Three-dimensional (3D) Printing Technology Assisted by Minimally Invasive Surgery for Pubic Rami Fractures

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Summary: The feasibility of three-dimensional (3D) printing technology combined with minimally invasive surgery in the treatment of pubic rami fractures was explored. From August 2015 to October 2017, a series of 30 patients who underwent surgical stabilization of their anterior pelvic ring (all utilizing the 3D printing technology) by one surgeon at a single hospital were studied. The minimally invasive incisions were made through anterior inferior cilia spine and pubic nodule. Data collected included the operative duration, the blood loss, the damage of the important tissue, the biographic union and the recovery of the function after the operation. Measurements on inlet and outlet pelvic cardiograph were made immediately post-operation and at all follow-up clinic visits. The scores of reduction and function were measured during follow-up. Results showed that the wounds of 30 patients were healed in the first stage, and there was no injury of important structures such as blood vessels and nerves. According to the Matta criteria, excellent effectiveness was obtained in 22 cases and good in 8 cases. According to the functional evaluation criteria of Majeed, excellent effectiveness was obtained in 21 cases and good in 9 cases. It was suggested that the 3D printing technology assisted by minimally invasive surgery can better evaluate the pelvic fracture before operation, which was helpful in plate modeling, and can shorten surgery duration and reduce intraoperative blood loss and complications. The positioning accuracy was improved, and better surgical result was finally achieved.
Key words: digital design; three-dimensional printing; anterior ring pelvic fractures; minimally invasive surgery

In recent years, the incidence of anterior ring pelvic fractures combined with asacroiliac joint complex injury is increasing due to the development of industrialization and transportation[1]. The data display that fractures of pubic rami are common, with an incidence of 26 per 100 000 people per year[2, 3]. Because pubic rami fractures combined with a sacroiliac joint complex injury which involves both anterior and posterior rings are unstable, surgical fixation is required to treat this type of injury[4].

For the treatment of pubic rami fracture, the traditional operation is minimally invasive. Minimally invasive internal fixation of anterior pelvic ring fractures has been described in many literatures[5–8]. However, repeated X-ray examination is required during the operation, and X-ray exposure of the patients and doctors has a great impact on their body. The complex anatomy of pelvic structure also limits the surgical treatment of pelvic fractures, so a detailed surgical plan is required before the operation. The traditional X-ray film and CT scan have certain limitation to the preoperative plan. In recent years, digital medical technology has been widely used in the field of orthopedics[9, 10]. The 3-dimensional (3D) printing technology based on CT scan can shows the whole pelvic picture, which is helpful to guide the diagnosis and treatment of fracture, and allows surgeons to evaluate fracture patterns and pathology *in vitro* in detail. Orthopedic surgeons can have a thorough understanding of the fracture before operation

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and make accurate diagnosis and classification. By selecting different surgical methods and adjusting surgical strategies, the best individualized operation scheme was worked out.

Li *et al*[11] used 3D printing technology to individualize and accurately treat patients with complex pelvic fractures. They designed surgical approaches before operation, prebent steel plates on 3D print models, and saved the time of repeated prebending of plates during surgery. Wu[12] used 3D printing model to reconstruct 9 patients, and the patients were followed up for 3–29 months (mean 5 months). The fracture healing time was 9–17 weeks (mean l0 weeks). No delayed incision healing, wound infection, or nonunions occurred. Fan[13] randomly divided 22 patients into 3D group and control group, and the operation time and the amount of intraoperative bleeding were compared between the two groups.

Therefore, 3D printing technology has been applied to assist the surgeon and to improve the surgical accuracy, which is beneficial to the early recovery of the patients. We used 3D printing technology to assist in preoperative planning for pubic rami fractures from August 2015 to October 2017, and the initial results of this clinical application are reported herein.

1 MATERIALS AND METHODS

1.1 Patients' General Information

From August 2015 to October 2017, 30 patients (including 18 males and 12 females) with anterior ring injury of unstable pelvic fracture were treated with 3D printed pelvic fracture model and simulated operation *in vitro*. According to Tile classification, there were 5 cases of type B1, 21 cases of type B2, and 4 cases of type C1. According to the injury mechanism, there were 19 cases of traffic injury, 6 cases of falling injury, 4 cases of heavy objects injury and 1 case of fighting injury. All the 30 patients were complicated with concomitant injuries, including 16 cases of pulmonary contusion, 5 cases of rib fracture, 7 cases of urethral injury, 1 case of femoral neck fracture, 1 case of ankle fracture, 1 case of tibia and fibula fracture, 1 case of humeral shaft fracture, 1 case of intestinal rupture, 2 cases of intracerebral hemorrhage, and 3 cases of hemorrhagic shock (table 1).

Table 1 The patients' characteristics

Cases	Gender (men/women)	Age (year)	Tile's type (*n*)			Mechanism of injury (*n*)			
			B1	B2	C1	Ⅰ	Ⅱ	Ⅲ	Ⅳ
30	18/12	30.4±7.2	5	21	4	19	6	4	1

Ⅰ: traffic injury; Ⅱ: fall injury; Ⅲ: heavy objects injury; Ⅳ: fight injury

1.2 Simulated Reduction and Establishment of Fracture Model Using Computer-Aided Analysis

The whole pelvis was scanned by SIMENS (Siemens, Germany) 256 slice spiral CT with a slice thickness of 0.625 mm. The 2D plane image was imported into Mimics 10.01 software by Dicom format. Through the threshold segmentation, the gray value was set to 226×3071, and the mask file of the data was achieved. Then the bone, joint and other hard tissues connected by pixels in each layer image were segmented, and then the 3D reconstruction image of pelvis was obtained. Rotation and translation tools were used to observe the displacement of pelvic fractures from various angles to determine the displacement and types of fractures. Using the segmentation function of the software, the 3D reconstruction image was segmented quickly, and the fracture block was marked with different colors. The software was used to simulate the reduction function, and the pelvic anatomy was reconstructed by moving, rotating, etc. The reduction and internal fixation of pelvic fractures were simulated by Mimics software. The computer software was applied to determine the position of steel plate, screw length, pin position and angle information. The simulated reset pelvis data were introduced into the FDM printer, and the reconstructed pelvic entity model was printed at the same proportion (fig. 1).

1.3 Surgical Procedures

The patient was placed on the operation bed in a supine position, and the hip and knee joints were bent before operation, perineal skin was prepared, and the general anesthesia was induced through tracheal intubation. The minimally invasive incision was made through anterior inferior iliac spine and pubic tubercle. The surgical procedures were as follows: (1) prebending the internal fixator before operation and performing simulated operation on 3D printing model, and sending the preformed plate and screw to the operating room for disinfection and standby; (2) If the pelvic fracture was unstable in the posterior ring, the posterior ring was first fixed in the prone position, and then the fracture of the anterior ring was fixed in the supine position (fig. 2); (3) Two minimally invasive incisions were required for unilateral fixation of the anterior pelvic ring: oblique incision through anterior inferior iliac spine and transverse incision centered on pubic nodule; for the bilateral fixation of the anterior pelvic ring, four incisions were required; (4) The subcutaneous channels were created under vascular and neural structures using periosteal dissecting devices; (5) For internal fixation, a gauze strip was used to fix the prebent steel plate and the oval forceps were used

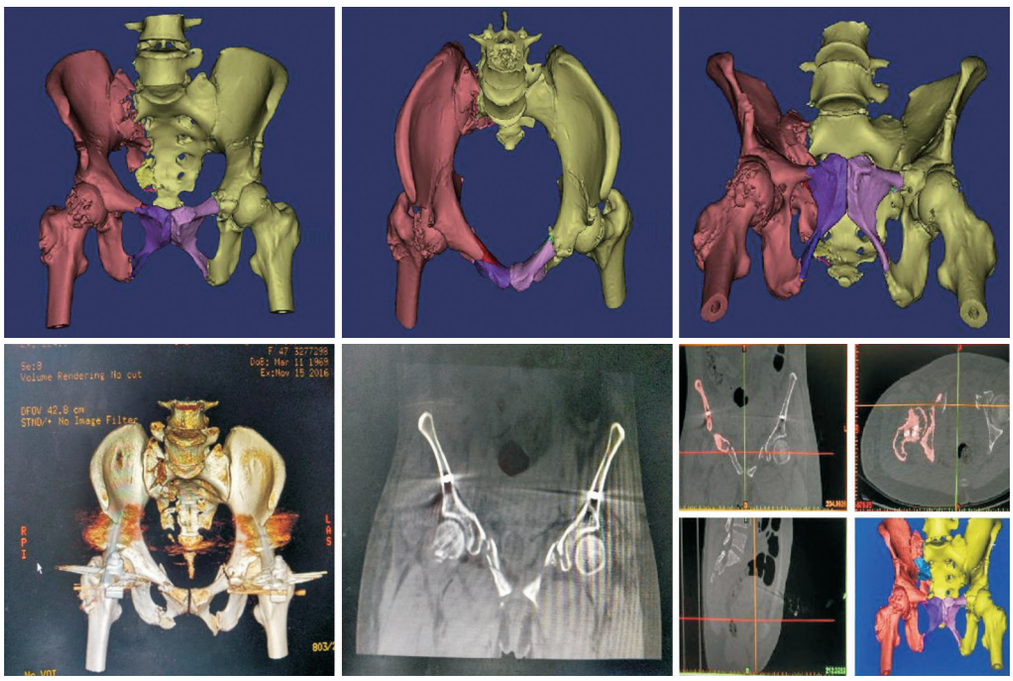


Fig. 1 A 55-year-old female with pelvic fracture caused by traffic accident was treated with external pelvic fixation and hollow nail fixation for right femoral neck fracture in the local hospital
The patient was transferred to our hospital for further treatment. After admission, CT and 3D reconstruction were performed. The CT results were imported into the Mimics software in the form of data, then segmented, simulated to reset after imaging, and 3D models were obtained.

to build channels, then the gauze was pulled out; (6) For screwfixation, the plate was attached to the end of the fracture, and the fracture block was pricked out and reduced. The screw used to simulate the operation on the 3D printing model before operation was directly fixed (fig. 3); (7) C arm X-ray examination displayed perspective pelvis position, entrance and exit position to determine the position of steel plate and screw; (8) Counting surgical instruments, suturing subcutaneous tissue layer by layer with absorbable line after dressing, and covering the intradermal suture wound with aseptic application (fig. 4).

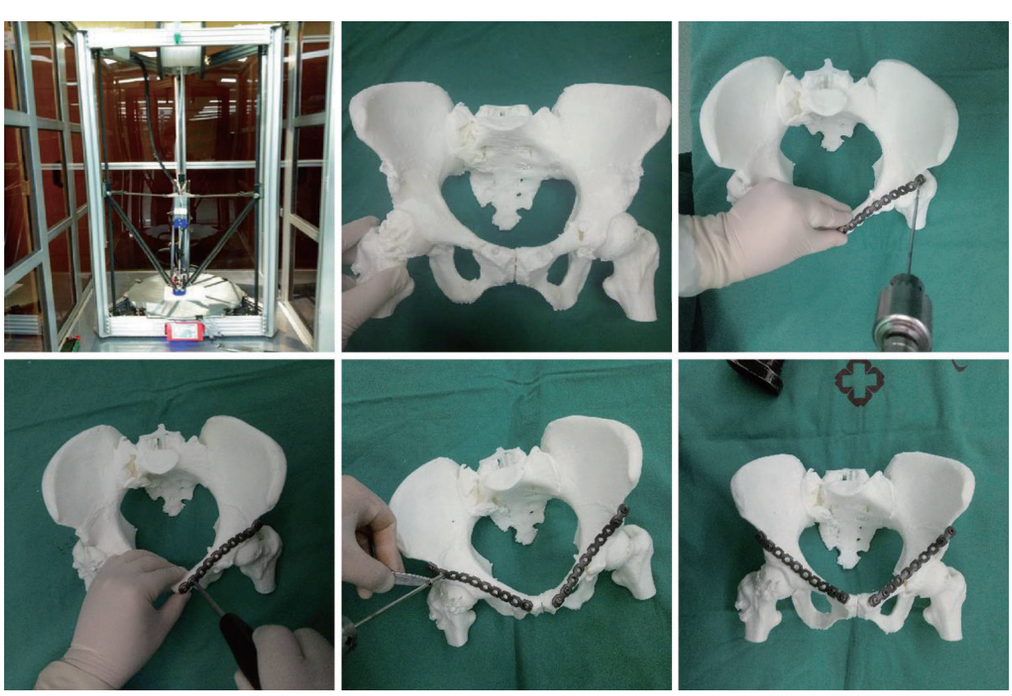


Fig. 2 The 3D model was designed to remove the support between the bone fragments, separate the bone fragments, and visualize the internal situation of the fracture. The plate was prebent on the 3D printing model, and the surgical approach and internal fixation were determined.

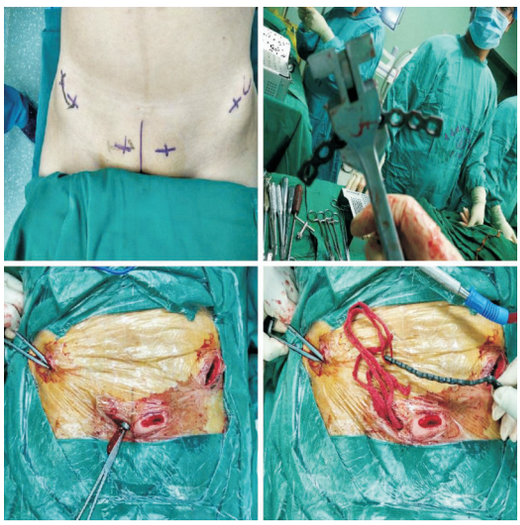
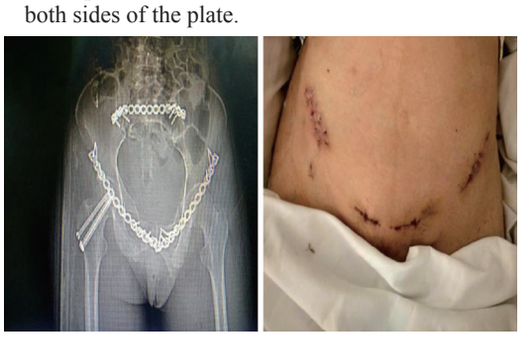


Fig. 3 According to the surgical incision designed before operation, the "tunnel" was formed by using oval forceps to open the superior pubic branch along the direction of anterior inferior iliac spine. The reconstructed plate was pre-sterilized on the 3D printed pelvis model before operation and placed at the anterior inferior iliac spine to the pubic tubercle. Two or three screws were fixed on both sides of the plate.



A B

Fig. 4 The pelvic radiographs after operation (A), and the first stage healing of the incision after the removal of the thread (B)

1.4 Perioperative Management

All patients underwent enema and perineum skin preparation one day before operation. Cefazolin (2.0 g) was given intravenously 0.5 h before operation and antibiotics were added according to the duration of operation. The changes of vital signs were detected by ECG monitoring after operation. Blood routine examination and macrobiochemistry were performed 1 day after operation, and pelvis X-ray beside the bed was reexamined. Low molecular weight heparin calcium was subcutaneously injected at 12 h after operation and lasted until 4 weeks after operation to prevent deep vein thrombosis of the lower limb. Muscle and joint function exercises were performed on the 1st day after operation. During bed rest, the patients moved their knees and ankles with slight hip flexion. In addition, excessive flexion, abduction and external rotation of the ipsilateral hip joint were avoided. At 2nd to 3rd week after injury, the ankle joint was stretched forcefully, slowly and completely, 5 min/group, 1–2 groups/h. Isometric contraction of bilateral quadriceps femoris and posterior femoral muscle group was done. At the same time, the upper limb muscle strength was strengthened, in order to maintain basic physical fitness, for the body position transfer and walking on the ground. At 3rd to 4th week after the injury, a gentle hip exercise began. But it must be done on the bed, at the same time, a gentle and slow initiative must be guaranteed. At 6th to 8th week after injury, the degree of fracture healing was strong enough for lateral decubitus. After the professional doctor has reviewed the permission, loading and balancing exercises began, and stepping forward and sideways started.

1.5 Observation Indicators

The observation indicators included operation time, amount of blood loss during operation, injury of important tissue structure, reduction of fracture and recovery of function after operation, etc. On the first 3 months after operation, the X-ray reexamination was done every month to check the fracture healing, and according to the fracture healing condition, the time of getting out of bed was determined.

The outpatient follow-up time was 1, 2, 3 month(s) and 1 year after operation.

The time of complete fracture healing and the time of returning to normal activity were recorded. The fracture reduction was evaluated according to the Matta criteria[14]: maximum displacement distance of fracture ≤4 mm as excellent, 4–10 mm as good, 10–20 mm as fair, >20 mm as bad. At the last follow-up, the limb function was assessed by Majeed criteria[15]: >85 as excellent, 70–84 as good and 55–69 as fair, <55 as bad.

1.6 Statistical Analysis

All data analyses were performed in SAI9.1 statistical software. The correlation between operative duration and blood loss was analyzed by Pesrson correlation test. $P<0.05$ was considered statistically significant (fig. 5). The clinical data are reported as mean±standard deviation.

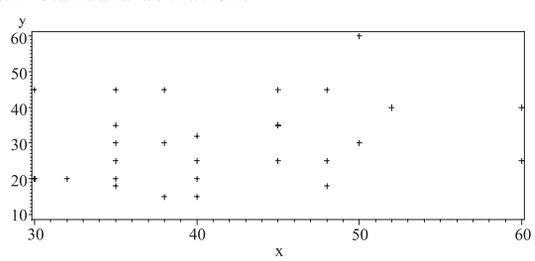


Fig. 5 Scatter plot of the relationship between operative duration and blood loss

The x axis represents the operative duration (min), and the y axis represents the blood loss (mL) during the operation. The above data were input into SAS9.1 software. By pesrson correlation test, the correlation coefficient between blood loss and operative duration was 0.2855. The correlation test (P=0.1220 >0.05) showed that there was no correlation between them. But in this study, with the increase of the number of cases, the skill of operation is improved obviously.

2 RESULTS

Thirty patients with pelvic posterior ring fracture or sacral ligament injury were identified by X-ray, CT and MRI findings. Among the 30 cases, 14 cases required only pubic rami fixation, whereas 16 patients underwent pubic rami fixation combined with sacroiliac fixation. All the 30 patients had complicated injuries, and the most common injuries were pulmonary contusion. Five patients were admitted to an intensive care unit (ICU) for further treatment, including 1 case of intestinal rupture, 1 case of cerebral hemorrhage and 3 cases of shock.

There were four patients who needed blood transfusion during the surgery. Three of the patients suffered hemorrhagic shock, and one suffered fracture of the shaft of the femur. The patient underwent internal fixation for femoral shaft fracture in addition to the pubic rami fracture fixation during the surgery. This patient received 1200 mL of non-autologous blood, and the rest 3 patients each received 800 mL.

The procedure time for pubic rami fixation ranged from 30 to 60 min, with an average of 41.6±8.1 min. The mean intraoperative blood loss was 30.6±11.3 mL (range, 15–60 mL). Patients with long operative time and great bleeding were associated with posterior ring injury and needed fixation.

Six patients had lateral femoral cutaneous nerve (LFCN) injury in this group, and no wound infections occurred in these patients, including the patient with urethral injures or intestinal rupture.

The quality of fracture reduction was evaluated according to the Matta criteria. Excellent effectiveness was achieved in 22 cases (73.3%), and good in 8 (26.7%). The functional score is based on the Majeed criteria, among them, 21 cases obtained excellent effectiveness (70%), and 9 cases obtained good effectiveness (30%).

The 30 patients had follow-up visits for 4 to 16 months (mean, 9.9 months). All patients returned to their jobs and lifestyles at the last follow-up (table 2).

Table 2 Intraoperative and postoperative indexes of patients

Time from injury to surgery (day)	Operative duration (min)	Blood loss (mL)	Follow-up time (month)	Fracture-healing time (week)	Matta criteria		Majeed criteria	
					Ⅰ	Ⅱ	Ⅰ	Ⅱ
6.0±2.8	41.6±8.1	30.6 ±11.3	9.9 ±3.3	12.5±2.4	22	8	21	9

Ⅰ: excellent; Ⅱ: good

3 DISCUSSION

The anterior pelvic ring is the weakest part of the pelvic ring and is more prone to fracture than the posterior ring. Scheyerer[3] found that the simple fractures of the pelvic anterior ring were rare, and most of them were complicated with hidden injuries of the posterior pelvic ring. Matta believes that the fixation of the pelvic anterior ring can maintain its original anatomical structure and increase the stability of the pelvis[11]. It can be seen that the treatment of the fracture of the pelvic anterior ring is significant for the restoration of pelvic stability and the improvement of the prognosis.

The particularity of pelvic structure brings great difficulties to surgical repair and internal fixation. The treatment of pelvic fractures has become one of the most important problems in the field of trauma orthopedics. The classification of pelvic fractures and preoperative surgical design are mostly based on the radiographic and CT images of 2D images, but the information provided by these imaging data is incomplete[16]. Depending on the operation plan designed by the above imaging data, the position of the plate implanted is often inaccuracy, and the prebending plate is difficult to fit the fracture well.

Minimally invasive surgery is one of the main advances in the treatment of pelvic fractures. However, no matter what minimally invasive operation is adopted, it is difficult to match the internal fixation well with the fracture ends, so as to achieve the results of small trauma and good reduction. In this study, 3D printing technique and minimally invasive incision were used to treat the fracture of the anterior ring of pelvis. The operation was simulated in model, and then the pelvic internal fixation was performed, and satisfactory results were obtained.

The pelvic fracture model was printed by 3D printing technique and minimally invasive incision was performed, which was made through anterior inferior iliac spine and pubic nodule before operation. Through 3D printing technology, orthopedic surgeons can make a comprehensive and detailed understanding of the fracture before operation, make accurate diagnosis and classification, and predict the results of simulated surgery and repair on the fracture model. Through selecting different surgical methods and adjusting surgical strategies through simulated operation, the best individualized operation scheme is worked out[17–20]. Before operation, 3D printing model can help the surgeon to master the patient's condition more deeply, and also help the patient and his family to understand the complexity of the disease and the risk of operation, and to obtain the understanding and cooperation of the patient. The application of 3D printing technology can provide accurate data and abundant information for

clinical repair operation, reduce bleeding and shorten repair time[21].

The advantage of 3D printing model is that the plate can be prebent according to the model before operation, simulated operation can be performed, and the plate and screw were directly implanted during the operation. The length and direction of the screws have been determined before operation, thus greatly reducing the time of measurement of screws. Through the analysis of 30 patients, female patients were treated with 10 holes plate, male patients with 12 holes plate, and anterior inferior iliac spine and pubic tubercle were fixed with 2 or 3 common screws respectively. However, there were still 7 cases of poor application during the operation, considering that the main reason was that the preformed plate was shaped according to the 3D printing model, and we found that the minimally invasive incision was adopted during the operation, and the reduction of the fracture end was difficult. Only by remolding the plate can the fracture be well reduced. Even so, according to the Matta criteria, postoperative fracture reduction evaluation showed that the fracture reduction was excellent in 22 cases and good in 8 cases.

In this study, 30 patients were designed with 3D printing technique to select suitable internal fixator, which shortened the operation time and reduced blood loss, and was obviously superior to the traditional minimally invasive surgery. The average operative time is 41.6±8.1 min, and the average blood loss was 30.6±11.3 mL. In addition, the fat tissue in the anterior pelvic ring is thicker, fat liquefaction is easy to occur after traditional open reduction, and the intraoperative hemorrhage is easy to lead to hematoma formation, which has an impact on postoperative recovery. In this group, all the patients healed at the first stage. Minimally invasive incision through anterior inferior iliac spine and pubic tubercle may injure the LFCN. The LFCN is located in the deep part of the inguinal ligament and under the anterior superior iliac spine. However, some scholars reported that there were variations in anatomy of LFCN, about 2.9% of the patients walked on the outer side of the anterior superior iliac spine[22]. Therefore, patients and their families should be informed of this variation and possible neurological dysfunction before operation. In this group, 6 cases (20%) developed anterolateral thigh paralysis symptoms, but those disappeared at the last follow-up. Most scholars believe that LFCN injury is temporary[3, 6].

The 3D printing technology has been proved to be very practical in clinical work[23, 24], but there are still some problems in clinical application: (1) Conservative in outlook: Although 3D printing can enable surgeons to understand more directly the type of pelvic fractures and develop more optimal surgical procedures, some of the patients and their families are not fully understood, the surgeons need to be patient to explain and do a good job of communication. (2) Cost problems: The price of 3D printing products is too expensive at present. On the one hand, the environmental requirements for printing are high; on the other hand, the equipment and materials required for printing are monopolized by large manufacturers. (3) Production cycle problem: In clinical application, the CT data of patients should be acquired first, then processed and reconstructed, and finally 3D model can be obtained by printer, which takes a long time. (4) Clinical application problems: The original data of 3D printing model are CT data, ignoring the influence of soft tissue around pelvic fracture. In addition, the changes of patient's posture and surgeon's operation during the operation may cause the simulation of the model to be inconsistent with the actual operation.

In conclusion, the computer aided technology of 3D printing has been proved to be very practical in clinical work[25, 26]. In this study, we used 3-D printing technology combined with minimally invasive incisions to treat anterior ring pelvic fractures. Preoperative computer-aided system was used to make adequate preoperative preparation for patients and simulate the operation process. The postoperative results showed that the operative duration and blood loss were significantly reduced, and the function of the patients recovered well after operation. According to Majeed criteria, this study found that the excellent and good rate was 100%, with no fair or bad patients. Although 3D printing technology requires a high degree of material science and computer operation, it can help us to understand fracture types and make effective preoperative planning. It can improve the accuracy and safety of surgery. It is believed that the future orthopedic field can be widely used, and benefits more and more patients.

Conflict of Interest Statement

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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