CLINICAL ARTICLE

Extended Fixation for Paprosky Type III Acetabular Defects in Revision Total Hip Arthroplasty with a Minimum Follow-Up of 2 Years

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Objective: Revision of total hip arthroplasty for patients with severe acetabular bone defects is challenging. This study aims to report the minimum 2 years outcome of the iliac extended fixation technique in patients with Paprosky type III acetabular defects.

Methods: Fifty-seven revision total hip arthroplasty patients were retrospectively reviewed who underwent reconstruction with the concept of iliac extended fixation from 2014 to 2017 in our hospital. We proposed a new concept of "iliac extended fixation" in revision total hip arthroplasty as fixation extending superiorly 2 cm beyond the original acetabular rim with porous metal augments, which was further classified into intracavitary and extracavitary fixation. Patients were assessed using the Harris Hip Score and the Western Ontario and McMaster Universities Osteoarthritis Index Score. Radiographs and patient-reported satisfaction were assessed.

Results: At an average follow-up of 63 months (range 25–88 months), the postoperative Harris Hip Score and Western Ontario and McMaster Universities Osteoarthritis Index scores were significantly improved at the last follow-up ($p < 0.001$). The center of rotation was significantly improved ($p < 0.05$). Fifty-three (93.0%) patients were satisfied with the outcome. The extracavitary iliac extended fixation group had higher rate of osteointegration in zone 1A (the superior lateral zone) than the intracavitary iliac extended fixation group (82.3% *vs* 55.0%, $p = 0.015$), and significantly more horizontal screws fixation ($5.1 \pm 24.7°$ *vs* $42.3 \pm 36.8°$, $p < 0.001$).

Conclusion: Intracavitary and extracavitary iliac extended fixation with porous metal augments and cementless cups are effective in reconstructing severe superior acetabular bone defects. The difference in screw direction might reflect the different biomechanics of augment fixation.

Key words: Extracavitary iliac extended fixation; Intracavitary iliac extended fixation; Porous metal augment; Revision total hip arthroplasty; Severe bone defect

Introduction

Superior acetabular bone defects are commonly encountered in revision total hip arthroplasty (THA).[1–4] Paprosky type III defects indicate severe and extensive superior acetabular bone loss, often requiring reconstruction to be extended to an area at least 2 cm above the original acetabular rim.[1] Several different methods exist as a means of reconstructing superior bone defects, including jumbo cups, structural allografts, cup-cage construction, and impaction bone graft with cemented cups.[3–6] However, these traditional methods frequently encountered low survivorship due to mechanical failures, or compromised hip biomechanics as a result of highly riding hip center of rotation (COR).[7,8]

Porous metal augments have provided a promising solution.[6,9–13] The metal augments are made from tantalum or titanium alloy with high porosity and low Young's

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modulus, which features excellent biocompatibility, improved capacity of osteointegration, and good initial stability for fixation while avoiding stress shielding.[13–17] Jenkins *et al.* described three basic techniques of using metal augments, namely "flying buttress," "dome," and "footing."[18] However, this classification does not reflect the mechanical principles of applying augments, especially those extending to the level of the sacroiliac joint, like buttress augments and stacked slope augments.

We proposed the concept of "iliac extended fixation," and defined it as acetabular components construct fixed to the iliac bone at a level 2 cm higher than the original superior edge of the acetabulum. The rationale for the 2 cm cut-off is based on two aspects: on one hand, the bone stock dramatically decreases compared with that of the juxta-acetabular area within 2 cm of the original acetabular rim[19]; and on the other hand, the increased risks of loosening, impingement, wear, and loosening by migrating center of rotation superiorly over 2 cm.[20–26] The original superior edge can be determined in two ways on anterior–posterior view radiography of the pelvis: the same level of the superior edge in the contralateral acetabulum, or at the level of 20% height of the pelvis from the inter-teardrop line if the contralateral acetabulum is abnormal.[27]

Based on the concept of extended fixation, we used buttress augment to chase healthy bone for primary stability and osteointegration if the defect is segmental and the bone bed was flat (extracavitary iliac extended fixation, EIEF). While the defect is cavitary, a slope augment with >2 cm height or two stacked augments were used to achieve mechanical stability and bone ingrowth (intracavitary iliac extended fixation, IIEF). Both IIEF and EIEF sought to provide stable superior points of fixation with a well-positioned cementless hemispherical cup.

Both IIEF and EIEF sought to anchor metal augments onto high-quality bone remote to the acetabular rim to establish a superior supportive point, and thus, stabilize the hemispheric cup and optimize hip biomechanics. We asked two major questions: (1) What are the clinical and radiological results of the iliac extended fixation technique in patients with Paprosky type III superior acetabular defects? (2) Are there any preoperative, intraoperative, and postoperative differences between the two groups of IIEF and EIEF patients?

Materials and Methods

Patients

The inclusion criteria include:

1. patients undergoing revision THA and
2. acetabular reconstruction with a cementless hemispherical cup and porous metal augments, and
3. construction extending superiorly to more than 2 cm above the original upper acetabular rim, and
4. minimal follow-up of 24 months.

Patients revised without augments or using cemented fixation for revision were excluded.

Ninety-nine consecutive patients who underwent revision THA at our institution from January 2014 to December 2017 were retrospectively reviewed, of whom 63 patients were enrolled in this study. We used porous metal augments made from tantalum (TM Augment; Zimmer, Warsaw, IN) or titanium (Restoration wedge augment; Stryker, Mahwah, NJ) to reconstruct the superior acetabular defects. There were six (9.5%) patients who were lost to follow-up, and 57 patients remained available for analysis. There were 17 patients reconstructed with the EIEF technique, using a single buttress augment (12 patients, 21.1%), a buttress augment combined with a superior slope augment (four patients, 7.0%) or a "flying buttress" technique with a slope augment (one patient, 1.8%)[18]; total of 40 patients reconstructed with the IIEF technique using a single slope augment (23 patients, 40.4%), or stacked slope augments (17 patients, 29.8%). Multiple holed revision cementless hemispherical cups (TM; Zimmer, Warsaw, IN) were inserted after the implantation of augments with an average diameter of 56 (range 44–66) mm.

Patients also underwent revision of the femoral component, including 45 (78.9%) with a modular revision femoral stem (RM; Stryker, Mahwah, NJ), seven (12.3%) with a monoblock femoral stem (Wagner; Zimmer, Warsaw, IN), and the other five (8.8%) patients with only femoral head revision using a ceramic head lined by a titanium sleeve (TS; DePuy, Warsaw, IN).

The average patient age at the time of surgery was 53 years (range 38–79 years), the average body mass index (BMI) was 24.6 (range 17.5–38.7), and 26 (45.6%) patients were female. On average, patients had 1.8 (range 1–5) previous hip operations. There were 45 patients (78.9%) revised for aseptic loosening, 7 (12.3%) for periprosthetic infection, 4 (7.0%) for recurrent dislocation, and one (1.8%) for periprosthetic fracture. The preoperative Charlson comorbidity score was 0 in 46 (80.7%) patients, 1 in eight (14.0%) patients, and 2 in three (5.2%) patients. The average duration from first THA to surgery was 11 (range 0.5–37) years.

Surgical Technique

All the patients were cleared of infection at the time of index revision surgery. A posterior approach was used in all hips. Extended trochanteric osteotomy was done in six (18.8%) hips. Patients with pelvic discontinuity were then treated with the distraction technique by inserting a 3 mm pin into the ilium and ischium ramus, respectively, and then distracting the cranial and caudal fragments with a plier holding the two pins, to stabilize the anterior and posterior column before preparation of augment and cup bony bed.[28,29]

The site, size, and shape of the bone defects were assessed before reaming and preparing for insertion of the augment and metal shell. A hemispherical cup trial or reamer was positioned to a target level by aiming at the optimal COR and contact of the bone bed. Trials were then used to determine the shape, size, and position of the final augment. The decision on EIEF and IIEF was made intraoperatively according to the shape and amount of bone left in the superior aspect of the acetabulum. The patient classifications were made according to the intraoperative surgical notes and confirmed by the radiographs. If the residual bony shell formed a cavitary bone defect in the superior medial aspect, the IIEF technique was used, and the EIEF was used vice versa.

Buttress and slope augments were fixed with screws to the host bone, followed by a multiple-holed, trabecular metal shell that was pressed fit to ensure the primary stability of the whole cementless construct. The number of screws depended mainly on the number of screw holes in the augment or cup, and also the amount of residual bone that can be used for screw fixation. There were 6.3 (range 2–10) screws used for each patient on average, among which 3.4 (range 1–5) screws for the cup, and 2.9 (2–5) screws for augments. No bone graft was used. Cement was placed between the augments and the augment-cup interface to unify these metal components into one solid unit. Multiple screws were then inserted through the porous metal shell. A 28-mm diameter Co-Cr-Mo alloy head was used in three (5.3%) patients, and 32 mm, 36 mm, and 40 mm diameter ceramic heads in 21 (36.8%), 32 (56.1%), and one (1.8%) patient, respectively. There were no significant differences in the preoperative demographic factors between the EIEF and IIEF groups (Table 2). The EIEF group had a significantly higher preoperative vertical location of COR (Table 2).

Clinical Data

Patients were asked to revisit the hospital at 3 months, 6 months, 1 year, and then yearly after surgery. The Harris Hip Score (HHS) and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC, range 0–96 with higher scores indicating worse outcome) were used for clinical evaluation. Clinical failure was defined as loosening or any complications requiring surgical removal of the cup. Patients also reported satisfaction based on a five-level subjective scale (very satisfied, satisfied, neutral, dissatisfied, or very dissatisfied), which was collected at the last follow-up.[30]

Radiographic Evaluation of Components

Anteroposterior, lateral, and Judet view radiographs and computed tomography scans of the bilateral hips were taken for all patients 1 week before the planned operation. Two surgeons (YH, HT) assessed the severity of the acetabular bone deficiency according to the preoperative radiographs based on the Paprosky acetabular bone defect classification.[1,4] Any discrepancies between the two surgeons were reexamined by the senior consultant surgeon (YXZ). There were 25 patients randomly selected to be assessed twice by one author (HT) to evaluate the intra-observer reliability. There were 32 (56.1%) patients classified as Paprosky type IIIA and 25 (43.9%) as type IIIB. Six (10.5%) of the type IIIB patients were assessed to have a pelvic discontinuity.

Anteroposterior and lateral radiographs of the bilateral hips were taken for all patients at follow-up. The magnification was corrected by referring to the already known diameter of the femoral head. The height and the horizontal location of the center of rotation (COR) were determined in reference to the inter-teardrop line.[18,31] Deviation of reconstructed COR was measured as the distance between postoperative COR and the anatomic COR mirrored from the normal contralateral hip to the revised side. In scenarios of the abnormal contralateral hip, the Ranawat triangle

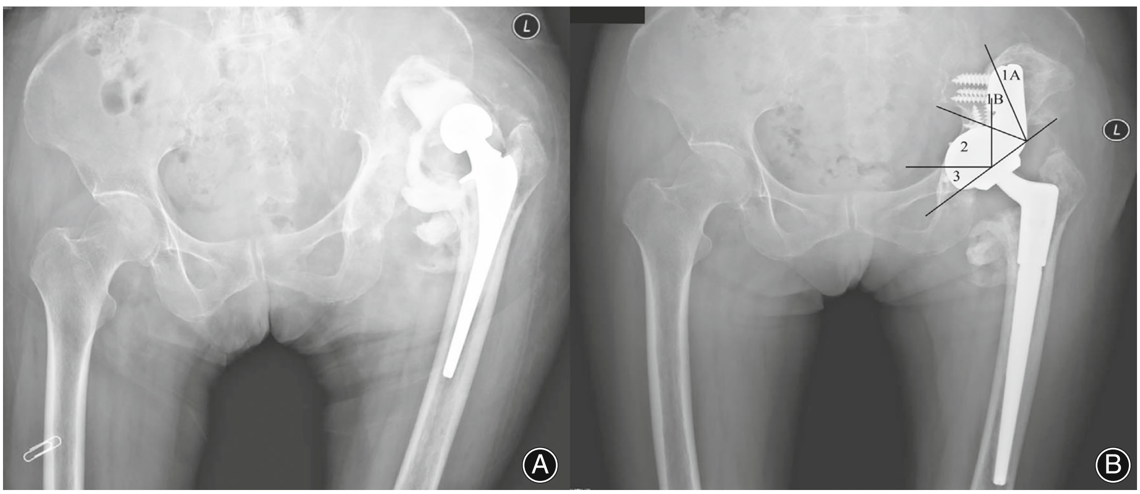

Fig. 1 A case of extracavitary iliac extended fixation. A preoperative radiograph (left panel) demonstrates loosening and migration of a cemented acetabular cup, pelvic discontinuity, and severe non-cavitary superior bone defect (A), which was reconstructed with a buttress augment and a shim augment combined with a hemispherical cementless cup (B). The Delee–Charnley zone 1 was further divided into lateral zone 1A and medial zone 1B by the line connecting the lateral junction of the buttress-cup interface and the superior corner of the buttress augment

method was utilized instead to determine the anatomic COR, by calculating the acetabular height as 20% of pelvis height.[32]

The radiographic abduction angle was assessed by calculating the angle between the inter-teardrop line and a line passing the longest axis of the cup's projected ellipse rim. The radiographic anteversion angle was defined as the arcsin (short axis/long axis), as defined by Lewinnek *et al.*[33]

Radiographic Evaluation of Osseointegration

The area surrounding the cup was divided into the three zones using the modified Delee-Charnley method, and zone 1 around the superior augments was further divided into two sub-zones 1A (the superior lateral half) and 1B (the inferior medial half) (Fig. 1–3). Radiolucent lines and osteointegration around the cup and augment were assessed to determine the stability of fixation of the acetabular components.[34] The acetabular cup was diagnosed as unstable if there was evidence of a continuous radiolucent line ≥1 mm wide around all three acetabular zones, or if any progressive prosthesis displacement could be detected during follow-up. The fibrous stable was defined as evidence of a radiolucent line <1 mm wide around two of the three acetabular zones, while bone ingrowth stability was

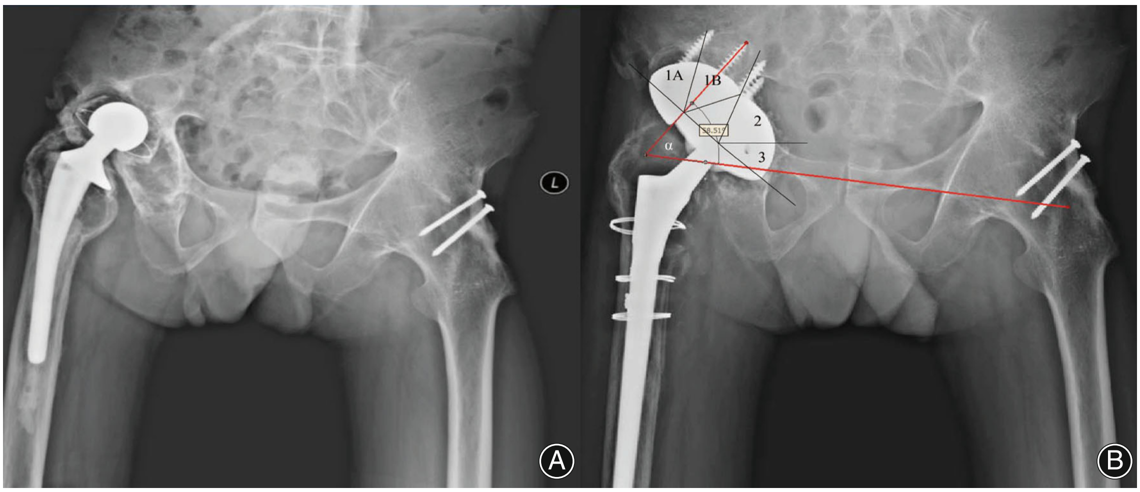

Fig. 2 A case of intracavitary iliac extended fixation with a single slope augment. A preoperative radiograph (A) demonstrates cranial migration and loosening of a cemented cup and severe intracavitary bone defect in the ilium, which was reconstructed with a single superior slope augment and a hemispherical cementless cup (B). The Delee–Charnley zone 1 was bisected from the center of the arc of the slope augment into zone 1A and 1B. The orientation of screws fixing the augments was measured in reference to the inter-teardrop line

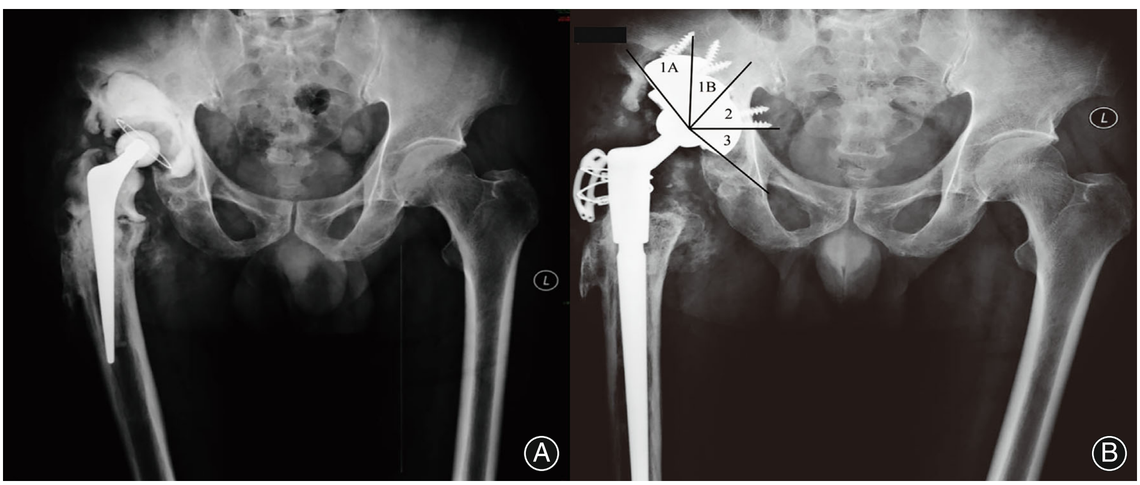

Fig. 3 A case of intracavitary iliac extended fixation with stacked augments. A preoperative radiograph (A) reveals severe osteolysis and a cavitary bone defect in the ilium, which was reconstructed with two stacked augments combined with a hemispherical cementless cup, when a single augment was unable to fill the defect (B). The Delee–Charnley zone 1 around the stacked augments was further bisected from the center of rotation into zone 1A and 1B

defined as intimate contact between the bone bed and metal surfaces, without any radiolucent lines.[34,35] The orientation of screws anchoring augments was measured in reference to the inter-teardrop line (Fig. 2B).

Statistical Analysis

The horizontal and vertical COR location data were compared between the preoperative and postoperative measurements and also between the studied and the contralateral hips using the Student *t*-test. Kappa values and intraclass correlation coefficient (ICC) were used to assess the intra- and inter-observer reliability for osteointegration assessment and angle measurement, respectively. All statistical analyses were performed using the SPSS statistical software package (version 15.0; IBM, Armonk, NY, USA), and the level of significance was set at $p < 0.05$ for a single comparison.

Results

Clinical Outcome

This cohort of patients was followed for an average of 63 months (range 25–88 months) after surgery. All patients were able to ambulate freely at last follow-up. The average HHS and WOMAC scores improved from 21.2 ± 11.6 and 51.4 ± 36.8 preoperatively, to 82.2 ± 22.5 and 16.6 ± 17.1 postoperatively, respectively ($p < 0.001$, Table 1).

There were 39 (68.4%) patients very satisfied with the outcome, 14 (24.6%) satisfied with the outcome, and four (7.0%) patients dissatisfied with the outcome. Two patients were dissatisfied because of inadequate pain relief; one patient was dissatisfied because of little improvement in hip function; and the other patient with rheumatoid arthritis and bilateral total knee arthroplasties was dissatisfied due to lower limb weakness. One (1.8%) patient was diagnosed as peri-prosthetic joint infection 6 months after the revision surgery, and subsequently underwent a two-staged revision and the patient-rated "satisfied" with the current outcome.

Radiographic Outcome

The average postoperative abduction and anteversion angles of the acetabular cup were 39.7° ± 13.1° and 12.5° ± 9.7°, respectively. The average deviation of COR from anatomic COR was 2.4 ± 7.2 mm horizontally and 6.4 ± 9.3 mm vertically, all of which were significantly improved from preoperative values ($p < 0.05$; Table 1). All components were found to be stable, with stable bone ingrowth identified for all patients based on the radiographic evaluation. There were 18 (31.6%) patients with regional radiolucent lines at the zone 1A augment region, and one (1.8%) patient found with regional radiolucent lines <1 mm wide in modified Delee–Charnley zone 2 of the acetabular cup between the extruded cement and sclerotic bone. There were no radiolucent lines found at zone 1B, zone 3, and the interface between cups and metal augments. All patients had sites of spot wielding between augments and bone, and between cups and host bone, identified on follow-up radiographs. The intra- and inter-observer kappa values for osteointegration assessment were 0.92 and 0.83, respectively. The intra- and inter-observer ICC values for cup orientation measurement were 0.972 and 0.913, respectively.

Between the EIEF and IIEF groups, there was no significant difference in HSS scores, WOMAC scores, and satisfaction rates. For radiological results, there was no significant difference between the two groups in the horizontal and vertical location of COR, and orientation of cups (Table 3). The EIEF group had a significantly higher rate of osteointegration in zone 1A than the IIEF group (82.3% *vs* 55.0%, $p = 0.015$, Table. 3). The angle formed between the intersection of screws and the inter-teardrop line was significantly smaller

TABLE 1 Comparison of preoperative and postoperative clinical and radiological results

	Preoperative	Postoperative	*p*
HHS Score			
HHS Pain	3.3 ± 4.8	40.7 ± 8.5	<0.001
HHS Function	14.0 ± 10.2	34.5 ± 14.3	<0.001
HHS Deformity	0.7 ± 1.0	3.3 ± 3.5	<0.001
HHS ROM	3.3 ± 3.9	3.7 ± 1.6	0.355
Total HHS score	21.2 ± 11.6	82.2 ± 22.5	<0.001
WOMAC Score			
WOMAC Pain	8.5 ± 9.2	1.4 ± 4.2	<0.001
WOMAC Stiffness	2.2 ± 4	0.4 ± 0.9	<0.001
WOMAC Function	40.6 ± 28.4	14.8 ± 17.7	<0.001
Total WOMAC score	51.4 ± 36.8	16.6 ± 17.1	<0.001
Horizontal location of COR from IT line (mm)	40.9 ± 22.3	12.1 ± 12.5	<0.001
Vertical location of COR from IT line (mm)	42.2 ± 30.4	11.1 ± 18.7	<0.001
Horizontal deviation from anatomical COR (mm)	7.9 ± 9.3	2.4 ± 14.5	0.012
Vertical deviation from anatomical COR (mm)	26.3 ± 29.0	6.4 ± 12.2	<0.001

Note: The *p*-value <0.05 was considered to be statistically significant.; Abbreviations: COR, Center of Rotation; HHS, Harris Hip Score; IT line, Inter-Teardrop line; ROM, Range of Motion; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

TABLE 2 Comparison of preoperative and intraoperative factors between the extracavitary and intracavitary iliac extended fixation

	Extracavitary group	Intracavitary group	*p*
Left side	50.0%	60.0%	0.934
Female gender	58.3%	40.0%	0.497
Paprosky classification 3B	66.7%	55.0%	0.396
Percentage of medial wall lysis	35.3%	27.2%	0.791
Percentage of tear drop lysis	13.3%	15.0%	0.920
Percentage of ischial lysis	17.6%	20.0%	0.862
Preoperative HHS Score			
HHS Pain	2.9 ± 3.3	3.3 ± 6.6	0.624
HHS Function	16.1 ± 8.8	13.1 ± 10.9	0.155
HHS Deformity	0.6 ± 1.0	0.7 ± 1.0	0.248
HHS ROM	1.9 ± 6.1	3.9 ± 8.1	0.125
Total HHS score	21.5 ± 11.2	21.1 ± 13.5	0.950
Preoperative WOMAC Score			
WOMAC Pain	9.6 ± 9.7	8.1 ± 9.7	0.247
WOMAC Stiffness	2.6 ± 4.8	2.1 ± 3.6	0.589
WOMAC Function	42.6 ± 30.8	39.8 ± 34.3	0.414
Total WOMAC score	54.8 ± 37.6	50.1 ± 41.7	0.316
Horizontal location of COR from IT line (mm)	44.1 ± 30.2	39.5 ± 18.4	0.497
Vertical location of COR from IT line (mm)	54.2 ± 35.1	37.1 ± 21.6	0.003
Horizontal deviation from anatomical COR (mm)	9.6 ± 36.7	7.2 ± 21.4	0.318
Vertical deviation from anatomical COR (mm)	37.6 ± 40.6	21.5 ± 18.3	0.011
Preoperative LLD	31.5 ± 43.8	22.4 ± 25.9	0.096
Proportion of ETO	29.4%	35.0%	0.682
Cup diameter (mm)	55.3 ± 13.3	57.4 ± 8.4	0.299
Number of augments used	1.2 ± 0.9	1.4 ± 0.7	0.766
Number of screws for augment fixation	4.0 ± 2.8	2.5 ± 2.5	0.001
Number of screws for cup fixation	3.0 ± 1.1	3.5 ± 2.0	0.315
Number of inferior screws	0.3 ± 0.8	0.2 ± 0.4	0.401
Total number of screws	7.0 ± 2.3	6.0 ± 3.6	0.076

Note: The *p*-value <0.05 was considered to be statistically significant.; Abbreviations: COR, Center of Rotation; ETO, Extended Trochanteric Osteotomy; HHS, Harris Hip Score; IT line, Inter-Teardrop line; LLD, Leg Length Discrepancy; ROM, Range of Motion; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

in the EIEF group than in the IIEF group (4.6 ± 25.7° *vs* 41.9 ± 37.8°, $p < 0.001$, Table 3).

Discussion

This study revealed that iliac extended fixation successfully reconstructed the hip COR and achieved satisfactory clinical and radiographic outcomes for patients with severe superior acetabular bone defects in revision THA. There were no statistical differences in the major clinical and radiological results between the IIEF and EIEF technique groups, despite the latter group having more severe proximal migration of COR in preoperative radiographs. We did find a statistical difference in the orientation of screws fixing the augments between IIEF and EIEF groups, which had potential biomechanical implications.

Clinical Outcome

In this study, the concept of "iliac extended fixation" is proposed as fixation extending beyond 2 cm superior to the anatomic acetabular rim, based on anatomical and biomechanical rationale.[19–26] Augments used in the juxta-acetabular region can be considered a rim restoration procedure, while in iliac extended fixation, a superior supporting point is created by extending porous metal across the worst bone bed to the healthy bone, which is remote to the acetabular rim. Compared with juxta-acetabular fixation, iliac extended fixation requires more surgical exposure and is more difficult to obtain adequate primary mechanical stability. Our data revealed that bone ingrowth fixation was identified between the bone-cup and bone-augment interface in all patients, indicating that iliac extended fixation achieved sufficient initial stability and subsequent biologic osteointegration without compromising COR and cup orientation (Tables 1–3). This high rate of osteointegration is consistent with the literature. Russel *et al.* reported that 93.5% of augments and 97% of the acetabular shells were well-osseointegrated.[6] Cassar *et al.* also reported that 96.7% of patients had signs of osteoinegration.[36]

Radiographic Outcome

The iliac extended fixation technique was aimed to reconstruct severe cranial acetabular defects, while reconstructing the COR and cup orientation as optimal as we can. In the present study, the postoperative COR were significantly lower compared with the preoperative COR, closer to the anatomic COR (Table 1). The hip biomechanics were

TABLE 3 Comparison of postoperative factors between the extracavitary and intracavitary iliac extended fixation

	Extracavitary group	Intracavitary group	*p*
Radiographic abduction of cup (°)	40.1 ± 14.4	37.9 ± 12.5	0.370
Radiographic anteversion of cup (°)	13.3 ± 8.6	11.5 ± 10.3	0.328
Horizontal location of COR from IT line (mm)	29.4 ± 13.7	32.6 ± 11.9	0.219
Vertical location of COR from IT line (mm)	20.5 ± 23.0	23.3 ± 16.9	0.466
Horizontal deviation from anatomical COR (mm)	3.5 ± 13.7	6.3 ± 14.3	0.295
Vertical deviation from anatomical COR (mm)	1.3 ± 13.7	−2.4 ± 20.4	0.292
Osteointegration			
Zone 1A	82.3%	55.0%	0.015
Zone 1B	94.1%	95.0%	1.000
Zone 2	88.2%	95.0%	0.575
Zone 3	100.0%	100.0%	1.000
RLL			
Zone 1A	17.6%	37.5%	0.214
Zone 1B	0.0%	0.0%	1.000
Zone 2	5.9%	0.0%	0.298
Zone 3	0.0%	0.0%	1.000
Screw-IT angle (°)	5.1 ± 24.7°	42.3 ± 36.8°	<0.001
Satisfaction rate	88.20%	95.00%	0.209
Postoperative HHS Score			
HHS Pain	41.0 ± 10.1	40.6 ± 8.3	0.694
HHS Function	33.0 ± 13.8	35.1 ± 16.3	0.809
HHS Deformity	3.7 ± 2.3	3.1 ± 3.5	0.256
HHS ROM	3.6 ± 1.9	3.8 ± 2.0	0.965
Total HHS score	81.3 ± 19.0	82.6 ± 24.7	0.926
Postoperative WOMAC Score			
WOMAC Pain	1.5 ± 4.7	1.3 ± 4.5	0.892
WOMAC Stiffness	0.2 ± 0.0	0.5 ± 1.0	0.120
WOMAC Function	15.2 ± 17.4	14.7 ± 18.0	0.496
Total WOMAC score	16.9 ± 21.1	16.5 ± 20.5	0.600

Note: The *p*-value <0.05 was considered to be statistically significant.; Abbreviations: COR, Center of Rotation; HHS, Harris Hip Score; IT line, Inter-Teardrop line; RLL, Radiolucent Line; ROM, Range of Motion; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index.

therefore improved, which is consistent with previous reports.[6,18] Restoration of the COR helps decrease leg length discrepancy and optimize the abductor lever arm,[37] thus, minimizing the risk of hip impingement, poly wear, and cup loosening.[38] Our data showed that the EIEF group had similar postoperative vertical and horizontal locations of COR compared with the IIEF group, despite the higher COR in preoperative radiographs. Spanyer *et al.* previously reported using a buttress augment for successful repairing the anterior column through the direct anterior approach,[39] while Ballester *et al.* reported the application of buttress augments in the treatment of severe acetabular bone loss.[31] The restoration of COR using the EIEF technique is similar to those of buttress augment reported in the literature.

The EIEF group had a higher rate of osteointegration in zone 1A compared with the IIEF group (82.3% *vs* 55.0%, Table 3). This might be caused by better bone-augment contact in zone 1A of the EIEF group and indicated that the EIEF technique successfully bridged the bony fixation of the acetabular cup to the ilium. There is a higher rate of radiolucent lines in zone 1A in the IIEF group than in the EIEF group, although not statistically significant ($p = 0.214$, Table 3). It is still unknown whether the radiolucent lines in zone 1A will cause possible loosening of the cementless construct, which necessitates longer term of follow-up.

The Biomechanical Implication of the New Classification

Although the clinical results of revision THA using metal augments have been reported to be good,[6,36,40–42] very few studies have reported the classifications of augment reconstructions in the superior acetabulum. The iliac extended fixation technique can be further classified into two groups of EIEF and IIEF. Derek *et al.* reported a 5–12 year follow-up of 85 revision THA cases with porous metal augments and classified the use of slope augments in the superior aspect into three types, namely "flying buttress," "doming," and "footing."[18,36] This surgical classification is not contradictory to the concept of iliac extended fixation, which is a more biomechanical definition. To the best of our knowledge, the doming techniques could fall into the IIEF group, and the flying buttress technique could be the subtype of EIEF if more than 2 cm superior to the acetabulum.

Interestingly, our data showed the orientation of screws in the EIEF group was significantly more horizontal than that in the IIEF group when measured in reference to the inter-teardrop line (5.1° *vs* 42.3°, Table 3). Although the direction of screws was closely related to the shape of augments and bone bed, it might also reflect the different biomechanics of the two techniques. As shear stress is always essential to the metal-bone interface, the EIEF cases featured more vertically directed shear stress than the IIEF group did as no bony wall was available to resist the vertical component of joint reaction force and hence required more horizontal screws as a buttress against the vertical shear stress. Differently, the more oblique screws in the IIEF group not only resisted the superior-lateral oriented shear stress but also allowed some degree of dynamic compression by the joint reaction force along with the screws due to their nonlocking design.

Limitation and Strength

This study had several limitations. First, there is no comparison group of conventional techniques. Further study comparing the iliac extended fixation technique with other techniques is required. Second, the cement bond between the stacked metal components must be evaluated with long-term follow-up or in vitro fatigue tests to exclude micromotion and subsequent generation of abrasion. Third, it requires further biomechanical analyses to assess any potential differences in mechanical properties between juxta-articular within 2 cm of the acetabulum and iliac extended reconstructions beyond 2 cm of the acetabulum, as well as between EIEF and IIEF reconstructions.

Despite these limitations, the current study reports a series of patients with severe Paprosky type III acetabular defects successfully treated using the technique of iliac extended fixation. The EIEF and IIEF techniques could guide the intraoperative application of porous metal augments using simple biomechanical principles.

Conclusions

The findings of this study indicate that EIEF and IIEF with porous metal augments and cementless cups are effective in reconstructing severe superior acetabular bone defects, with promising short-term clinical and radiographic outcomes. The EIEF group required more horizontal screw fixation for the augments, which might reflect local biomechanics and principles of augment fixation distinct from the IIEF reconstruction technique.

Conflict of Interest Statement

The author(s) have no conflicts of interest relevant to this article.

Authors' Contributions

All authors (HT, YH, YXZ, ZYM, and SJG) made substantial contributions to the design, data processing, and interpretation. YXZ, SJG, and HT conceived the study. YH and ZYM coordinated data collection. HT, YH, and YXZ performed the radiological assessment. HT drafted the article, and all other authors revised it critically for important intellectual content. All authors read and approved the final manuscript.

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Ethics statement

This study was approved by the hospital ethics committee (No. JST20180302-8).

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