A combination of three-dimensional printing and computer-assisted virtual surgical procedure for preoperative planning of acetabular fracture reduction

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ABSTRACT

Objective: Treatment of acetabular fractures remains one of the most challenging tasks that orthopaedic surgeons face. An accurate assessment of the injuries and preoperative planning are essential for an excellent reduction. The purpose of this study was to evaluate the feasibility, accuracy and effectiveness of performing 3D printing technology and computer-assisted virtual surgical procedures for preoperative planning in acetabular fractures. We hypothesised that more accurate preoperative planning using 3D printing models will reduce the operation time and significantly improve the outcome of acetabular fracture repair.

Methods: Ten patients with acetabular fractures were recruited prospectively and examined by CT scanning. A 3-D model of each acetabular fracture was reconstructed with MIMICS14.0 software from the DICOM file of the CT data. Bone fragments were moved and rotated to simulate fracture reduction and restore the pelvic integrity with virtual fixation. The computer-assisted 3D image of the reduced acetabula was printed for surgery simulation and plate pre-bending. The postoperative CT scan was performed to compare the consistency of the preoperative planning with the surgical implants by 3D-superimposition in MIMICS14.0, and evaluated by Matta's method.

Results: Computer-based pre-operations were precisely mimicked and consistent with the actual operations in all cases. The pre-bent fixation plates had an anatomical shape specifically fit to the individual pelvis without further bending or adjustment at the time of surgery and fracture reductions were significantly improved. Seven out of 10 patients had a displacement of fracture reduction of less than 1 mm; 3 cases had a displacement of fracture reduction between 1 and 2 mm.

Conclusions: The 3D printing technology combined with virtual surgery for acetabular fractures is feasible, accurate, and effective leading to improved patient-specific preoperative planning and outcome of real surgery. The results provide useful technical tips in planning pelvic surgeries.

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Introduction

Acetabular fractures occur primarily in young adults as a result of high-velocity trauma. The treatment of acetabular fractures remains one of the most challenging tasks that orthopaedic surgeons face because of the complex anatomy, limited surgical access to the fracture sites, and postoperative uncertainties [1,2]. Although some fractures may not require surgery for a satisfactory outcome, displaced fractures in the weight-bearing area of the acetabulum should be treated with open reduction and internal fixation to restore the congruity and stability of the hip joint [3]. Acetabular fractures are often complex injuries, and there is no single surgical approach applicable to all acetabulum fractures. For an excellent outcome of the fracture reduction, the surgeon has to know the precise anatomy and type of fracture, the fracture extent, joint congruency, step-offs or gaps in the joint surface and entrapped osteochondral fragments that he or she deals with after examination of the plain films as well as the CT...
scans. In addition, there is no unified anatomically correct implant to fix the variable, patient-specific fractures. Contouring plates and planning screw length during the operative procedure may not be accurate enough and could significantly prolong the operation time. Therefore, it is necessary to prepare custom-made plates and screws for each patient prior to surgery.

In recent years, with the development of digital medicine and imaging modalities, a 3D bone model of the fracture pattern can be generated to plan the position of inter-fragmentary screws and prepare a pre-bend fixation plate to adapt the complex orthopaedics. Wong et al. successfully performed a partial acetabular resection in a patient with pelvic chondrosarcoma and subsequent reconstruction with a custom pelvic implant in a one-step operation using a CT-based method for surgical planning, with engineering software for implant design and validation, and 3D printing technology for implant and patient-specific fabrication [4]. A pre-operative contouring of the plate could also be obtained with a mirror image of the uninjured half of the pelvis from CT scanning [5]. Hu and his colleagues [6] recently reported a computer-assisted virtual surgical procedure to simulate the reduction and internal fixation for acetabular fractures using real CT scan data. Their studies, as well as, other studies have demonstrated that surgeons can obtain an optimised operative plan on their personal computers with the exported CT data of the injuries [7,8] and achieve satisfactory results via an interactive surgical planning tool that is adapted with the virtually reduced pelvis [7]. However, the outcomes of the preoperative plan on surgical treatment sometimes remains a problem and fails to yield optimal results because of a lack of a handy 3-D fracture model available at the time of operation.

In order to provide a more accurate method of preoperative planning, we used 3D printing technology to produce actual size 3D models for surgical simulation. The technique in combination with computer-assisted virtual surgical procedures allows surgical simulation of complex acetabular fractures more economically and efficiently. We compared the postoperative results with the preoperative planning and found that the 3D printing technology combined with virtual surgery for acetabular fractures is feasible, precise, and effective improving patient-specific preoperative planning and actual surgery of the fracture reduction. These procedures provide useful technical tips in clinical practice.

Materials and methods

Patients and data acquisition

Patients with acetabular injuries acquired from June 2013 to February 2015 were screened for the study. Patients who were diagnosed with acetabular fractures and eligible for surgery were included in the study. Patients who had simple wall fractures or dislocated hips that needed immediate surgery to restore hip joint function were excluded. The study was approved by the Human Research Ethics Committee, Southern Medical University, Guangzhou, China and consents were obtained from all patients.

Patient’s pelvises were scanned by spiral computed tomography (CT) when he or she was admitted to the hospital. The CT scans were saved as DICOM files and then uploaded into Materialise’s interactive medical image control system (MIMICS) 14.0 software (Materialise, Belgium) for 3D reconstruction and editing.

Segmentation and fracture reduction

The function model of Edit task in 3D was used for semiautomatic segmentation of the fracture fragments and pelvic bones on the 3D model. Each fractured fragment was assigned with a different colour as an independent object, followed by reconstruction of the fractured acetabulum models. After moving and rotating the pelvis and fragment and determining the characteristics of the fractures, the fractured bones were reduced and restored anatomically. The reduced model of the pelvis was then exported in STL format for 3D printing.

Virtual internal fixation, 3D printing and simulation

Internal fixation approaches were determined to be dependent on the direction and locations of the fracture lines. The simulation of internal fixation including screw positions, orientation, plate location, and number of screws and plates was determined using MIMICS software. The reduced pelvis were saved as “.stl” files and loaded into the MakerBot Desktop Beta software (MakerBot, America) to set up parameters such as resolution, temperature, and support material for 3D printing. The 3D model generated from MakerBot Replicator 2 (MakerBot, USA) was then used to simulate the internal fixation in vitro to determine if the pre-bend plates fit each reduced fracture model. After adjusting and re-validating in a surgical simulation, the osteosynthesis implants including the pre-bent plates and the screws were disinfected for real operation.

Surgical procedures and comparison between virtual planning and real surgery

Ten cases were classified according to the Letournel [9] classification. A novel pararectus approach was used for the surgical management of the acetabular fractures for anterior column fracture [10]. The Kocher–langenbeck (K–L) approach was preferably adopted for the posterior column fracture of the acetabula. The combined approaches of pararectus and K–L were used for the patients with both column fractures. The patients with generally good health were encouraged for early rehabilitation. One week after surgery, all patients were subjected to a follow-up CT scan for a reconstruction of the virtual 3D model of the osteosynthesis implants. The generated 3D osteosynthesis implants from post-surgery were then compared with pre-planned plates and screws from simulated models and evaluated according to Matta’s [11] method. Displacement of 1 mm or less was defined as anatomic reduction; displacement between 2 and 3 mm was considered as a satisfactory reduction; and displacement of more than 3 mm was determined as an unsatisfactory reduction.

Results

A total of 10 patients including 5 men and 5 women (19–52 years old) met the screening requirements and were recruited for the study. The classification and detailed characteristics of the pelvic fractures were listed in Table 1. There were 3 cases with anterior column fractures, 1 case of a T shaped fracture, 5 cases of both column fractures, and 1 case with a transverse and posterior wall fracture. To build the 3D images and reduce the fractures precisely, we first removed the soft tissue structures by increasing the cylinder screw intervals of the anatomic plates as well as the screw holes for internal fixation. To fix the injured pelvis, we determined the distance of the screw intervals of the anatomic plates as well as the screw holes for simulation of internal fixation. The cylinders which have the same diameter as the screws were also generated and applied to simulate the screws. The direction and length of the cylinders were
then adjusted to meet the needs of the simulated pelvic injuries, and the length of each screw was measured for pre-surgery planning as shown in Fig. 2a. We used the manipulated 3D image to print a 3D physical model that has the same size and had the same geometric features as the patient’s acetabulum to select the pre-bend plates for simulated fixation of the anterior and posterior acetabular walls (Fig. 2b–d).

To compare the position and orientation of implants from post-surgery with pre-operative panning, postoperative X-ray and CT scans were taken one week after surgery. As shown in Fig. 3a, X-ray images show that the acetabular fractures were successfully reduced and internally fixed with bend plates and screws. The sagittal CT image of the fixed acetabula revealed an anatomic reduction of the articular surface of the acetabulum (Fig. 3b). We next extracted the plate and screw images from the post-surgery CT scans and performed the simulated fixation on the pre-surgical 3D image of the computer-assisted reduced acetabula. As shown in Fig. 3c, the plates used in the patients fixed the 3D model well. The

<table>
<thead>
<tr>
<th>Case</th>
<th>Age/gender</th>
<th>Fracture type</th>
<th>Planed management</th>
<th>Operation management</th>
<th>Articular reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44/F</td>
<td>Anterior column</td>
<td>Pararectus approach A 6-hole plate with 5 screws A 11-hole plate with 9 screws</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
<tr>
<td>2</td>
<td>52/M</td>
<td>Anterior column</td>
<td>Pararectus approach A 6-hole plate with 6 screws A 9-hole plate with 8 screws 1 screw outside the plate</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
<tr>
<td>3</td>
<td>46/M</td>
<td>Transverse and posterior wall fractures</td>
<td>Combined anterior and posterior approach A 5-hole plate with 4 screws A 5-hole plate with 4 screws A 9-hole plate with 4 screws A 6-hole plate with 5 screws (anterior) A 8-hole plate with 6 screws A 7-hole plate with 5 screws 1 screw outside the plate</td>
<td>Identical to the planned operation Satisfactory</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>19/F</td>
<td>Both columns</td>
<td>Combined anterior and posterior approach A 4-hole plate with 4 screws A 4-hole plate with 4 screws A 9-hole plate with 6 screws A 7-hole plate with 5 screws A 5-hole plate with 5 screws (anterior) A 11-hole plate with 10 screws A 6-hole plate with 5 screws (posterior)</td>
<td>Identical to the planned operation Satisfactory</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>38/M</td>
<td>Both columns</td>
<td>Pararectus approach A 9-hole plate with 8 screws 2 screws outside the plate (anterior)</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
<tr>
<td>6</td>
<td>28/M</td>
<td>Both columns</td>
<td>Combined anterior and posterior approach A 9-hole plate with 8 screws A 10-hole plate with 5 screws (anterior) A 8-hole plate with 8 screws (posterior)</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
<tr>
<td>7</td>
<td>27/F</td>
<td>Anterior column</td>
<td>Pararectus approach A 12-hole plate with 11 screws 2 screws outside the plate (anterior)</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
<tr>
<td>8</td>
<td>23/M</td>
<td>Both columns</td>
<td>Combined anterior and posterior approach A 12-hole plate with 11 screws (anterior) A 6-hole plate with 6 screws A 10-hole plate with 10 screws (posterior)</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
<tr>
<td>9</td>
<td>23/F</td>
<td>Both columns</td>
<td>Combined anterior and posterior approach A 9-hole plate with 7 screws A 7-hole plate with 5 screws (anterior) A 7-hole plate with 6 screws A 5-hole plate with 4 screws (posterior)</td>
<td>Identical to the planned operation Satisfactory</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>23/F</td>
<td>T shaped</td>
<td>Pararectus approach A 3-hole plate with 2 screws A 4-hole plate with 4 screws A 7-hole plate with 6 screws A 7-hole plate with 6 screws (anterior)</td>
<td>Identical to the planned operation</td>
<td>Anatomic</td>
</tr>
</tbody>
</table>
positions and orientations of the implanted plates and screws from post-surgery were consistent with pre-operative panning (Fig. 3d). Most of the plate and screw images extracted from post-surgery CT scans overlapped with the preoperative plans although some of the simulated screws were longer than the screws actually used in the surgery. All surgical procedures were in agreement with pre-operative planning for all patients (Table 1). Seven out of 10 patients had a displacement of fracture reduction of less than 1 mm while the other 3 cases had a displacement of fracture reduction between 1 and 2 mm. The actual fixation parameters including the fixation plate length and the screw numbers were completely consistent with the preoperative planning in all cases. The congruence of the hip joint surface was considered to be either anatomic or satisfactory (Table 1). There were no cases with acetabular penetration or with mal-reduction observed. No serious postoperative complications such as infection, failure of fixation and deep venous thrombosis (DVT) occurred within a week of follow-up.

Discussion

Acetabular fractures are serious intra-articular traumas resulting from high-energy injuries [12]. The surgical treatment principles for displaced acetabular fractures include an anatomic reduction of the articular surface with stable fixations to restore the biomechanical characteristics of the acetabulum and achieve early postoperative rehabilitation [13,14]. Although significant progress has been made in interval fixation of fractures in recent years, some specific issues such as the first choice of operative approach and the sequential procedures of reduction and fixation of the acetabular fractures remain unanswered. Recently, 3D printing of pelvic bone based on CT scans of patients has been successfully used in clinics. The new technology provides 3D models for surgical simulation and specific implant selection. In this study, we tested a combination of 3D printing and computer-assisted virtual surgical procedure assessment for preoperative planning of acetabular fracture reduction. We applied a simulated virtual surgery on a 3D-printed gesso model to mimic each patient-specific fracture reduction and to design specific screws and pre-bend plates prior to the actual surgery. We found that the preoperative planning can be completed in a couple of days. All acetabular fractures including those of the single posterior column,
with both column fractures, and combination of transverse with posterior wall fractures were reduced either anatomically or satisfactorily with the pre-operative planning. The great consistency of the implant positions and orientations applied in the actual surgery with the pre-operation design, and the efficient restoration of the acetabular fractures provides convincing evidence that computer-assisted, 3D printing simulations in pre-operative planning allows for superior acetabular surgery management providing shorter, less invasive, more precise, and more reliable surgeries. In addition, 3D printing and simulation promote postoperative recovery of the patient and lower the medical costs.

The virtual surgical simulation consists of three consecutive steps, including the image segmentation, the fracture reduction and the internal fixation. Image segmentation is critical for the virtual surgery because pelvic fractures usually involve joint surfaces or are very complex. Therefore, the 3D reconstructions of the fracture anatomy are necessary for visualising the fractures, determining the fracture type, and choosing a proper surgical approach [15]. In this study, we found that assessment of the femoral head images from the fracture sites is necessary for a complex fracture. Without femur images, surgeons can manipulate the segmented bones or fragments for the virtual surgical simulation and determine the best sequential procedures of reduction and optimal replacements of internal implants.

The 3D printing was first designed for industrial use, but now it has been extended to all fields including medicine [16–23]. This technology has become feasible and accessible for use in orthopaedic surgery. In this study, we compared pre-operative designs of 10 cases with the positions and orientations of the post-surgical implants. We found that the pre-bent plates selected on physical 3D printed models have anatomical shapes perfectly matched with the reduced pelvis. Based on our past experience, the new combination of virtual simulation with 3D printing significantly improves the accuracy and safety of the orthopaedic surgery compared to conventional surgery, and the time taken for operation and reduction was significantly less in all four types of acetabular fractures.

Although our studies demonstrate excellent results of fracture restoration a week after surgery, long-term outcomes are not known, and need to be followed up. In addition, the surgical simulation was performed in a situation without soft tissues so that the screws could be placed in any direction. Therefore, some elements during the actual surgery must be considered and prepared before an operation. It should be noted that the surgeon’s skill in surgical planning and execution is a primary determinant of surgical outcomes, and prolonged exposure of patients to radiation is potentially harmful. Pregnant patients or children should avoid the radiation exposures.

In conclusion, a combination of the use of a 3D model from CT scan and a computer-assisted virtual surgical procedure helps to better understand the anatomy and pathology, providing better preoperative planning and an opportunity to perform a surgical simulation for the specific pre-band implant preparation. This technique can significantly improve the outcome of acetabular fracture surgery via providing a better pre-operation plan, and a training platform for residents and surgical teams to completely understand the surgical procedures.

Conflict of interest
None of the authors have any conflicts of interest with regards to this research.

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