Observational Study

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Application of a 3-dimensional printed navigation template in Bernese periacetabular osteotomies

A cadaveric study

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Abstract

The aim of the present study was to describe the application of 3D printed templates for intraoperative navigation and simulation of periacetabular osteotomies (PAOs) in a cadaveric model.

Five cadaveric specimens (10 sides) underwent thin-slice computed tomographic scans of the ala of ilium downwards to the proximal end of femoral shaft. Bernese PAO was performed. Using Mimics v10.1 software (Materialise, Leuven, Belgium), 3D computed tomographic reconstructions were created and the 4 standard PAO bone cuts—ischial, pubic, anterior, and posterior aspects of the ilium—as well as rotation of the dislocated acetabular bone blocks were simulated for each specimen. Using these data, custom 3D printed bone-drilling templates of the pelvis were manufactured, to guide surgical placement of the PAO bone cuts. An angle fix wedge was designed and printed, to help accurately achieve the predetermined rotation angle of the acetabular bone block. Each specimen underwent a conventional PAO. Preoperative, postsimulation, and postoperative lateral center-edge angles, acetabular indices, extrusion indices, and femoral head coverage were measured and compared; *P* and *t* values were calculated for above-mentioned measurements while comparing preoperative and postoperative data, and also in postsimulation and postoperative data comparison.

All 10 PAO osteotomies were successfully completed using the 3D printed bone-drilling template and angle fix wedge. No osteotomy entered the hip joint and a single posterior column fracture was observed. Comparison of preoperative and postoperative measurements of the 10 sides showed statistically significant changes, whereas no statistically significant differences between postsimulation and postoperative values were noted, demonstrating the accuracy and utility of the 3D printed templates.

The application of patient-specific 3D printed bone-drilling and rotation templates in PAO is feasible and may facilitate improved clinical outcomes, through the use of precise presurgical planning and reduced surgical complications with the precisely guided bone drilling.

Abbreviations: AC = acetabular index, AD = acetabular dysplasia, EI = extrusion index, LCE = lateral center-edge, OA = osteoarthritis, PAO = periacetabular osteotomy.

Keywords: 3D printing, dysplasia, hip, navigation, periacetabular osteotomy

1. Introduction

Acetabular dysplasia (AD) refers to the incomplete coverage of the femoral head by the acetabulum and is a leading cause of hip osteoarthritis (OA) in young adults, with 40% to 50% of those with AD developing OA before the age of 50.[1,2] In addition, nearly 100% of patients with instability or dislocation of the hip will suffer from OA due to degeneration of hip joint cartilage.[3,4] While total hip arthroplasty is curative for OA, there remains controversy on its application in younger patients due to the service life of artificial prostheses and operative complications.[5] Bernese periacetabular osteotomy (PAO), first proposed in Switzerland by Ganz et al in 1988,[6] is a more efficacious option for reducing pain and improving function in patients' hip dysplasia without changing the size of the true pelvis and with reduced complication potentials, and involves a triple osteotomy of the pelvis at the body of the ischium, the pubic ramus of the acetabulum, and anterior and posterior sides of the ilium.[6] Bernese PAO is indicated in active patients with AD and addresses structural and mechanical sequel of OA.[6]

PAO offers a posterior column stability preservation and protection of acetabular blood supply, and avoids alterations in proximal femur, which may prove significant if these patients need hip replacement later in life.[6] Complications such as iatrogenic joint injury, injury to the femoral or sciatic nerve, nonunion, or developing ischemic necrosis of the acetabulum may arise with PAO.[15]

PAO is commonly used in the treatment of AD and involves cutting bone around the acetabulum and repositioning the hip socket.[6] The major surgical challenge in PAO is determining the

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direction and degree of rotation of the osteotomized segment. In combination with spiral computed tomographic (CT) and 3D reconstruction, we describe the development and assess the application of 3D printed templates for intraoperative navigation in PAO in a cadaver model.

2. Materials and methods

PAOs, and all associated imaging, were performed at Kunming Medical University on 5 preserved adult cadaveric pelvises (10 sides) and lower limbs, with no history or trauma, malformation, and/or surgery in these regions. This study was approved by the Ethical Committee of Kunming General Hospital of Chengdu Military Region (KGH2014021).

2.1. Imaging

All specimens underwent thin-slice CT scans (General Electric LightSpeed-16, GE, Milwaukee, WI) of the ala of ilium downwards to the proximal end of femoral shaft while positioned supine with the anterior-superior iliac spines positioned level with bilateral hip and knee joints laid horizontally and extended to a neutral position. Knees and ankle joints were closed and toes were positioned upwards. The long axes of both lower limbs were positioned vertical to scanning plane, so that the midpoint of a horizontal line connecting the centers of the bilateral hip joints was the center of the scan. Anteroposterior x-rays of the pelvis were also obtained in each specimen using the same positioning.[7] All obtained images were imported into Mimics v10.1 software (Materialise, Leuven, Belgium) in order to create 3D reconstructions (Fig. 1A).[8,9]

2.2. PAO simulation

Using Mimics and the 3D CT reconstructions, each of the 4 standard PAO bone cuts—ischial, pubic, anterior aspect of the ilium, and posterior aspect of the ilium—as well as rotation of the dislocated acetabular bone blocks were simulated for each specimen (Fig. 1B and C). The model was adjusted to a neutral position and the Wiberg's lateral center-edge (LCE) angle (the angle formed by a vertical line and a line connecting the center of the femoral head with the lateral edge of the acetabulum), the acetabular index (AC; angle formed by the horizontal line and a tangent from the lowest point of the sclerotic zone of the acetabular roof to the lateral edge of the acetabulum), and the femoral head extrusion index (EI; the percentage of the femoral head in comparison to the total horizontal head diameter) were measured.[10] Coverage over the femoral head was also measured using the so-called top-view technique described by Nakamura et al.[9]

2.3. Template design

The 3D CT reconstructions were exported from Mimics in stereolithography format and imported into Geomagic v11.0 software (Geomagic Inc, Morrisville, NC) in order to create a cast (overlay) of each pelvis for the development of both a custom 3D printed bone-drilling template of the pelvis (to guide surgical placement of the PAO bone cuts; Fig. 2) and an angle fix wedge (to help accurately achieve the predetermined rotation angle of the acetabular bone block; Fig. 3). The bone-drilling template was designed to conform to the specific same morphological internal surface anatomy of each pelvis. The stereolithography files for both the bone-drilling template and the angle fix wedge were transferred to a 3D printer for printing.

2.4. Surgical procedure

Each specimen underwent a conventional Ganz PAO.[6] Skin incisions were made beginning from the anterior-superior iliac spine and continued distally along the sartorius muscle. The fascia lata was carefully incised and the lateral femoral cutaneous nerve was separated and carefully retracted. The hip was exposed and the custom 3D printed bone-drilling template was placed into position on the superior surface of the ilium and used as a stencil for placement of the bone cuts (Fig. 4A). An oscillating saw was used to fashion the 4 standard bone cuts, beginning at the pubis where the saw was advanced medially along the superior ramus. The ischium was then drilled at its medial edge immediately lateral and distal to the pubic osteotomy, followed by the ilium between the anterior-superior iliac spine and the anterior-inferior iliac spine. A 5-mm Schanz screw was inserted into the anterior-inferior iliac spine and the acetabular bone block was mobilized. The acetabular bone block was then moved slightly outwards, the acetabulum was rotated, and the angle fix wedge was placed into the bone opening of the ilium to ensure accurate rotation acetabular bone block into the preplanned fixation position (Fig. 4B). Fixation was achieved using Kirschner wire and postoperative x-rays and CT were obtained to measure LCE angle, AC angle, EI, and coverage over the femoral head.

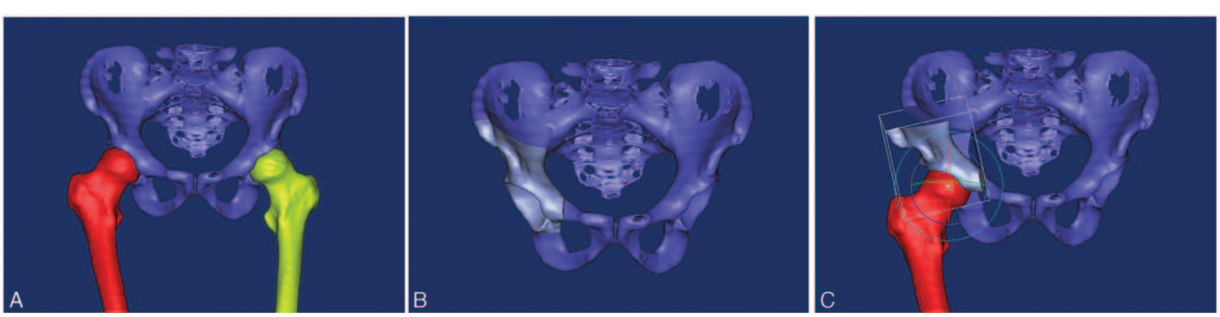

Figure 1. (A) 3D surface reconstruction of the proximal end of a pelvis and bilateral femurs; (B) 3D reconstruction of the pelvis showing placement of the 4 PAO bone cuts and full dissociation of the acetabular bone block; and (C) 3D reconstruction of the pelvis showing outward displacement and rotation of the acetabular bone block, centered around the femoral head. PAO = periacetabular osteotomy.

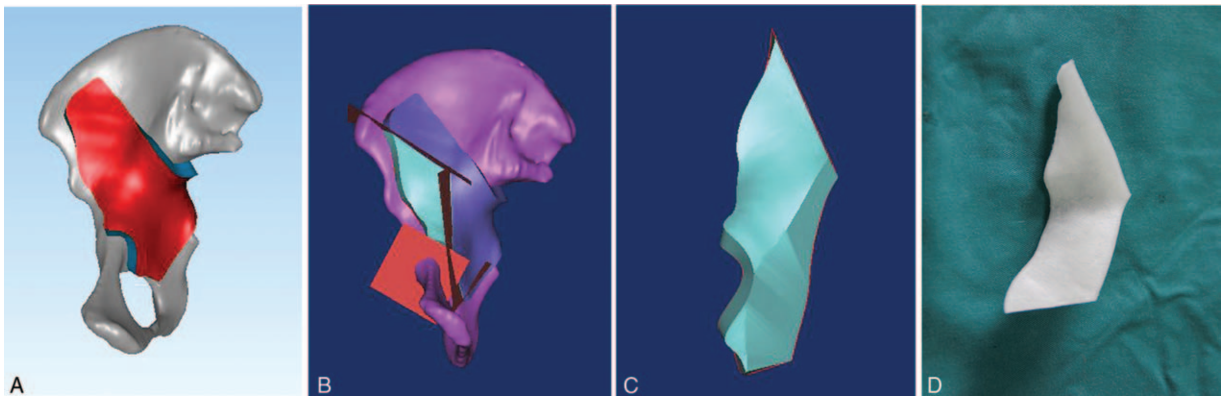

Figure 2. Design of the bone-drilling template. (A) A virtual cast (overlay) of each pelvis was created in order to model the pelvic surface anatomy. (B) The position of the bone cuts determined during simulation was plotted, and the cast was trimmed at the margin of the cuts in order to create a (C) drilling template. (D) The 3D printed bone-drilling template.

2.5. Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics v19.0 (SPSS, Chicago, IL). Descriptive statistics, 1-way univariate analysis of variance and a paired Student t test, was used to compare preoperative planned and postoperative LCE angles, AC angles, femoral head EIs, and coverage over the femoral head. Statistical significance was considered when $P<0.05$. A Bonferroni-corrected α level of 0.05 was used as the significance threshold.

3. Results

All 10 PAO osteotomies were successfully completed using the 3D printed bone-drilling template and angle fix wedge (Table 1). Of these, no osteotomy entered the hip joint and a single posterior column fracture was observed, likely due to excessive force used while rotating the acetabulum. All participating surgeons found that the 3D printed bone-drilling template and angle fix wedge greatly facilitated intraoperative rotation and fixation, and allowed for accurate final placement of the acetabulum based on the preplanned data. Postoperative measurements of the 10 sides showed a statistically significant increase in LCE angles and femoral head coverage and significant decrease in AC angle and EI, compared to preoperative values (Fig. 5; Table 2). No statistically significant differences between postsimulation and postoperative values were noted, demonstrating the accuracy and utility of the 3D printed templates (Table 3).

4. Discussion

AD is characterized by insufficient coverage of the femoral head and reduced acetabular bearing and effective contact areas, and can lead to OA. There remains some debate as to the optimal time for performing PAO for AD, with some scholars advocating for PAO before the development of OA in order to delay or avoid its development.[11–14] Aside from determining optimal time for intervention, the main difficulty of PAO is surgically determining the direction and degree of rotation of the osteotomized segment and avoiding joint or fracture complications. In 1999, Hussell et al reported on the complications of 508 patients who underwent early PAO and found that 2.5% of these patients suffered from iatrogenic joint injury, 1.2% from posterior column fracture, 0.6% to 1% from injury to the femoral or sciatic nerve, and 2.2% from nonunion, and noted the possibility of developing ischemic necrosis of the acetabulum.[15] Therefore, comprehensive surgical planning and understanding of the surgical dynamics, including degree of acetabular deformity, is essential for successful surgery and accurate positioning of the acetabular bone block.[16]

PAOs are further complicated by the pathoanatomy of AD and the limited degree of surgical exposure. As a result, correct placement of the osteotomies can be difficult and incorrect placement can result in injury to the joint capsule or posterior column, leading to pelvic instability. Additionally, the narrow range of safe hip joint indices requires high intraoperative precision.[16]

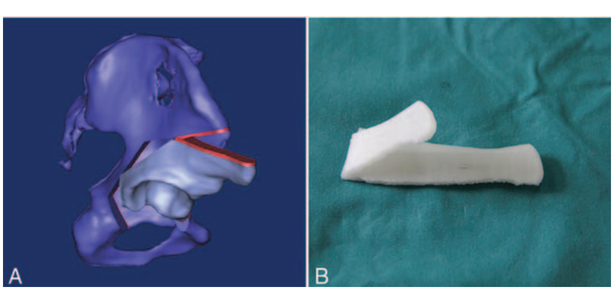

Figure 3. Design of the angle fix wedge. (A) Using the rotation of the acetabular bone black determined during simulation, a surface overlay was created on the upper and lower surfaces of the bone opening of the ilium. (B) The 3D printed angle fix wedge.

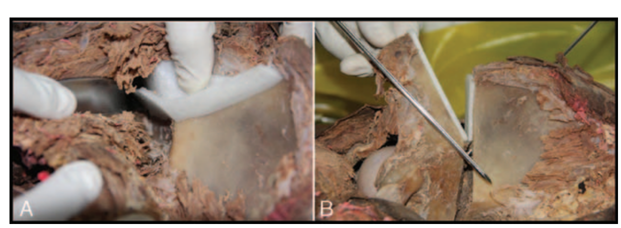

Figure 4. (A) Surgical placement of the bone-drilling template in a cadaver. After exposure of the hip, the bone-drilling template was placed into position on the superior surface of the ilium and used as a stencil for placement of the bone cuts. (B) Surgical placement of the angle fix wedge in a cadaver. Following displacement of the acetabular bone block, the angle fix wedge was placed into the bone opening of the ilium to ensure accurate rotation of the acetabular bone block into the preplanned fixation position.

Table 1

Preoperative, postsimulation, and postoperative measurements.

	LCE angle, °			AC, °			EI, %			Coverage, %		
Cadaver side	Preoperative	Postsimulation	Postoperative	Preoperative	Postsimulation	Postoperative	Preoperative	Postsimulation	Postoperative	Preoperative	Postsimulation	Postoperative
1	35	60	61	3	−15	−15	17.5	0	0	82.7	97.9	100
2	33	45	43	7	−8	−10	23	14.6	12.7	76	100	92.5
3	33	50	52	12	−10	−11	24.2	12.1	14.3	82	95.4	94.2
4	30	54	51	13	−12	−15	27	13.9	12.1	79	91.2	98.6
5	31	56	60	14	−15	−15	26.5	4.65	6.89	81.4	92.2	93.4
6	33	64	60	8	−23	−24	23.5	3.75	4.11	86.9	100	100
7	39	64	64	5	−14	−13	19.0	0	0	82	100	100
8	35	70	68	3	−25	−24	21.4	0	0	79	100	100
9	36	59	60	4	−17	−16	18	2.33	0	83	96.2	98.1
10	35	60	62	5	−14	−14	21	6.52	7.37	82	92.6	93.1

AC = acetabular index, EI = extrusion index, LCE = lateral center-edge.

While current 3D CT reconstructions allow for thorough understanding of the anatomy preoperatively, they do not allow for manipulation or preoperative simulation. Several authors have proposed computer-assisted techniques for planning or navigating PAO,[13,14,17] which has been shown to enhance clinical precision, although with some limitation.[18–21] In order to bridge 3D reconstruction, surgical planning and simulation, and intraoperative navigation, we propose the use of 3D printed navigation templates for accurate osteotomy placement and precise rotation of the acetabulum. Using this technique, the

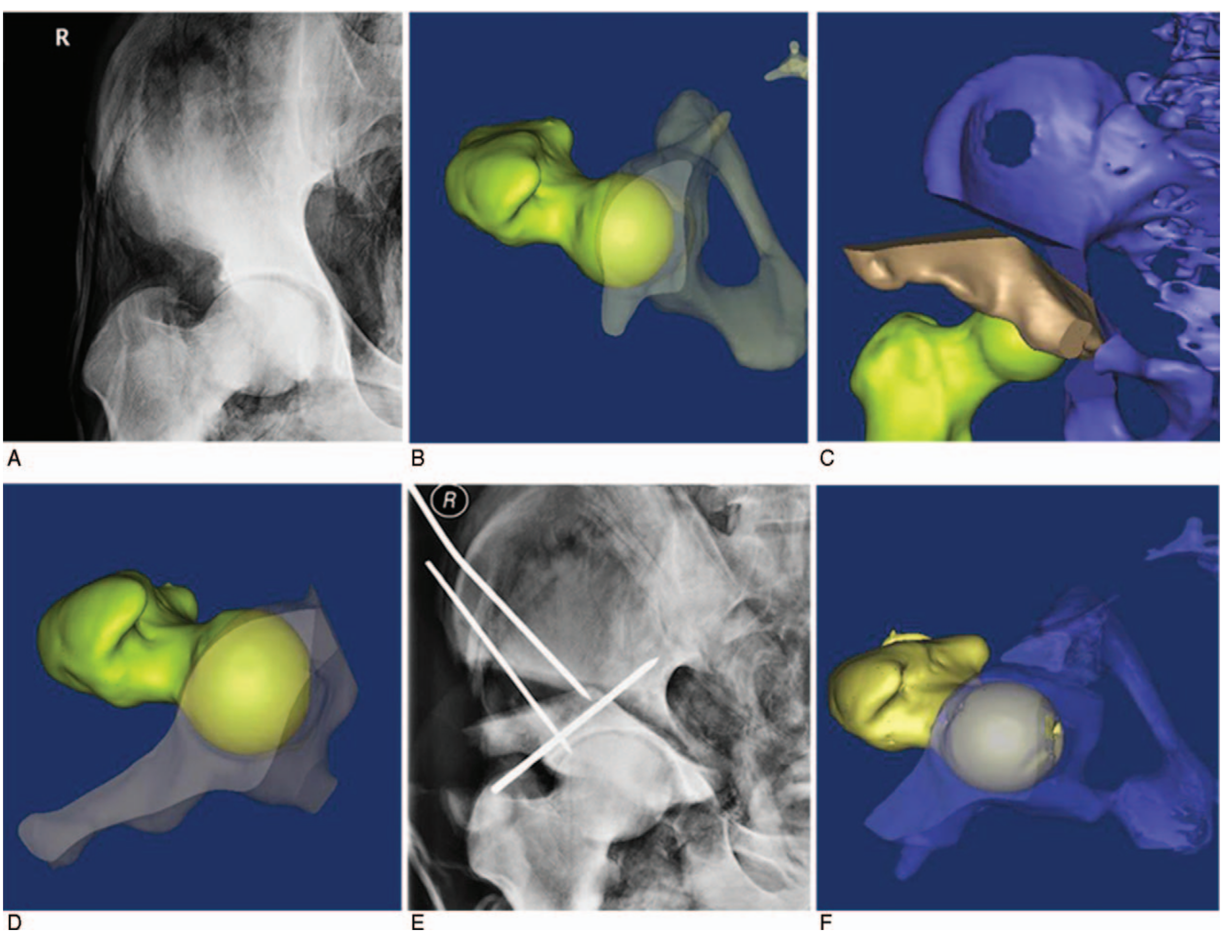

Figure 5. Preoperative, postsimulation, and postoperative measurements of cadaver side 1. (A) Preoperative x-ray of a right hip with a LCE angle of 35°, AC angle of 3°, EI of 17.5%, and (B) femoral head coverage of 82.7%. (C) Postsimulation of cadaver 1 with a LCE angle of 60°, AC angle of −15°, EI of 0%, and (D) femoral head coverage of 97.9%. (E) Postoperative x-ray of the same specimen with a LCE angle of 61°, AC angle of −15°, EI of 0%, and (F) femoral head coverage of 100%. AC = acetabular index, EI = extrusion index, LCE = lateral center-edge.

Table 2

Comparison of preoperative and postoperative data.

	Preoperative	Postoperative	*t* value	*P* value
LCE angle, °	34.0±2.58	58.0±7.30	−12.0	0.00
AC, °	7.40±4.20	−15.7±4.76	13.4	0.00
EI, %	22.1±3.33	5.76±5.79	12.9	0.00
Coverage, %	81.4±2.89	97.0±3.26	−14.4	0.00

AC = acetabular index, EI = extrusion index, LCE = lateral center-edge.

Table 3

Comparison of postsimulation and postoperative data.

	Preoperative	Postoperative	*t* value	*P* value
LCE angle, °	58.4±7.37	58.0±7.30	0.52	0.61
AC, °	−15.3±5.29	−15.7±4.76	0.94	0.37
EI, %	5.80±5.79	5.76±5.79	0.07	0.95
Coverage, %	96.4±3.53	97.0±3.26	−0.42	0.64

AC = acetabular index, EI = extrusion index, LCE = lateral center-edge.

surgeon can fully understand the pathoanatomy from the 3D CT reconstruction and then virtually perform the bone cuts and acetabular rotation to generate optimal patient-specific specifications for these maneuvers in order to achieve the most favorable clinical outcome. The lack of statistically significant differences between postsimulation and postoperative values illustrates the accuracy and utility of the 3D printed templates.

This is further translated from the virtual environment to the operating room with 3D printing. The use of sterilized 3D printed templates helps facilitate accurate surgical placement of the bone cuts and accurate rotation of the acetabulum in order to achieve the preplanned result. This is both feasible and safe, given the noninvasive nature of this technique, and has been previously applied to other procedures including pedicle screw placement, hip replacement, and knee replacement.[22]

Computer assistance in pelvic bone cutting has been reported to increase the accuracy of surgical procedures following simulation.[23,24] In 2016, Ma et al reported on the use of a 3D printed template for osteosarcoma resection, and found it to aid surgical accuracy and reduce operative time.[24] This technique, however, is inherently by the quality of the CT scan data as this will directly affect the accuracy of the plan and 3D printed templates. Additionally, the Mimics software uses surface reconstruction techniques and thus may not account for nonsurface defects, including acetabular cysts, which may complicate the surgical plan. Ultimately, this technology is still based on morphology, and there remains uncertainty as to whether the optimal acetabular position is that of minimum contact stress. Furthermore, the study is limited by its cadaveric nature, and, as it is exceedingly difficult to obtain cadavers with AD, this technique cannot be fully evaluated using a cadaveric model. Future studies are thus necessary to determine the full clinical potential of this technique as well as any other mitigating biomechanical factors.

5. Conclusion

The application of patient-specific 3D printed bone-drilling and rotation templates in PAO is feasible and may facilitate improved clinical outcomes, through the use of precise presurgical planning and reduced surgical complications with the precisely guided bone drilling. Further clinical studies are necessary to determine the utility of this technique.

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