 14.70	86.30 ± 13.26	0.013*

Data are presented as mean ± standard deviation.
*Statistically significant values.
TPT, traditional three-dimensional printing technology; MTT, mirror three-dimensional printing technology; HHS, Harris hip score.

Table 3. Follow-up secondary outcomes.

Variable	TPT (n = 56)	MTT (n = 58)	*p*-value
Operation time, minutes	124.26 ± 38.71	82.21 ± 20.53	<0.001*
Intraoperative blood loss, mL	587.1 ± 101.76	412.3 ± 70.21	<0.001*
Number of fluoroscopic screenings	7.12 ± 4.71	4.12 ± 1.26	0.012*
Reduction quality			0.016*
Anatomical	35 (62.5)	48 (81.0)	
Non-anatomical	21 (37.5)	10 (19.0)	
Key orthopaedic complications			
Loosening	17 (30.4)	8 (13.8)	0.033*
Implant failure	11 (19.6)	3 (5.2)	0.019*
Refracture	4 (7.1)	1 (1.7)	0.176
Lower limb shortening (>1.5 cm)	7 (12.5)	2 (3.4)	0.073
Heterotopic ossification (grade ≥III)	15 (26.8)	3 (5.2)	0.002*
Peripheral nerve injury	5 (8.9)	1 (1.7)	0.085
Osteoarthritis	6 (10.7)	3 (5.2)	0.273

Data are presented as mean ± standard deviation.
*Statistically significant values.
TPT, traditional three-dimensional printing technology; MTT, mirror three-dimensional printing technology.

details, which plays a crucial role in intraoperative fracture reduction. They also referred to the contralateral acetabular 3D model to evaluate the normal anatomical relationship of the affected side.[18] Another study also suggested that the use of 3D models facilitates perception of the spatial relationship between anatomical marks and fracture lines.[1]

For some small bone fragments or comminuted fractures, splicing or separating on a 3D model is extremely difficult because the process is likely to remove anatomical markers, especially in the case of compression fractures.[11] The currently available 3D technology remains in the early stage, the accuracy of model printing is low, and the edges of the model are rough.[5]

Furthermore, the resolution and parameters need to be adjusted by professional technicians because of the lack of uniform parameters, which results in different printed models.[4] Some models may not meet actual requirements.[19] Therefore, intuitively determining the spatial relationship between fractures through the model may have limitations.[11] Additionally, the splice of fracture blocks based on the printed acetabular model may differ from the actual acetabular shape, which is mainly limited by the printed materials.[8,15]

MTT is based on the bilateral symmetry of human bones.[11] This is the theoretical basis for establishing the contralateral acetabular model. When difficulties are encountered during intraoperative reduction, the pre-bent plate can be used as a reference to fit the bone block with the pre-bent steel plate to achieve fracture reduction without the need for bone-to-bone reduction.[2,11] The plate and fracture block as a whole is then fine-tuned and fixed with the other end of the fracture. Considering that the accuracy of 3D printing is generally 0.1 to 0.2 mm, the potential details are not fully displayed and there may be a certain error between the crack line on the model and the actual crack line position.[11]

The key orthopaedic complications (loosening, implant failure, and heterotopic ossification) may be associated with an imprecisely pre-bent plate.[1,12] Fully understanding the position of the fracture block and the normal acetabular anatomical relationship may play a key role in accurate reduction.[7] Combined with the strong internal fixation of the fractures, such an understanding can ultimately achieve good postoperative results.[9,20] Traditional surgical strategies are frequently based on the use of X-ray or CT images to determine the morphological features of the fractures while ignoring the normal contralateral acetabular structure.[11] Fracture information captured by conventional CT reconstruction techniques is limited; this is mainly due to the fact that the fracture information is not personalised because the rim of each individual's acetabulum varies in shape.[3,11]

Undeniably, surgeons may determine the approximate location of the fractures based on their previous experience.[11,21] However, it is difficult to obtain the full details of the fracture (the direction and degree of fracture displacement) based on previous techniques.[1,2,4] The recent emergence of 3D printing technology may be beneficial for surgeons.[22] The 3D model of the acetabulum exposes more details of the fracture.[5,22] With the help of this model, surgeons can accurately assess the degree of articular surface collapse; determine the number and shape of fractures; print, segment, splice, simulate, and reconstruct the fracture blocks separately; and verify the position, length, thickness, and number of reconstructed plates as well as the diameter and length of the screw.[9,11,23,24]

Several limitations should be acknowledged in this retrospective review. First, confounding factors related to the patients and interventions exist; however, highly matched baseline data weakens these confounding factors. To further weaken these factors, we adjusted the exclusion criteria by addition of the following conditions: lack of follow-up data, nerve injury of the affected limb, arterial dissection, coagulation disorders, and others. Second, in this review, direct causality was difficult to present, mainly because of our primary outcome. Third, the symmetry of the acetabulum on both sides is not absolute. In some patients, such as those affected by disease or trauma, this mirror image relationship may not exist. In the preoperative evaluation, we did not objectively evaluate the acetabulum to determine whether such a mirror relationship was present because after one AF, evaluation of the mirror relationship seems to be of little significance.

Moreover, preoperative acetabular mirror image detection may be difficult to achieve under the current technical conditions. If a mirror image relationship is not present between the acetabula, the intraoperative procedure is still based on this mirror image relationship, which will lead to a mismatch between the plate and screw data and the actual data; ultimately, the entire acetabulum will become extremely difficult to repair or poor reduction will result. The mismatch of pre-bent plates will lead to the possibility of poor or limited function after surgery. Overlong screws may initiate damage to surrounding nerves and blood vessels. Screws that are too short may reduce the strength of the fixation or even have no fixation effect. Fourth, we did not perform a sample size calculation, and the limited number of samples may have affected the statistical significance of our results.

In conclusion, the clinical effect of MTT in adjuvant management of IAFs may be better than that of TPT, with a shorter operation time, less intraoperative blood loss, and fewer fluoroscopic screenings as well as a higher anatomical reduction number and a lower rate of major orthopaedic complications. Because of the retrospective nature of our analysis and the limited sample size, our current conclusions have certain limitations. However, the present study has demonstrated precise treatment of IAFs by means of MTT, providing a full perspective for selection of the surgical treatment of IAFs. Although numerous challenges remain in the management of IAFs, MTT may enable surgeons to achieve perfect fracture reduction and approximately ideal hip functional outcomes with improvements in 3D printing accuracy and materials.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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