CLINICAL ARTICLE

# Personalized Three-Dimensional Printed Anterior Titanium Plate to Treat Double-Column Acetabular Fractures: A Retrospective Case-Control Study

Hai-yang Wu, Qi-peng Shao, Cheng-jing Song, Ran-ran Shang, Xi-ming Liu, Xian-hua Cai

*Department of Orthopaedic Surgery, General Hospital of Central Theater Command, Wuhan Clinical Medicine College of Southern Medical University, Wuhan, China*

**Objective:** To compare the clinical efficacy and safety of a personalized three-dimensional (3D) printed dynamic anterior plate–screw system for the quadrilateral area (DAPSQ) titanium plate and a traditional DAPSQ reconstruction plate in the treatment of double-column acetabular fractures.

**Methods:** This was a retrospective case-control study. From May 2014 to January 2018, 43 patients with double-column acetabular fractures underwent open reduction and internal fixation. Among these, 20 cases were fixed with a 3D printed DAPSQ plate (3D printed group) and 23 cases were fixed with a DAPSQ reconstruction plate (control group). The 3D printed group comprised 15 men and 5 women, with an average age of $50.1 \pm 8.2$ years. The control group comprised 16 men and 7 women, with an average age of $51.0 \pm 8.6$ years. The evaluation index included the surgical data (i.e. blood loss, operating time, duration of hospital stay, and intraoperative and postoperative complications), position and length of implants, reduction quality, hip function, and related complications. The reduction quality was evaluated using the Matta scoring standard and hip function was evaluated using the modified Merle d'Aubigné score.

**Results:** A total of 43 patients met the inclusion criteria. The mean postoperative follow up was 35.2 months in the 3D printed group and 36.9 months in the control group. There were no significant group differences in demographic data between the two groups. The position and length of the 3D printed implants were generally in accord with preoperative planning using a 3D pelvic model. Patients in the 3D printed group had significantly shorter operation time (223.2 *vs* 260.5 min, $P < 0.05$) and less intraoperative blood loss (930.4 *vs* 1426.1 mL, $P < 0.05$) compared to the control group. Anatomic, imperfect, and poor reduction was obtained in 13, 5, and 2 cases in the 3D printed group, respectively, and was obtained in 12, 8, and 3 cases in the control group. The modified Merle d'Aubigné scores were excellent in 11 cases, good in seven cases, and fair in two cases in the 3D printed group. They were excellent in 11 cases, good in eight cases, fair in three cases, and poor in one case in the control group. The reduction quality and hip function did not differ within the groups ($P > 0.05$). The general complication rate in the 3D printed group and the control group was 15% and 26.1%, respectively, but the difference between the two groups was not statistically significant.

**Conclusion:** Use of a personalized 3D printed DAPSQ plate has potential advantages in reducing the operation time and blood loss during the treatment of double-column acetabular fractures.

**Key words:** Acetabulum; Bone plates; Fracture fixation; Fractures; Printing; Three-dimensional

**Address for correspondence** Xian-hua Cai, MD, Department of Orthopaedic Surgery, General Hospital of Central Theater Command, Wuhan Clinical Medicine College of Southern Medical University, Wuhan, China 430070 Tel: +8602750772521; Fax: +00862750771320; Email: lzgkcxh@163.com

**Grant Sources:** This work was supported by the Technological Innovation Projects of Hubei Province (Grant No. 2017ACA099).

**Disclosure:** Each author certifies that they have no commercial or any other associations that might pose a conflict of interest in connection with the submitted article.

Received 1 April 2020; accepted 3 June 2020



**Orthopaedic Surgery** 2020;12:1212–1222 • DOI: 10.1111/os.12741

## Introduction

Currently, the incidence of acetabular fractures has an increasing trend worldwide, which is mainly ascribed to the rising incidence of high-energy trauma, such as falling injuries and traffic injuries. Letournel and Judet *et al.*[1] classified acetabular fractures into 10 types, including five with elementary and five with associated fracture patterns. Double-column fractures are among the most common and complicated types of acetabular fractures. The fracture involves the anterior column, the posterior column, and the quadrilateral area of the acetabulum (also called a quadrilateral plate); these are intra-articular fractures. The quadrilateral plate is located in the medial surface of the acetabulum. Because of its complex anatomy, deep location and weakness of the bone, as well as the neighboring vulnerable vascular and neural structures, open reduction and internal fixation (ORIF) is difficult and the surgical risks are high[2–3].

Our research group has been developing a novel method called the dynamic anterior plate–screw system for the quadrilateral area (DAPSQ) to fix acetabular fractures since 2005 and has obtained satisfactory clinical results[4]. DAPSQ consists of two major components: a special shaped reconstruction plate and several dynamic compression screws for quadrilateral plates (which we call quadrilateral screws). However, the DAPSQ reconstruction plate needs to be shaped temporarily during the operation. Surgeons need to consider the length-dependent zonal division of the three parts: the iliac region, the quadrilateral region, and the pubic region[4]. The torsion angle at both ends of the DAPSQ plate is adjusted based on surgeons' experience. The above shaping process may prolong the operation time and increase blood loss, and can even increase the likelihood of complications.

Three-dimensional (3D) printing technologies have attracted increasing interest in medicine, with various applications in the orthopaedic field. 3D printing is applied in many areas in orthopaedics, ranging from production of customized surgical tools and prostheses, implants and internal fixations to operative rehearsal and visualization of complex surgical procedures[5–6]. To tackle the problems mentioned with the DAPSQ reconstruction plate, we have used personalized 3D printed DAPSQ plates to fix complex acetabular fractures since 2014[7–8].

In light of this background, the aims of this study were to investigate the following questions. First, in the treatment of double-column acetabular fractures, is a 3D printed DAPSQ plate superior to the traditional DAPSQ reconstruction plate in reducing operation time and intraoperative blood loss? Second, is the method of 3D printing technology more beneficial to the fracture reduction and hip function recovery after the operation? Third, is there a difference between the two methods in regard to the incidence of postoperative complications?

## Materials and Methods

### Inclusion and Exclusion Criteria

#### Study Design

This retrospective case-control study was conducted at the Department of Orthopedics in the General Hospital of Central Theater Command from May 2014 to January 2018. It was approved by the ethics committee of our hospital (No. 2018024-1) and informed consent was obtained from every patient. The inclusion criteria followed the ICOS principle.

#### Inclusion Criteria

The inclusion criteria were: (i) patients aged older than 18 years, diagnosed with displaced (more than 2 mm) double-column acetabular fractures according to Letournel–Judet classification[1]; (ii) treated with a 3D printed DAPSQ plate through a single ilioinguinal approach; (iii) treated with a traditional DAPSQ reconstruction plate through a single ilioinguinal approach; (iv) efficiency (clinical and functional outcomes) and safety (complications); and (v) retrospective case-control study.

#### Exclusion Criteria

Patients with the following circumstances were excluded: (i) time from injury to surgery more than 3 weeks; (ii) open or pathologic acetabular fractures; (iii) significant pre-existing hip dysplasia and avascular necrosis of the femoral head before injury; (iv) posterior wall fracture of the acetabulum requiring combination of the Kocher–Langenbeck approach; and (v) incompleted clinical data and followed for less than 12 months.

### Patient Demographics and Characteristics

According to the inclusion and exclusion criteria, 43 patients with displaced double-column acetabular fractures were included and medical records and images were retrieved. A total of 23 patients were treated with a 3D printed DAPSQ plate (3D printed group) and 23 patients were treated with a traditional DAPSQ reconstruction plate (control group). The two cohorts had similar baseline characteristics, including gender distribution ($P = 0.692$), mean age ($P = 0.727$), mechanism of injury ($P = 0.791$), fracture side ($P = 0.571$), concomitant injuries ($P = 0.954$), and time to surgery ($P = 0.\ 845$) (Table 1).

### Digital 3D Model Reconstruction and 3D Printed DAPSQ Plate

Anatomical data obtained by CT scanning (volume thickness, 1 mm; 64-detector, Siemens AG, Germany). The data were exported to a DICOM file and imported into Mimics 20.0 software (Materialize, Belgium) to reconstruct a 3D pelvic model. A complete pelvis of the affected side was

**Table 1 The baseline characters of patients**

| Variable | 3D printed group (*n* = 20) | Control group (*n* = 23) | *P*-value |
|---|---|---|---|
| Gender | | | |
| Male | 15 (75%) | 16 (69.6%) | 0.692 |
| Female | 5(25%) | 7(30.4%) | |
| Age (years) | 50.1 ± 8.2 | 51.0 ± 8.6 | 0.727 |
| Mechanism of injury | | | |
| Fall from height | 8(40%) | 9(39.1%) | 0.791 |
| Traffic accident | 8(40%) | 11(47.8%) | |
| Fall | 4(20%) | 3(13%) | |
| Fracture side, left | | | |
| Left | 13(65%) | 13(56.5%) | 0.571 |
| Right | 7(35%) | 10(43.5%) | |
| Concomitant injuries | | | |
| Yes | 12(60%) | 14(60.9%) | 0.954 |
| No | 8(40%) | 9(39.1%) | |
| Time to surgery (days) | 9.0 ± 3.0 | 9.2 ± 2.8 | 0.845 |

Concomitant injuries including limb fracture or dislocation, rib or clavicle fracture, spine fracture, head trauma, and other trauma-related injuries requiring surgery.

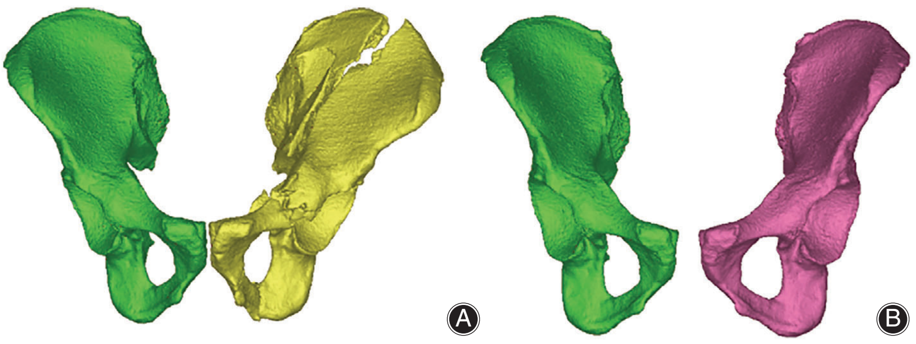


**Fig 1** (A) Three-dimensional (3D) reconstruction of the pelvic model without sacrum after segmentation using Mimics 20.0. The 3D pelvic model showing associated both-column fracture of the left acetabulum; (B) A complete left pelvis was generated by using the "mirror" function in the Mimics software.

generated using the "mirror" function in Mimics software (Fig. 1). The DAPSQ plate was divided into three parts according to the placement trajectory on the pelvis: the iliac region, the quadrilateral region, and the pubic region (Fig. 2). Based on this division method, the straight-line distance of each region was determined. Finally, the actual arc length corresponding to the straight-line distance of the three regions was calculated using the "circle drawing" function in the Mimics software. After obtaining the anatomical parameters of DAPSQ. The data were transferred to Huasen Medical Instruments to produce a personalized 3D printed DAPSQ plate (Fig. 3). Diagrams of the mechanism perspective to

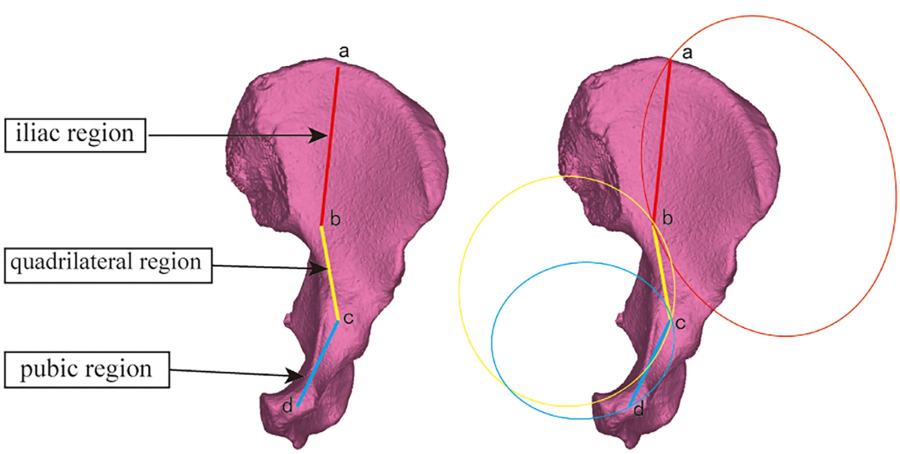


**Fig 2** According to the placement trajectory on the pelvis, the DAPSQ plate was divided into three parts: the iliac region (A–B), the quadrilateral region (B–C), and the pubic region (C–D). The actual arc length corresponding to the straight-line distance of the three regions is calculated using the "circle drawing" function in the Mimics software.

**Fig 3** 3D printed DAPSQ plate.

show the characteristics and working process of DAPSQ are presented in Fig. 4.

### *Surgical Technique*

Preoperative plain radiographs including anteroposterior (AP), Judet views (iliac and obturator oblique views), and 2D CT and 3D CT reconstruction were obtained for all patients. The fracture pattern was assessed by two experienced orthopaedists according to the Judet and Letournel classification system[1].

After general anesthesia and intubation, patients were placed in a supine position. All the surgical procedures were performed with the cooperation of two senior surgeons using a standard ilioinguinal approach (Fig. 5). Antibiotics were administered within 30 minutes of skin incision. The incision began from the 1/3 junction of iliac crest, extended anteriorly over the inguinal ligament, and ended 2 cm above the pubic symphysis. The first window of the ilioinguinal approach was mainly used to expose the internal side of the ilium, although the second window, the acetabular anterior column or anterior wall, and the quadrilateral plate could also be exposed. The superior pubic ramus and the pubic symphysis were exposed through the third window.

The method of fracture reduction was performed as we described in detail previously[4]. It should be noted that the reduction of double-column fractures follows certain principles: fracture fragments should be reduced successively from the proximal side to the distal side, and from the periphery to the center. Fractures involving the iliac wing and the sacroiliac joint should achieve satisfactory reduction and fixation first (Fig. 5).

After fracture reduction, the pre-prepared 3D printed DAPSQ were used in the patients in the 3D printed group directly to fix the acetabular fractures (Fig. 5). Patients in the control group needed additional steps for plate shaping. The plate shaping process comprised three major steps: measuring the total anatomical length of the DAPSQ trajectory on the pelvis, choosing an appropriate length of C-shape reconstruction plate, and making both ends of the plate upturned and reverse twisted. The specific screw placement sequence was performed using the method described previously[4], which was crucial to the success of fixation (Fig. 5). Both groups received the same postoperative management.

### *Outcome Measures*

All surgical data, including blood loss, operating time, duration of hospital stay, and intraoperative and postoperative complications were recorded. After discharge, all patients received routine postoperative follow up at 1 month, 2 months, 3 months, 6 months, 1 year, and yearly thereafter. Fracture healing, clinical function, and complications were recorded during the follow-up visit.

#### *Implant Evaluation*

Implants evaluation was undertaken through intraoperative observation and postoperative 3D CT reconstruction. The 3D printed DAPSQ plate was evaluated based on the matching degree of the length between the pelvis and each

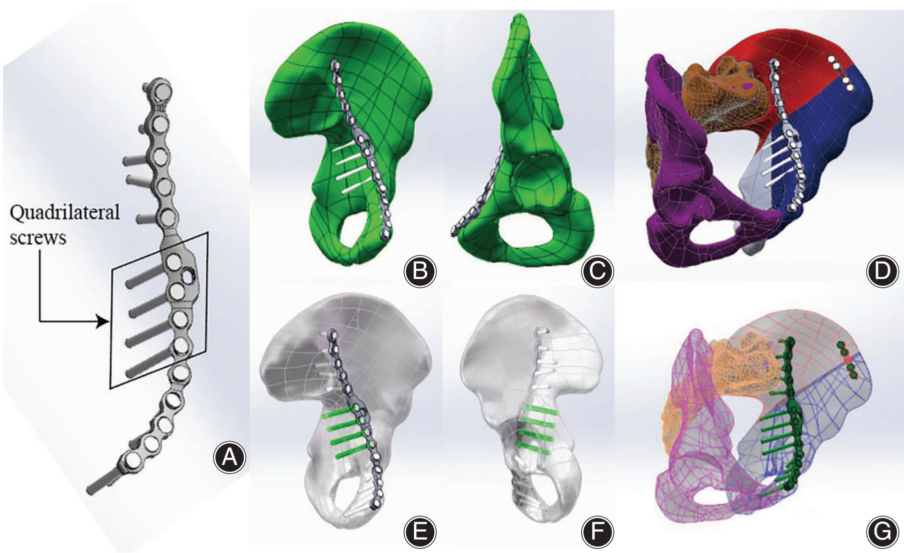


**Fig 4** The 3D model of personalized DAPSQ plate and corresponding screws have been reconstructed by using UG software (A). Interior and exterior lateral views (B, C) of 3D model of pelvis fixed with a personalized DAPSQ plate showing that four quadrilateral screws were placed parallel to the surface of the quadrilateral plate. The 3D model of double-column acetabular fracture fixed with DAPSQ, also presented in (D) to show the characteristics and working process of DAPSQ. (E), (F), and (G) show the position, length, and angle of the screws in each part of the DAPSQ plate.

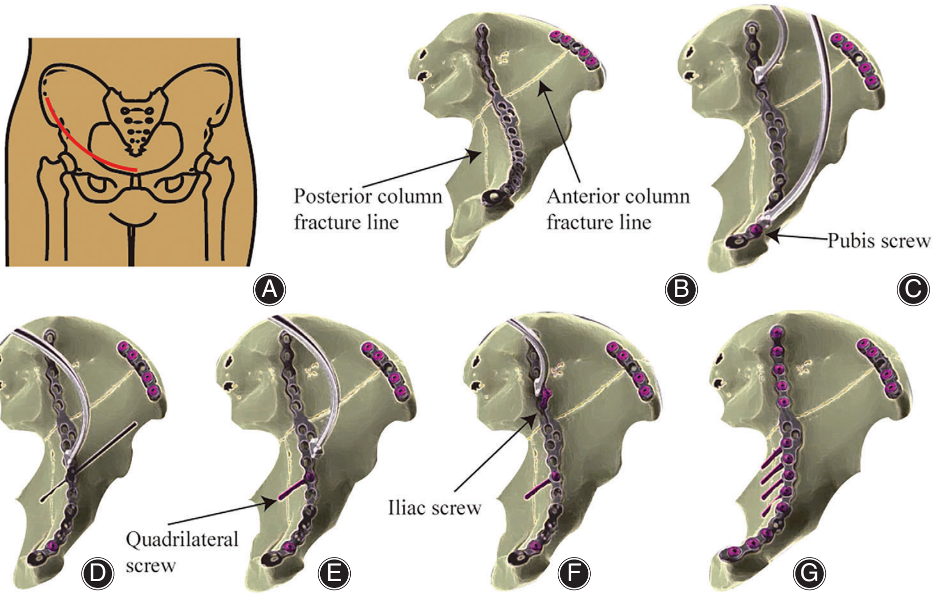


**Fig 5** Schematic diagram of open reduction and internal fixation (ORIF) of acetabular double-column acetabular fracture using a standard ilioinguinal approach. (A) The incision for the ilioinguinal approach began from the 1/3 junction of iliac crest, extended anteriorly over the inguinal ligament, and ended 2 cm above the pubic symphysis. (B) According to the fixation principle of double-column fractures, fractures involving the iliac wing should achieve satisfactory reduction and were fixed by five-hole reconstruction plate. The fractures of the quadrilateral plate were reduced and pre-prepared 3D printed DAPSQ was placed in the proper position. (C) Following the specific screw placement sequence described previously[4], the plate was pressed onto the bone surface using special instruments and the first screw was fixed on the pubis (also called the pubis screw). (D–E) Drilling holes along the surface of the quadrilateral plate; the first quadrilateral screw was placed parallel to the surface of quadrilateral plate. (F) Another screw was fixed on the iliac to stabilize the acetabular anterior column. (G) The residual screws were placed and the quadrilateral screws parallel to the surface of the quadrilateral plate formed a plane like a "bamboo raft."

part of the plate. Temporary adjustments were recorded during the operation. If there was an unplanned deviation between the actual results and the planned result, the 3D printed DAPSQ plate needed to be temporarily changed to a traditional DAPSQ reconstruction. The main issues were as follows: (i) the length of the 3D printed DAPSQ in the quadrilateral region exceeded or was shorter than 10% of the actual length, which made it difficult to insert the quadrilateral screws; (ii) the length of the plate in the iliac and pubic region exceeded 20% of the actual length (the plate exceeded the boundary of the pelvis); and (iii) the length of the plate in the iliac and pubic region was shorter than 30% of the actual length of the pelvis. Too short a length at both ends of the DAPSQ plate will cause insufficient torsion arm of the force during the process of quadrilateral screws placement.

*Matta Grading Score*

The Matta scoring system was used to evaluate the postoperative fracture reduction quality of the acetabulum[9]. It was evaluated based on the millimeters of residual displacement using standard postoperative X-rays (including AP, iliac, and obturator oblique views) and CT scans. Displacement of 1 mm or less was considered anatomic reduction; displacement between 2 and 3 mm was defined as imperfect reduction; and displacement of more than 3 mm was considered poor reduction.

*Modified Merle d'Aubigné Score*

A modified Merle d'Aubigné score was a principal condition-specific outcome measure used to assess patient progress in hip function after acetabular fracture surgery[10]. The modified Merle d'Aubigné score system included three parts: pain, walking, and range of activity. Each possible response to each of the three items had been assigned a score on an increasing scale and the total score of each section was 6 points. The degree of pain ranged from severe pain to no pain, corresponding to 2 to 6 points; walking function ranged from unable to walk to normal, corresponding to 1 to 6 points; range of activity <50% was rated as 1 point, and 95%–100% corresponded to the highest score of 6 points. The total score was the sum of each response to the three items and had a maximum of 18 points (best possible outcome). The results were categorized as excellent (18 points), good (15–17 points), fair (13 or 14 points), or poor (<13 points).

### *Statistical Analysis*

Statistical analysis was performed using the Statistical Package for the Social Sciences software (version 19.0, USA). Continuous variables with normal distribution were presented as mean ± standard deviations. Two-group comparisons were performed using a *t*-test for independent samples. Categorical variables were presented with absolute frequencies ($n$) and percentages (%). The count data were analyzed by $\chi^2$-test and the rank data were analyzed using the Wilcoxon rank sum test. A value of $P < 0.05$ was considered statistically significant.

## Results

### *Follow Up*

All patients were followed up in the outpatient department. The mean follow-up time of the 3D printed group was 35.2 months and for the control group was 36.9 months. All fractures were considered radiographically healed within 6 months after surgery. Most of the patients were symptom-free and returned to normal life after acquiring satisfactory function at last follow up.

### *The General Surgical Outcomes*

For both cohorts, the surgical time was significantly less in the 3D printed group (223.2 and 260.5 min, $P < 0.05$). Blood loss was also significantly less in patients with 3D printed DAPSQ plates compared to the control group (930.4 and 1426.1 mL, $P < 0.05$). There was no significant difference in duration of hospital stay between the two cohorts after surgery (24.6 and 26.4 days, $P = 0.340$) (Table 2). No intraoperative complications were encountered and there was no evidence of intra-articular screw penetration in the two groups.

### *Implant Evaluation*

All patients underwent surgery through a standard ilioinguinal approach. Three or four quadrilateral screws were used to control the medial displacement of the quadrilateral plate. In the 3D printed group, no further contouring of the DAPSQ plate was required to enable it to sit on the pelvic brim appropriately according to the placement trajectory planned before surgery. The position and length of the 3D printed implants were in general accord with preoperative planning using a 3D pelvic model and no one case in the 3D printed group had to be been temporarily changed to a traditional DAPSQ reconstruction during the operation. There was no one patient with the length of 3D printed plate in the three regions exceeding 10% of the actual length. In the iliac and pubic region, there were five cases (25%) and three cases (15%), respectively, in which the length of the 3D printed plate was shorter than the actual length, but all cases were within the limit of 30%.

### *Matta Grading Score*

According to Matta criteria, the quality of reduction was graded as anatomical in 13 (65%) cases, imperfect in five (25%) cases, and poor in two (10%) cases in the 3D printed group. In the control group, the quality of reduction was graded as anatomical in 12 (52.2%) cases, imperfect in eight (34.8%) cases, and poor in three (13%) cases. There was no significant statistical difference between the two groups ($P = 0.422$) (Table 2).

### *Modified Merle d'Aubigné Score*

According to the modified Merle d'Aubigné score, the functional outcomes achieved in the 3D printed group (excellent in 11 [55%] cases, good in seven [35%] cases, and fair in two [10%] cases) were similar to those in the control group (excellent in 11 [47.8%] cases, good in eight [34.8%] cases, fair in three [13%] cases, and poor in one [4.3%] case) at the last follow up ($P = 0.620$) (Table 2). Two typical cases are shown in Figs 6 and 7.

**Table 2 Surgical results and postoperative outcome measurements**

| Variable | 3D printed group (*n* = 20) | Control group (*n* = 23) | *P*-value |
|---|---|---|---|
| Surgical time (min) | 223.2 ± 44.6 | 260.5 ± 57.3 | 0.023 |
| Blood loss (mL) | 930.4 ± 523.2 | 1426.1 ± 733.1 | 0.016 |
| Duration of hospital stay (days) | 24.6 ± 4.9 | 26.4 ± 7.2 | 0.340 |
| Quality of reduction | | | |
| Anatomic | 13(65%) | 12(52.2%) | 0.422 |
| Imperfect | 5(25%) | 8(34.8%) | |
| Poor | 2(10%) | 3(13%) | |
| Mean follow-up time (months) | 35.2 ± 6.7 | 36.9 ± 7.4 | 0.430 |
| Modified Merle d'Aubigné score | | | |
| Excellent | 11(55%) | 11(47.8%) | 0.620 |
| Good | 7(35%) | 8(34.8%) | |
| Fair | 2(10%) | 3(13%) | |
| Poor | 0 | 1(4.3%) | |

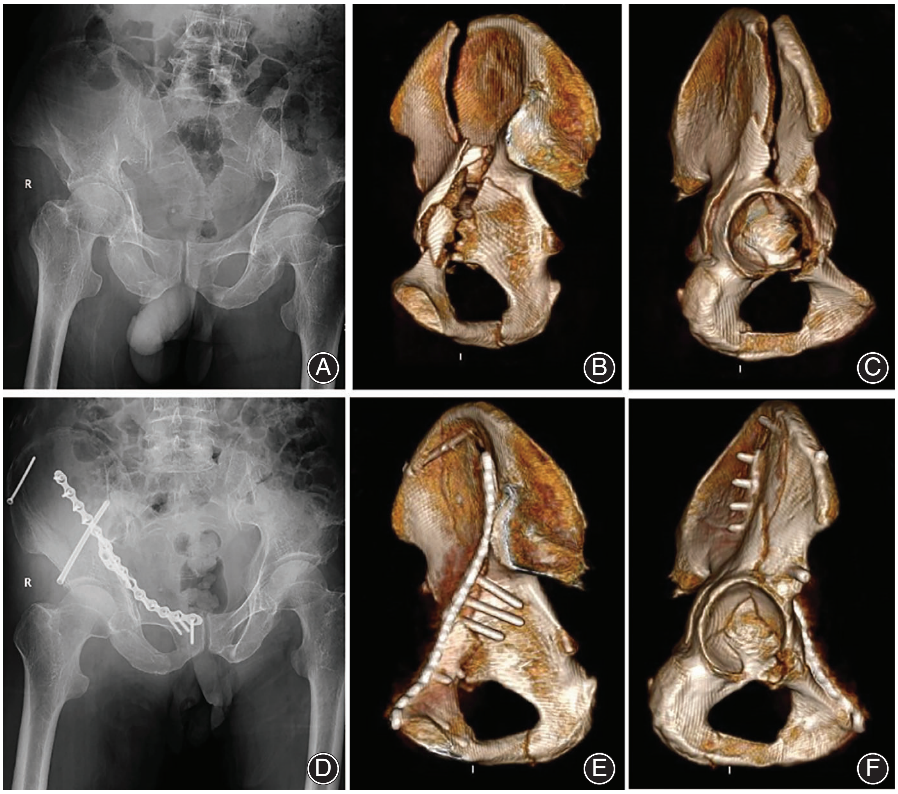

**Fig 6** A typical case of 3D printed DAPSQ group. A 57-year-old man presented with acetabular fracture of the right acetabulum. Preoperative anteroposterior (AP) pelvis view (A) and 3D CT reconstruction (B, C) demonstrated double-column fractures according to Letournel–Judet classification. Open reduction and internal fixation (ORIF) was performed *via* a single ilioinguinal approach at 7 days. Postoperative X-ray (E) and 3D view (F, G) show an anatomical reduction according to Matta grading score and quadrilateral screws were placed on the surface of the quadrilateral plate.

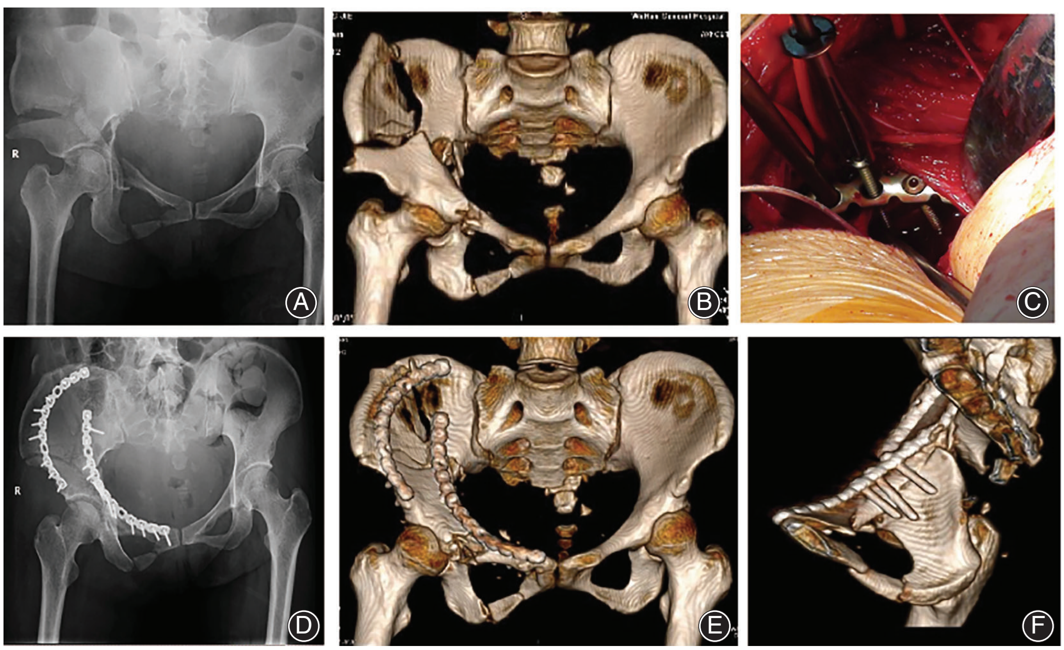

**Fig 7** A typical case of DAPSQ reconstruction plate group. A 63-year-old woman presented with double-column fracture of the right acetabulum following a traffic accident. Preoperative AP view (A) and 3D CT reconstruction (B) show that the quadrilateral plate was separated from the anterior column with medial displacement. A quadrilateral screw was inserted along the pelvic brim and parallel to the surface of the quadrilateral plate through the middle window of the ilioinguinal approach (C). Postoperative X-ray (D) and 3D view (F, G) show an anatomical reduction according to Matta grading score. The modified Merle d'Aubigné evaluation was scored as excellent at the last follow up at 49 months.

**Table 3 Descriptive data of postoperative complications**

| Complications | 3D printed group (*n* = 20) | Control group (*n* = 23) | *P*-value |
|---|---|---|---|
| Deep venous thrombosis | 0 | 1 | |
| Lateral femoral cutaneous nerve injury | 1 | 2 | |
| Posttraumatic arthritis | 2 | 3 | |
| Incidence of complication (*n*, %) | 3(15) | 6(26.1) | 0.232 |

### *Complications*

No failure of internal fixation or loosening or migration of the quadrilateral screws was observed during the follow-up period. The complications are presented in Table 3. One lateral femoral cutaneous nerve injury occurred in the 3D printed group, and two occurred in the control group. They all recovered in 3 to 8 months after surgery. One case of postoperative deep vein thrombosis was observed in the control group and the patient underwent acute thrombolytic therapy. Two cases in the 3D printed group developed slight traumatic arthritis and experienced slight pain during walking. There were two mild cases and one severe case in the control group. The severe case was that of a 58-year-old man with a fracture in the femoral neck and hip dislocation. Four months after the primary surgery, he did not follow doctor's advice and returned to heavy physical work. Eight months later, he was found to have developed collapse of the femoral head, limited hip joint mobility, and joint pain. Therefore, he underwent total hip arthroplasty.

## Discussion

### *Fracture Characteristics of Double-Column Acetabular Fractures*

Double-column fractures are complex acetabular fractures (Letournel and Judet classification) involving both the anterior column and the posterior column of the acetabulum; these are Type C fractures according to the classification of the Association for the Study of Internal Fixation (ASIF/AO). Their main characteristic is the entire weight-bearing articular surface being separated from the sacroiliac joint and losing the connection with the axial skeleton; the acetabulum is set free (also called a "floating acetabulum")[11–12]. The fracture lines involve multiple planes and usually divide the acetabulum into three main fracture fragments, including the anterior column fragment, the posterior column fragment, and the iliac wing fragment. For more complicated fracture patterns, each fragment can be further divided into two or three parts, and even be comminuted. Due to the axial force generated from the femoral head and pulled by the pelvic muscle and joint capsule, the anterior column fragments often present with inward and external rotation displacements. By contrast, the posterior column fragments mainly pulled by the sacrotuberous ligament and sacrospinous ligament demonstrate inward and internal rotation displacements. According to the anatomical definition of the quadrilateral plate described by ElNahal *et al.*[13], double-column fractures will inevitably involve the quadrilateral plate, and the fracture fragments in this region are partially connected with the anterior column or posterior column fragments. Yang *et al.*[14] analyzed the fracture line distribution in the quadrilateral plate using the three-dimensional CT reconstruction, and found that the anterograde-oblique fracture line was most common in double-column fractures. Combined with the previous evidence and our own experience[11, 15], the typical radiographic appearance of double-column fractures can be summarized as follows: (i) on the anteroposterior radiograph, the continuity of the iliumpubic and ilioischeial line was interrupted, indicating that the fracture involved both the columns; (ii) the mismatch between the femoral head and the acetabular fossa and often complicated with the dislocation of the femoral head; and (iii) on the conventional obturator oblique radiographs or CT images, the characteristic "spur sign" is encountered only in both-column fractures[16]. The spur sign is produced when the detached fragments are displaced medially into the pelvis and a piece of iliac bone remains attached to the sacroiliac joint.

### *Key Surgical Technology of Double-Column Acetabular Fractures*

The double-column acetabular fracture is an intra-articular fracture, often with marked and complicated displacement. Anatomical reduction and rigid fixation is the main principle in treating these fractures. Because of the special fracture characteristics mentioned above, the reduction of double-column fractures follows certain principles; that is, the fracture fragments should be reduced successively from the proximal side to the distal side, and from the periphery to the center. In other words, fractures involving the iliac wing and the sacroiliac joint should achieve satisfactory reduction and fixation first. Previous studies have demonstrated that anatomical reduction in the iliac wing should be achieved as much as possible, because it is the foundation of accurate reduction in the posterior column fragments[15]. After the reduction of the anterior column fragment, immediately followed by the reduction of the acetabular dome, the posterior column and the quadrilateral plate were used to restore the structural integrity of a compromised acetabulum. Several studies have shown that poor reduction of the acetabular dome can lead to high incidence of traumatic arthritis or dysfunction of the hip[17–18]. The standard definitions of satisfactory reduction in the posterior column and quadrilateral plate applied, including restoring the continuity of the arcuate line and the greater sciatic notch, and no obvious fracture step was touched in the quadrilateral plate surface. Among these processes, various reduction techniques, such as the double-screw reduction technique recommended by AO, and surgical instruments (e.g. Schanz pin, ball spike, cob elevator, and pelvic clamp) can be applied.

### *Technical Characteristics of the DAPSQ Plate*

Double-column acetabular fractures will involve quadrilateral plate fractures. How to reduce the quadrilateral plate fracture effectively has been a hot topic of research. In our previous research, we reported a new fixation technique called DAPSQ for complex acetabular fractures with quadrilateral plate involvement and obtained satisfactory clinical results[4]. Biomechanical studies have investigated the biomechanical stability of DAPSQ devices[19–20]. As described earlier, the DAPSQ plate was a simple and ingenious design based on the traditional reconstruction plate and specially shaped, just like a "curl" or "Moebius strip." Before screws insertion, both ends of the DAPSQ plate were slightly upturned, and not firmly attached to the bone surface. After all the screws were inserted, the upturned plate was firmly attached to the bone surface like an anatomic plate. While restoring the shape of the both ends of the DAPSQ plate, the middle part of the DAPSQ plate is twisted continually so that it is inclined, with a low inside and a high outside. In the process, the torsion of the DAPSQ plate will generate a strong torque force so that the quadrilateral screws are firmly and continuously attached against the quadrilateral surface[4]. The screw thread of quadrilateral screws in the middle of the DAPSQ plate also prevents the screws from pulling out and shaking left and right. Therefore, medially quadrilateral screws damage the important neurovascular and abdominal structures in the pelvis will not happen.

In addition, screws used on the quadrilateral surface were nonlocking screws. Many scholars have asked why locking screws are not used on the quadrilateral surface and we want to explain this here. Indeed, using locking screws may reduce the risk of screws loosening or coming out. Because the degree of comminution and displacement of the fractures in the square plates is different, quadrilateral screws must be stepless lateral compression screws to achieve the bone stability in the quadrilateral plate. However, the locking screws can only provide fixed angle fixation between the plate and screws, which cannot achieve the effect of stepless fixation. Sometimes the quadrilateral screws may even penetrate the thin quadrilateral plate and cannot be adjusted. Nonlocking screws can provide the stepless lateral fixation through the connection between the screw cap and the plate holes. In addition, as mentioned previously, the special placement methods can provide sufficient stability to prevent the quadrilateral screws from coming out or loosening.

### *Design Features of 3D Printed DAPSQ Plate*

The traditional DAPSQ reconstruction plate needs to be shaped temporarily during the operation, which inevitably prolongs the operation time and increases intraoperative blood loss. This may hamper large-scale industrial production and limit potential clinical application. To solve these problems, our team took advantage of the technological advances in tridimensional printing and designed the personalized 3D printed DAPSQ plate for direct intraoperative use. We also improved and modified the 3D printed DAPSQ plate based on the traditional plate. The design features are as follows. First, according to the placement trajectory of DAPSQ, anatomical parameters of the three parts of the DAPSQ plate are obtained before surgery using Mimics software. Then the 3D printed DAPSQ plate is printed according to the anatomical parameters. Consequently, compared with the traditional DAPSQ plate, the partition of the 3D printed DAPSQ plate is more rationalized, standardized, and personalized. Second, torsion angles of the iliac region and the pubic region are fixed when printed. This pre-torsion design can avoid the loss of elastic strength due to the repeated shaping and bending during surgery. Moreover, it is the most time-consuming step during the shaping of the traditional DAPSQ plate. Third, the number of screw holes in the quadrilateral region increases from three to four. This design is more reasonable for the distribution of quadrilateral screws according to the specific fracture line. Meanwhile, compared with the traditional DAPSQ plate, it can be observed that one additional screw hole is added besides the pre-exist screw holes in the quadrilateral region. This additional screw is used for the insertion of a special instrument so that it is more convenient to place the quadrilateral screws in the quadrilateral surface.

### *Therapeutic Effect Evaluation*

In recent decades, 3D printing, as a new technology, has been rapidly developed with a variety of applications in orthopaedics fields. A previous study integrated 3D printing and computer aided design to produce a 3D printed personalized titanium plate for the surgical resection of bone tumors and the results indicated that the use of such a plate could significantly improve the clinical outcomes in the surgical removal of bone tumor[21]. Another study conducted by Shuang *et al.*[22] found that 3D printed plates are safe and effective for the treatment of intercondylar humeral fractures and using them can significantly reduce operative time.

According to the Matta criteria, the excellent and good rate of fracture reduction in the 3D printed group was 90%. The excellent and good rate of hip functional assessment was also 90% according to the modified Merle d'Aubigné score. Both the excellent and good rate were higher than those in the control group (87.0% and 82.6%, respectively). However, the two groups did not differ significantly. We speculate that this might be due to the relatively small sample size. Although statistically meaningful results have not been obtained, our study showed that the mean operative time was significantly shorter and intraoperative blood loss was significantly less in the 3D printed group than in the control group. This is mainly associated with avoiding the additional shaping and bending steps which were required with the traditional DAPSQ plate. Maini *et al.*[23] conducted a prospective randomized case-control study to evaluate the accuracy of patient-specific pre-contoured plates in the treatment of acetabular fractures. They also found that patient-specific pre-contoured plates made using a 3D model were better implants than intraoperatively contoured plates.

In addition, Mimics software allowed for the preoperative simulation of plate positioning and screw placement, which greatly simplified the surgical procedure and reduced the operation time. In addition, it is worth noting that individuals with different injury mechanisms have different fracture types; an individualized plate is necessary for acetabulum reconstructive surgery. The 3D printed DAPSQ plate can meet the needs of individualized pre-surgical planning. In terms of complications, no failure of internal fixation, loosening, or migration of the quadrilateral screws was observed during this period. This also further indicated the safety of DAPSQ.

### *Several Caveats of 3D Printed DAPSQ Plate*

Despite these promising results, there are several caveats worth noting. First, the DAPSQ plate needs sufficient time and full preparation before the operation, which is not applicable for emergent cases. Second, the cost of a personalized 3D printed DAPSQ plate is higher and, thus, difficult to produce in a large scale. Therefore, our research group has planned a study with a large sample size on anatomical measurements of the trajectory length and the partition ratio of the three parts of the DAPSQ. According to the anatomical measurements, we have preliminary designed three different models of DAPSQ since 2016, and this group of cases also under clinical investigation. Third, although the 3D printed DAPSQ plates in this study were all well fitted to the bone surface, the torsion angle may still need to be slightly adjusted during surgery in some special cases. Notably, because the pelvis has an irregular curved surface, the real length of the three parts of the DAPSQ plate do not match the virtual length measured before surgery, especially in the iliac region. However, it does not affect the use of the DAPSQ plate and all the patients in the 3D printed group have acquired satisfactory fixation effect. More reasonable measurement methods should be further discussed and researched.

### *Limitations*

Several limitations of the present study must be acknowledged. First, the sample size was small. Thus, a large-scale, prospective randomized controlled study should be designed to further confirm this result. Second, previous studies of the biomechanical properties of the DAPSQ plate are limited, and the actual biomechanical properties of the DAPSQ are not completely understood. Further biomechanical research on the technique is necessary.

### *Conclusion*

The 3D printed personalized DAPSQ plate can be produced before surgery according to the patient's anatomical parameters and no additional shaping and bending is needed during surgery. Compared with the traditional DAPSQ plate, the personalized 3D printed DAPSQ plate is rationalized, standardized and personalized. Although the 3D printed DAPSQ plate cannot improve the fracture reduction and hip function recovery after the operation, it can significantly decrease the intraoperative blood loss and shorten the operation time, and may demonstrate better clinical efficacy and feasibility.

## Acknowledgment

Thanks to Yanjun Zhong, for the data analysis through this work.

## References

**1.** Judet R, Judet J, Letournel E. Fractures of the acetabulum: classification and surgical approaches for open reduction. Preliminary report. J Bone Joint Surg Am, 1964, 46: 1615–1646.
**2.** White G, Kanakaris NK, Faour O, Valverde JA, Martin MA, Giannoudis PV. Quadrilateral plate fractures of the acetabulum: an update. Injury, 2013, 44: 159–167.
**3.** Tosounidis TH, Gudipati S, Panteli M, Kanakaris NK, Giannoudis PV. The use of buttress plates in the management of acetabular fractures with quadrilateral plate involvement: is it still a valid option?. Int Orthop, 2015, 39: 2219–2226.
**4.** Wu H, Shang R, Cai X, Liu X, Song C, Chen Y. Single ilioinguinal approach to treat complex acetabular fractures with quadrilateral plate involvement: outcomes using a novel dynamic anterior plate-screw system. Orthop Surg, 2020, 12: 488–497.
**5.** Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: a systematic literature review. Biomed Eng Online, 2016, 15: 115.
**6.** Liu ZJ, Jia J, Zhang YG, Tian W, Jin X, Hu YC. Internal fixation of complicated acetabular fractures directed by preoperative surgery with 3D printing models. Orthop Surg, 2017, 9: 257–260.
**7.** Wang XZ, Shi Z, Lu QL, *et al*. Treatment of old acetabular posterior wall fracture with 3D printing combined with composite plate internal fixation. Zhongguo Gu Shang, 2019, 32: 395–400.
**8.** Lu QL, Zhu YL, Li XG, *et al*. Comparison of efficacy between 3D navigation-assisted percutaneous iliosacral screw and minimally invasive reconstruction plate in treating sacroiliac complex injury. Curr Med Sci, 2019, 39: 81–87.
**9.** Matta JM. Fractures of the acetabulum: accuracy of reduction and clinical results in patients managed operatively within three weeks after the injury. J Bone Joint Surg Am, 1996, 78: 1632–1645.
**10.** D'Aubigne RM, Postel M. The classic: functional results of hip arthroplasty with acrylic prosthesis. Clin Orthop Relat Res, 2009, 467: 7–27.
**11.** Gansslen A, Frink M, Hildebrand F, Krettek C. Both column fractures of the acetabulum: epidemiology, operative management and long-term-results. Acta Chir Orthop Traumatol Cech, 2012, 79: 107–113.
**12.** Gansslen A, Krettek C. Internal fixation of acetabular both-column fractures via the ilioinguinal approach. Oper Orthop Traumatol, 2009, 21: 270–282.
**13.** ElNahal WA, Abdel KM, Khaled SA, Abdelazeem AH, Abdelazeem H. Quadrilateral plate fractures of the acetabulum: proposition for a novel classification system. Injury, 2018, 49: 296–301.
**14.** Yang Y, Zou C, Fang Y. A study on fracture lines of the quadrilateral plate based on fracture mapping. J Orthop Surg Res, 2019, 14: 310.

**15.** Zhang R, Yin Y, Li S *et al*. Minimally invasive treatment of both-column acetabular fractures through the Stoppa combined with iliac fossa approach. Sci Rep, 2017, 7: 8044.
**16.** Johnson TS. The spur sign. Radiology, 2005, 235: 1023–1024.
**17.** Tosounidis TH, Stengel D, Giannoudis PV. Anteromedial dome impaction in acetabular fractures: issues and controversies. Injury, 2016, 47: 1605–1607.
**18.** Zhuang Y, Lei JL, Wei X, Lu DG, Zhang K. Surgical treatment of acetabulum top compression fracture with sea gull sign. Orthop Surg, 2015, 7: 146–154.
**19.** Lei J, Dong P, Li Z, Zhu F, Wang Z, Cai X. Biomechanical analysis of the fixation systems for anterior column and posterior hemi-transverse acetabular fractures. Acta Orthop Traumatol Turc, 2017, 51: 248–253.
**20.** Fan Y, Lei J, Zhu F, Li Z, Chen W, Liu X. Biomechanical analysis of the fixation system for T-shaped acetabular fracture. Comput Math Methods Med, 2015, 2015: 370631.
**21.** Ma L, Zhou Y, Zhu Y *et al*. 3D printed personalized titanium plates improve clinical outcome in microwave ablation of bone tumors around the knee. Sci Rep, 2017, 7: 7626.
**22.** Shuang F, Hu W, Shao Y, Li H, Zou H. Treatment of intercondylar humeral fractures with 3D-printed Osteosynthesis plates. Medicine (Baltimore), 2016, 95: e2461.
**23.** Maini L, Sharma A, Jha S, Sharma A, Tiwari A. Three-dimensional printing and patient-specific pre-contoured plate: future of acetabulum fracture fixation?. Eur J Trauma Emerg Surg, 2018, 44: 215–224.