



Original article

Application of computer-assisted virtual surgical procedures and three-dimensional printing of patient-specific pre-contoured plates in bicolumnar acetabular fracture fixation



Kaifang Chen, Fan Yang, Sheng Yao, Zekang Xiong, Tingfang Sun, Fengzhao Zhu, Dionne Telemacque, Deepak Drepaal, Zhengwei Ren, Xiaodong Guo*

Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, Hubei Province China

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ABSTRACT

Introduction: With the rapid development of three-dimensional (3D) printing and computer technology, adopting computer-assisted virtual surgical procedures and 3D printing of patient-specific pre-contoured plates can greatly reduce surgical invasiveness and operative time and simplify the procedure.

Hypothesis: Use of computer-assisted virtual surgical procedures and 3D printing of patient-specific pre-contoured plates reduce the operative time and blood loss in bicolumnar acetabular fracture fixation.

Methods: A retrospective analysis was performed for 52 bicolumnar acetabular fracture cases treated surgically in our department from January 2013 to January 2017. According to the patients' willingness to accept 3D printing services, 52 patients were divided into groups A and B. In group A (28 patients), computer-assisted virtual surgical procedures and 3D printing of patient-specific pre-contoured plates were adopted. In group B (24 patients), the conventional method was adopted. Fracture type, operative blood loss, surgical time, complications, radiographic quality of reduction, and hip function were compared between groups. All patients were operated by the same surgeon.

Results: The real surgical procedure of all patients in group A was almost identical to the preoperative virtual operation. Operative time and intraoperative blood loss were significantly reduced in group A than in group B ($p < 0.05$), while the postoperative fracture reduction quality and hip function obtained slightly higher levels of satisfaction in group A.

Conclusions: Computer-assisted virtual surgical procedures, 3D printing technology and patient-specific pre-contoured plates can reduce the operative time and blood loss with less surgical invasiveness and ensure completely satisfactory clinical outcomes. However, promotion of this technology requires additional work.

Level of evidence: III, therapeutic study.

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1. Introduction

Acetabular fracture is a serious intra-articular fracture of a weight-bearing joint, and anatomic reduction and strong internal fixation is its eternal pursuit [1,2]. However, because of the complex local anatomy of the pelvis and close-set neurovascular structure, acetabular fracture surgery has always been very challenging.

Because the osseous morphological structure of the pelvis is extremely complex, orthopedic surgeons often found it difficult to conceptualize the various fracture patterns and shape the plates during an acetabular operation [3]. Especially for the inexperienced surgeons, it may take a long time to bend the plates repeatedly, which would decrease the strength of the plates or lead to re-displacement of fractures because of unsatisfactory contouring, ultimately resulting in a high risk of surgical complications and unsatisfactory clinical outcomes [4,5].

With the rapid development of computed tomography (CT) imaging technology and digital orthopedic surgery methods, computer-aided design (CAD) and rapid prototyping (RP) technology have been widely used in clinical practice [2,6,7]. In order to solve the above problems, many studies have reported the application of computer-assisted virtual surgery procedure and

* Corresponding author at: Department of Orthopedics, Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, 1277 Jiefang Avenue, Wuhan, Hubei Province 430022 China.

E-mail addresses: xiaodongguo@hust.edu.cn, gxdwh@qq.com (X. Guo).

three-dimensional (3D) printing technology, which finally obtained good clinical outcomes in acetabular fracture surgeries [2,3,8,9].

However, there are still rare studies comparing CAD and RP techniques for patient-specific pre-contoured plate and the conventional method of intraoperative contouring of the reconstruction plate. Therefore, we performed a retrospective analysis on the clinical data of 52 patients with complex acetabular fractures involving two columns over the past 4 years from January 2013 to January 2017, comparing CAD and RP techniques for patient-specific pre-contoured plate and the conventional method in terms of surgery index, reduction quality, and hip function.

2. Materials and methods

2.1. Inclusion criteria

The inclusion criteria are as follows:

- Age between 18–70 years.
- According to the Letournel-Judet fracture classification [10], a fracture type of closed complex acetabular fracture involving two columns with a history of surgical treatment.

2.2. Exclusion criteria

The exclusion criteria are as follows:

- Abnormal activity of the hip joint on one or both sides before injury.
- Injury Severity Score [11] ≥ 25 points or inability to undergo surgery within 3 weeks of injury.

2.3. General materials

According to the above inclusion and exclusion criteria, 52 patients admitted in our department from January 2013 to January 2017 were enrolled in this study.

The patients were divided into two groups according to every patient's willingness to accept 3D printing services. In group A, 28 patients (18 men) with an average age of 46.11 ± 13.63 years accepted patient-specific surgery by applying preoperative CAD and RP techniques for patient-specific pre-contoured plate. For the other 24 patients (group B, 14 men) with a mean age of 42.38 ± 12.28 years, the conventional method of intraoperative

contouring plates was adopted. Informed consent was obtained from each patient.

According to the Letournel-Judet fracture classification [10], there were 10 cases of "T" shaped fractures, 16 cases associated with anterior column + posterior hemi-transverse (ACPHT) fractures, and 26 cases of double column fractures. The time from injury to operation was 4–21 days, with an average 9.44 ± 4.17 days. All patients' surgeries were performed by the same surgeon (X.D.G).

2.4. Preoperative preparation

2.4.1. Group A

2.4.1.1. Collection of the CT scan data. After obtaining the consent of the radiology department, the data of CT scan of the pelvis (Siemens, Germany; 64-row spiral CT with 1-mm layer thickness) were transferred to the engineers in our hospital's 3D printing center for further image processing.

2.4.1.2. Computer-assisted virtual surgical procedure. The thin-slice CT scan data in Digital Imaging and Communications in Medicine (DICOM) format were imported into Mimics 16.0 (Materialise, Belgium) on the computer. The segmentation needs to be performed manually in all slices in all three planes, and different colors were assigned to different fracture fragments. After the segmentation process, each fracture fragment becomes a separate object. Then, the pelvic 3D model with the fractured acetabulum for the simulation was built (Fig. 1) and saved in .STL format. The pelvis can be turned in all directions during the virtual operation, and key bone fragments can be identified. Next, the healthy hemipelvis was mirrored and used as a template for reduction (Fig. 2). Reduction of the fracture was performed because bone fragments can be moved and rotated in all three planes (Fig. 3). Finally, the models of post-reduction hemipelvis and mirrored healthy hemipelvis were exported and saved in the .STL format.

The model of the post-reduction hemipelvis (in .STL format) was imported into the software, 3-matic (Materialise, Belgium), to design the placement of plates (Fig. 4), and then the output of the data (in .STL format) was fed into Mimics 16.0 (Materialise, Belgium) again to check the placement of plates in cross-sectional, sagittal, and coronal planes.

2.4.1.3. Printing and simulation of the surgery in vitro. The data of the fractured hemipelvis before reduction and those of the mirrored healthy hemipelvis in .STL format were imported into the

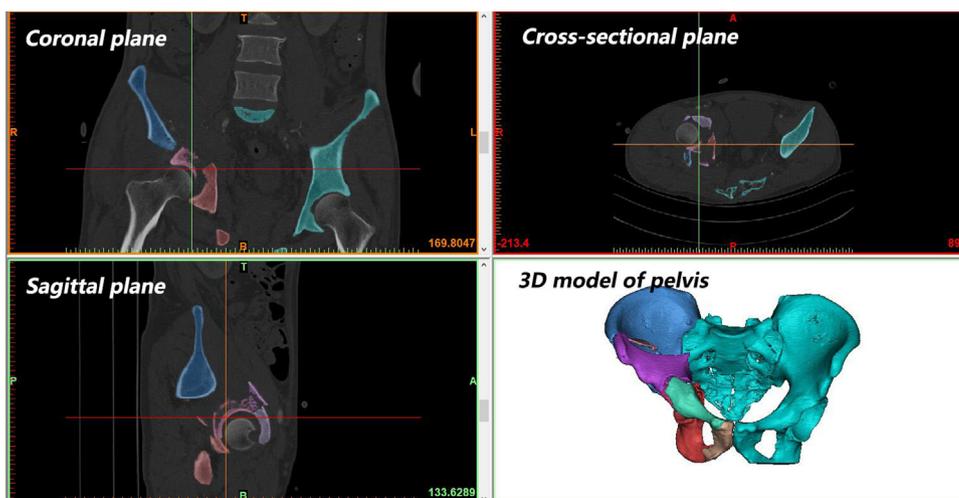


Fig. 1. Each fracture fragment was segmented manually in all slices in all three planes, and different colors were assigned to different fracture fragments. Then, a multi-colored pelvic 3D model with the fractured acetabulum was built and the pelvis could be turned in all directions during the virtual operation.

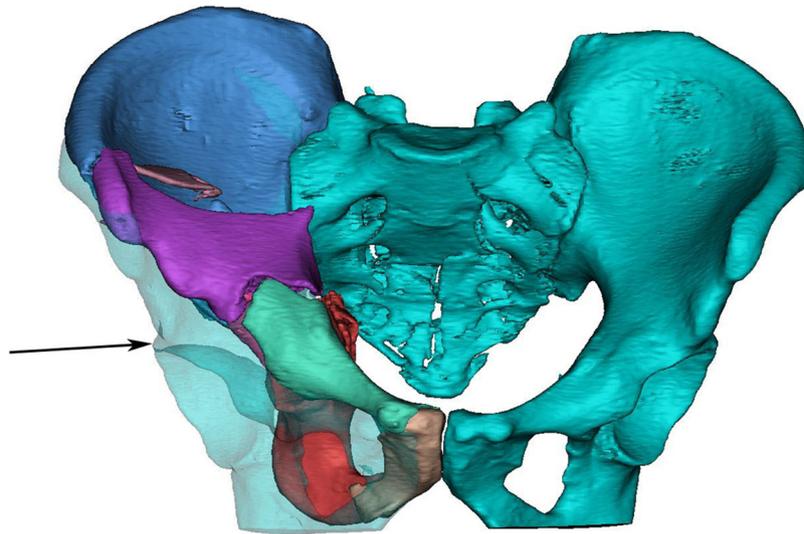


Fig. 2. The healthy hemipelvis was mirrored and used as a template for reduction. The black arrow shows the semitransparent mirrored healthy hemipelvis.

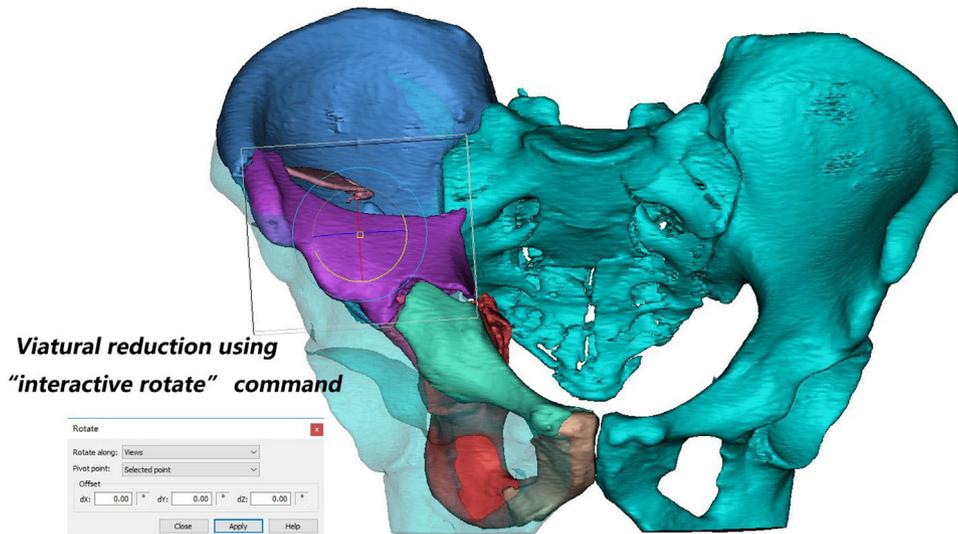


Fig. 3. The virtual reduction of the fracture was performed because bone fragments could be moved and rotated in all three planes using the mirrored healthy hemipelvis as a template.

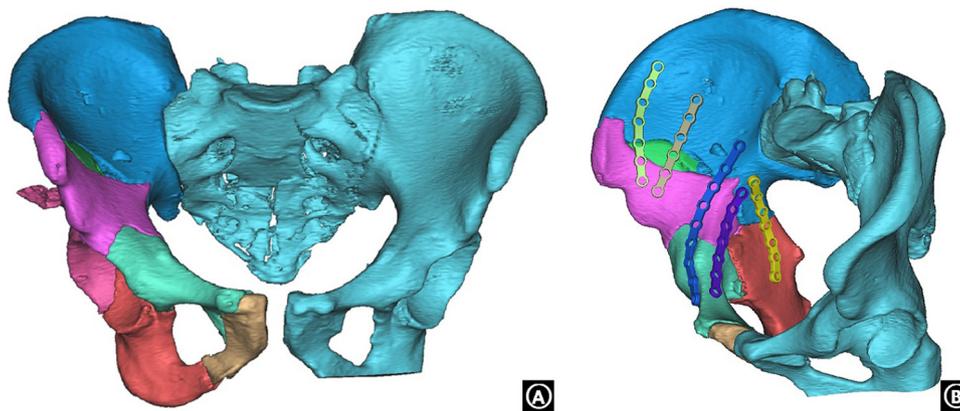


Fig. 4. After the virtual reduction was completed (A), virtual plating was performed using another software 3-matic (Materialise, Belgium) (B).

software, Cura (Ultimaker, Netherlands), for slicing to generate a series of G codes that could be identified by the printer. Subsequently, the 3D models of the fractured hemipelvis and mirrored healthy hemipelvis in .STL format were printed using a 3D printer

using polylactic acid (PLA). Thereafter, the 3D printing model of the mirrored healthy hemipelvis replaced the anatomical reduced fractured hemipelvis, allowing us to complete preoperative contouring of the plates on the mirrored hemipelvis model while being

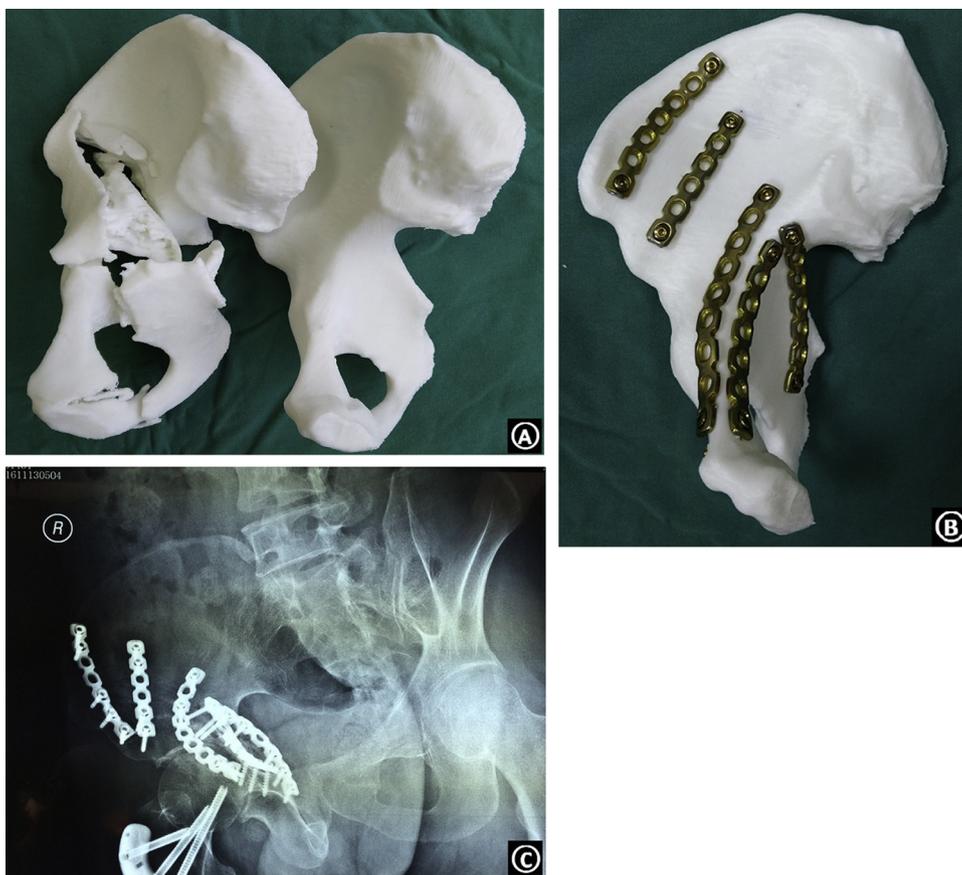


Fig. 5. The 1:1 models of the fractured hemipelvis and mirrored healthy hemipelvis were printed using polylactic acid (PLA) (A). Then preoperative contouring of the plates on the mirrored hemipelvis model was performed while being consistent with virtual surgical procedures (B). C. post-operative radiograph showing the iliac oblique view of pelvis.

consistent with virtual surgical procedures (Fig. 5). Finally, these patient-specific pre-contoured plates were sterilized for operation.

2.4.1.4. Real surgery. The detailed preoperative planning made it possible to reduce and fix the bicolumnar fractures through a single supra-ilioinguinal approach [12]. After reduction of the fracture, the pre-bending plates could be placed smoothly without recontouring, which was highly consistent with the preoperative planning. Sometimes, when encountering separation of fracture segments that are difficult to reduce, the pre-bending plates could be placed to assist reduction of the fracture displacement. As these plates were the absolute personalized anatomical plates, small fracture displacement could be reduced by the compression of plates.

2.4.2. Group B

Conventionally, the preoperative planning was performed on the reconstructed images of the pelvic CT scan, and the same supra-ilioinguinal approach was adopted in every case. The plates were all contoured intraoperatively and the time required for contouring was recorded.

2.5. Assessment parameters

Based on the CT scans of the pelvis, the quality of reduction was evaluated according to the reduction criteria published by Matta [13]: 1 mm or less was an excellent reduction; 2 mm to 3 mm, good reduction; and greater than 3 mm, poor reduction. Until the last follow-up, hip function was evaluated by the first author (K.F.C.) using the Modified Merle d'Aubigné scoring system [14]: 18 points

indicated an excellent outcome; 17 to 15 points, good; 14 to 13 points, fair; and less than 13 points, poor.

2.6. Statistical analysis

All data from the study were statistically processed and analyzed using the SPSS 19.0 software. The measurement data were analyzed using the *t*-test of independent samples or paired samples. The rank-sum test was used in analyzing the ranked data. Statistical significance was indicated by a *p*-value of < 0.05.

3. Results

3.1. General results

As for the sex, age, time from injury to operation, and fracture type, there was no significant difference between groups A and B ($p > 0.05$). In other words, there was comparability between the two groups in other assessment parameters.

3.2. Intraoperative blood loss

Blood loss during the operation in group A was less than that in group B, with mean values of 696.07 ± 166.54 mL and 833.75 ± 227.44 mL, respectively, resulting in a statistical difference ($p = 0.018$) (Fig. 6).

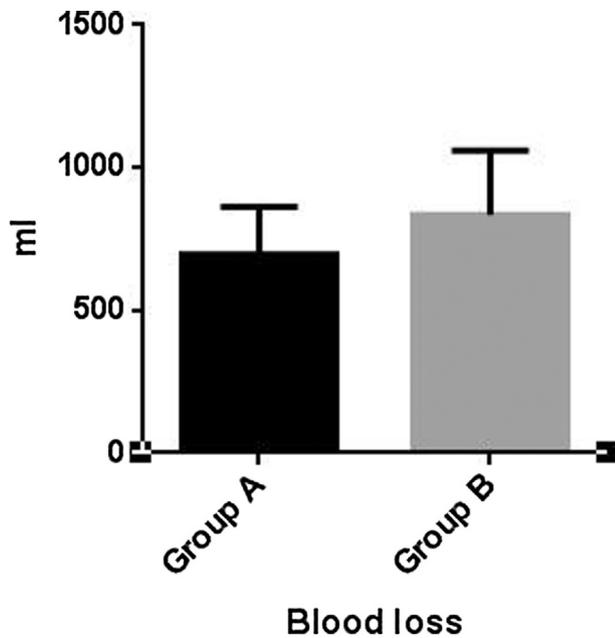


Fig. 6. Comparison between the intraoperative blood loss of group A and group B.

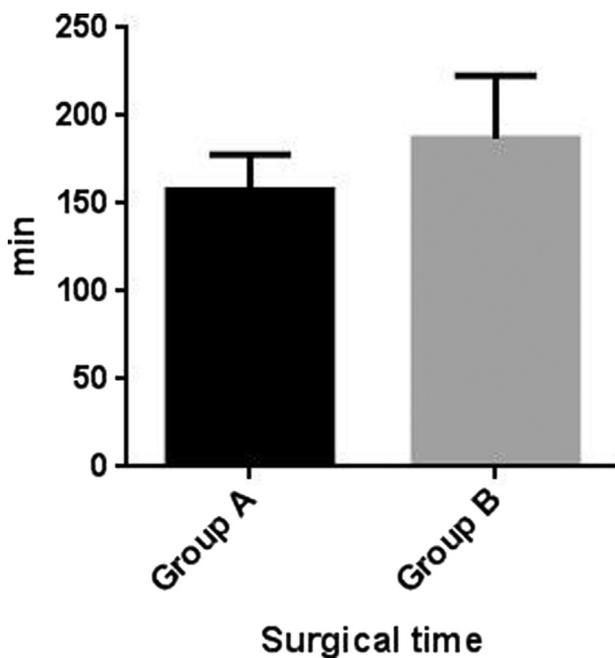


Fig. 7. Comparison between the surgical time of group A and group B.

3.3. Surgical time

Surgical time in group A was found to be shorter than that in group B, with average values of 157.5 ± 20.48 min and 187.08 ± 35.81 min, respectively, also presenting a statistical difference ($p = 0.001$) (Fig. 7).

3.4. Time required to contour plates during the operation

In group A, re-contouring was unnecessary during the operation; therefore, this parameter could not be compared with that in group B. The plates used in all patients in Group B underwent intraoperative bending conventionally, and the average time required to

contour the plates was 18.81 ± 5.89 min per case, and the average time spent on contouring one plate was 4.7 min.

3.5. Quality of reduction

According to the Matta scoring system [13], 18 cases (64.3%) of reductions were graded as excellent; 7 cases (25.0%), good; and 3 cases (10.7%), poor in group A with an excellent/good rate of 25/28, which was slightly higher than that in group B (19/24). However, there was no statistical difference between the two groups ($p = 0.448$).

3.6. Scoring of hip function

According to the Merle d'Aubigné scores [14], the mean score was 16.25 ± 1.64 and 15.83 ± 1.88 in groups A and B, with an excellent/good rate of 24/28 and 18/24, respectively, resulting in no statistical difference ($p = 0.398$).

Fig. 8 illustrate one case with both column fracture treated by the computer-assisted virtual surgical procedures and 3D printing of patient-specific pre-contoured plates.

4. Discussion

Acetabular fracture surgery has been a relatively challenging “hotspot” for orthopedic surgeons. The difficulties of the surgery lie in the complexity of the local anatomy of the pelvis, diversity of fracture morphology, and inconvenience of bending plates, so a detailed preoperative planning combined with accurately contoured plates can ensure the success of acetabular fracture surgery [3,15]. During the past decade, the CAD technology has been applied more and more widely in the clinical work, making preoperative computer-aided virtual surgery become a reality [16,17]. Later, with the rise of RP technology, images of two-dimensional space could be turned into real models of 3D space in a real sense, resulting in a more intuitive understanding of the fracture morphology and an ideal surgical scheme for orthopedic surgeons [18]. For clinicians, however, the real benefit is that preoperative bending plates in vitro or directly prints various personalized internal plants [8,9,19].

In 2011, Hu et al. reported a computer-assisted simulation method based on CT data for the preoperative planning of acetabular fracture reduction and osteosynthesis [2]. The virtual reduction and fixation helped surgeons to better understand fracture characteristics and determine the right surgical strategy, leading to a large profit, especially for younger and less experienced surgeons. However, Hu et al. did not perform pre-contouring of plates before the operation. In 2012, Shen et al. adopted a computer-assisted augmented reality (AR) technique to simplify the surgical procedure and develop a preoperative reconstruction plate design system for acetabular fracture reduction and internal fixation surgery, which could achieve favorable results but lacked a control group for comparison [17]. Later, in 2016 and 2017, Maini et al. reported better clinical results by using 3D printing technology and pre-contoured reconstruction plates in acetabular fracture surgery, in comparison to conventional intraoperative contouring [3,20]. They found that this was a good method and technique to achieve ideal surgical outcomes such as regards duration of surgery, blood loss, and quality of reduction of fracture. However, a drawback in this study was that the fracture pattern of patients in the two compared groups differed in a thousand ways and the choices of the surgical approach were also varied, so the reliability of the results was questionable and evaluation of hip function and a long-term follow-up were lacking.

Our study was unique in case and control groups in which patients with similar fracture patterns were included, which were treated surgically by the same supra-ilioinguinal approach. In this

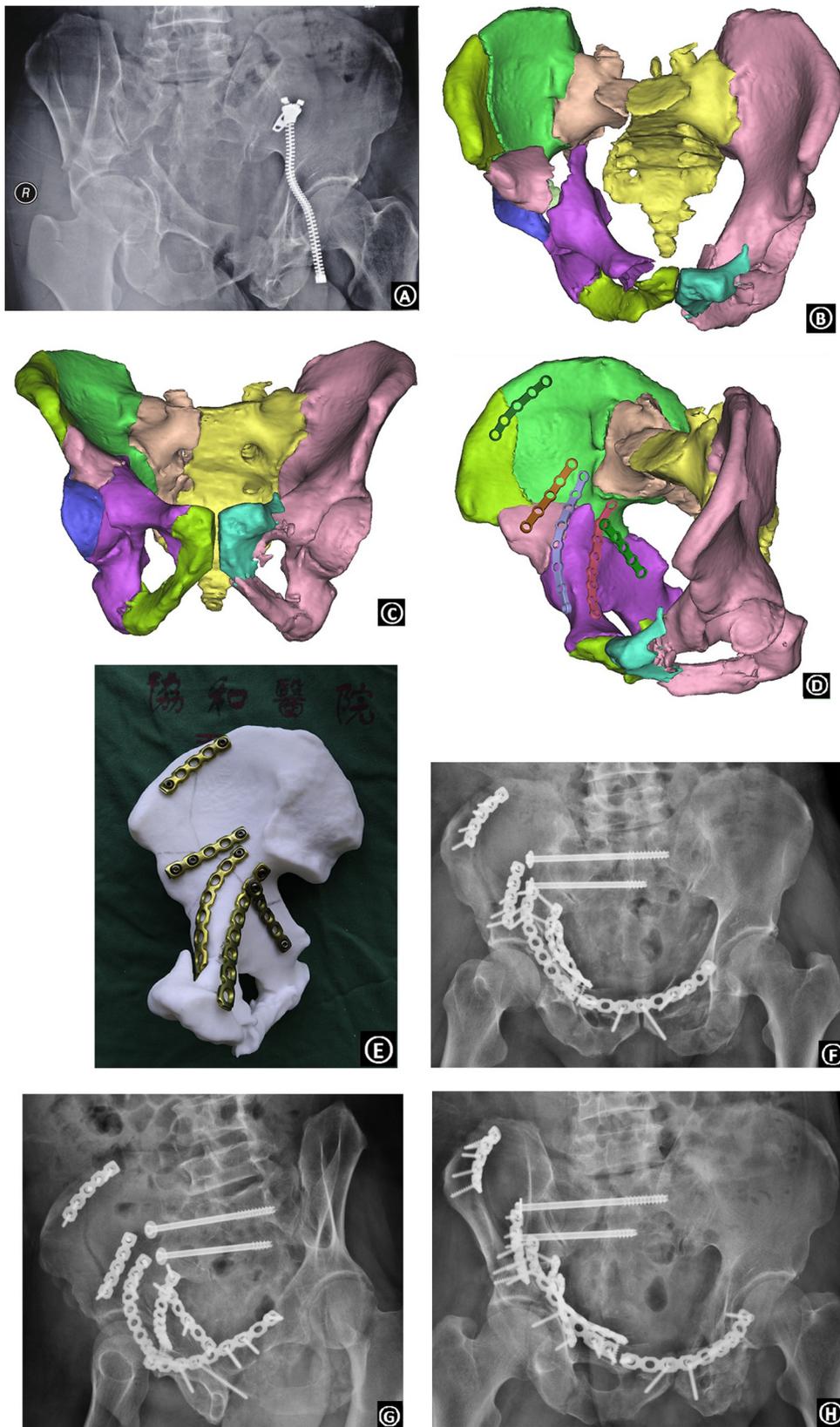


Fig. 8. One case: Luo XX, M54y falling injury. The classification of acetabular fracture was double-column fracture, combined with ipsilateral sacral fracture and contralateral ramus pubis fracture. Computer-assisted virtual surgical procedures and three-dimensional printing of patient-specific pre-contoured plates were applied for the treatment. A. Radiography showing the preoperative X-ray of pelvis. The figure B shows the preoperative multi-colored 3D model of pelvis. The figures C and D show the procedure of virtual reduction and plating on computer. Then 1:1 model of the mirrored healthy hemipelvis was printed, and patient-specific pre-contoured plates were ready for intra-operative placement (E). F–H. Radiography showing the postoperative pelvic X-rays in three positions.

way, the interference factors of the research could be minimized as soon as possible with a higher reliability. In addition, the methods we adopted to bend plates preoperatively was by mirroring the contralateral healthy hemipelvis on the computer and pre-contouring plates on the 3D printing model of the mirrored healthy pelvis directly. This method was rarely reported except in a case report written by Upex et al. in 2017 [8]. In our opinion, this method can provide a template for simulating fracture reduction on the computer, and it is relatively easy to obtain a completely normal model after reduction of the fractured pelvis to make the pre-contouring plates more anatomically accurate.

In this study, we retrospectively analyzed the data of 52 cases with acetabular fractures according to the inclusion and exclusion criteria, and the 52 cases were divided into A/B 2 groups for comparative analysis according to whether they received 3D printing and patient-specific pre-contoured plate services. Among them, 24 patients in group B did not accept the 3D printing service, because they might not be willing to spend the money, or they might doubt about the benefits of this extra step. However, in fact the results of our study showed that, compared with conventional surgical methods of intraoperative contouring plates in group B, both intraoperative blood loss and surgical time in group A were reduced significantly by pre-contouring plates on the mirrored healthy pelvis. In addition, the surgeons have been better aware of the fracture lines and fixation strategy during the whole planning process of 3D printing, including computer-assisted virtual surgery and pre-contouring plate procedure. So the quality of fracture reduction and hip-function scores in 3D printing group A were slightly higher than those in conventional group B. In group A, re-contouring of the plates was unnecessary during the operation; therefore, this parameter could not be compared with that in group B. For all patients in group B, intra-operative bending of the plates were inevitable performed repeatedly.

Our work confirmed the feasibility of CAD and 3D printing technology in preoperative planning of acetabular fracture surgery and introduced the application method in detail [21]. As mentioned in other studies, the drawback of computer-assisted virtual surgical procedure and 3D printing technology is their cost of production and prolonged preoperative time [3,8,20]. However, through our constant improvement, we only printed two 1:1 models of the hemipelvis and used 2 printers to print at the same time, which needed only 12 h. All data processing and computer-assisted virtual surgical procedures could be operated on a computer software during the 12-h period of 3D printing of the hemipelvis models (2 h may be considered sufficient). Thus, it may almost take 36 h to complete all the preoperative preparation (including the time needed to bend and sterilize the plates). Hence, it is not an obstacle for acetabular fracture surgery which is recommended 5 to 10 days after the injury [8,22,23]. Moreover, the cost of using PLA as printing material is controlled as 500 Yuan commonly per patient, but 3D printing and pre-contouring plates can save 30 min of the surgical time on average. To our knowledge, just like intraoperative blood loss, the surgical cost will also increase with prolonged duration of surgery and general anesthesia, and the surgical cost for 30 min is far more than 500 Yuan, which might be higher in the United States or Europe [24].

5. Conclusion

Computer-assisted virtual surgical procedure and 3D printing technology is a highly clinically relevant technology, especially in the treatment of complex acetabular fractures. A patient-specific pre-contoured plate can indeed reduce the operative time and blood loss to improve the accuracy and preciseness of surgical

implant preparation in a real sense. However, many obstacles still remain to promote this technology widely.

Compliance with ethical standards

This study has been approved by the Hospital Ethics Committee.

Disclosure of interest

The authors declare that they have no competing interest.

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Authors' contributions

Both Dr. Xiaodong Guo and Kaifang Chen conceived and designed the study; Both Fan Yang and Sheng Yao performed the data collection and analysis; Zekang Xiong, Tingfang Sun and Fengzhao Zhu helped perform the analysis with constructive discussions; Kaifang Chen, Fan Yang and Zhengwei Ren completed the evaluation of postoperative reduction quality and hip function; Kaifang Chen wrote the manuscript; Dionne Telemacque and Deepak Drepaal helped with the language proofreading of manuscript. All authors read and approved the final manuscript and consented to publish this manuscript.

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