OPERATIVE TECHNIQUE

Reconstruction of Paprosky Type III Acetabular Defects by Three-Dimensional Printed Porous Augment: Techniques and Clinical Outcomes of 18 Consecutive Cases

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Objective: To introduce the surgical technique of reconstruction of Paprosky type III acetabular defects by 3D printed porous augments.

Methods: First, CT scans of pelvis were obtained to establish the 3D reconstruction model of 3D printed porous augment. Then, a nylon pelvis model was printed to simulate operation with the surgeons. At this time, the augment was designed and modified according to the surgeon's suggestions and the 3D printing principles. Eighteen patients with Paprosky type III acetabular defects receiving reconstructive surgery by 3D printed porous augments were included in current study. Their data, including general information, intra-operative findings, imaging results, functional scores, and complications were retrospectively analyzed.

Results: The mean follow-up time lasted 33.3 ± 2.0 (24–56) months. The average limb-length discrepancy (LLD) was 31.7 ± 4.2 (3–59) mm preoperatively, 7.7 ± 1.4 (1–21) mm postoperatively ($P < 0.0001$), and 7.5 ± 1.2 (0–18) mm at the latest follow-up. The mean vertical position of hip center of rotation (HCOR) from the interteardrop line changed from preoperative 50.7 ± 3.9 (23.3–75.3) mm to postoperative 22.9 ± 1.9 (10.1–40.3) mm ($P < 0.0001$), with the latest follow-up revealing an HCOR of 22.3 ± 1.7 (11.0–40.5) mm. Follow-up study showed that no hip had radiolucencies and radiological loosening of the acetabular components and augment. The average Harris hip score (HHS) improved from 40.3 ± 4.5 (10.5–71) before operation to 88.4 ± 1.9 (75–97) at the last follow-up ($P < 0.0001$). Moreover, follow-up exhibited that no periprosthetic joint infection, hip dislocation, fracture, and re-revision occurred.

Conclusion: Surgical treatment of Paprosky type III acetabular defect with 3D printed porous augment was simple, achieved good match between porous augment and the defect bone surface and the acetabular component, ideally restored LLD and HCOR after operation, significantly improved HHS and attained good early clinical outcomes. It is a promising personalized solution for patients with severe acetabular bone defect.

Key words: 3D printed augment; Acetabular bone defect; Clinical application; Porous; Surgical technique

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Introduction

Total hip arthroplasty (THA) has been one of the most successful surgeries in the 20th century and has been used for easing pain, correcting deformity, and improving hip joint function[1,2]. The management of severe acetabular bone defects in primary or revision THA is challenging and the ideal reconstruction of the defect represents one of the critical factors for a successful THA[3]. The basic principles of acetabular defect reconstruction include restoring hip center of rotation (HCOR) and acetabular ring integrity, preserving acetabular bone stock, and establishing normal biomechanics of the hip, which could accomplish immediate and long-term stability of acetabular components[4].

Traditionally, major acetabular defects have been reconstructed by impaction bone grafting, metal augments, and cup/cage constructs[2]. Different implant designs and sizes are available for THA acetabular revisions, which include mainly reinforcement devices (roof-reinforcement rings and anti-protrusio cages), custom-made triflanged acetabular components, jumbo cups, and tantalum metal (TM) systems. Each designs and methods has various success rates as well as various complication rates. Recently, given the excellent biocompatibility and biomechanical properties of TM, TM augments and cups are most commonly employed and they yielded good clinical mid-term outcomes. Since TM augments are mass-produced in standard sizes and shapes, they do not always fit in with the morphology of acetabular bone defects, and reaming the residual bone stock of acetabular defects is required in most cases[5–7]. Therefore, individualized augments are needed in these cases to better reconstruct the acetabular bone defects.

With rapid development of 3D printing technology, the 3D printed medical models are being extensively applied in orthopedic prosthesis surgery for its ability to personalize prostheses[8,9]. Though a case report reported a clinical application of 3D printed augment for the repair of acetabular defect[8], the result of implant-bone integration is still poorly understood. In our previous study, we established a finite element analysis (FEA) model of acetabular bone defects reconstructed by 3D printed porous augments, and analyzed

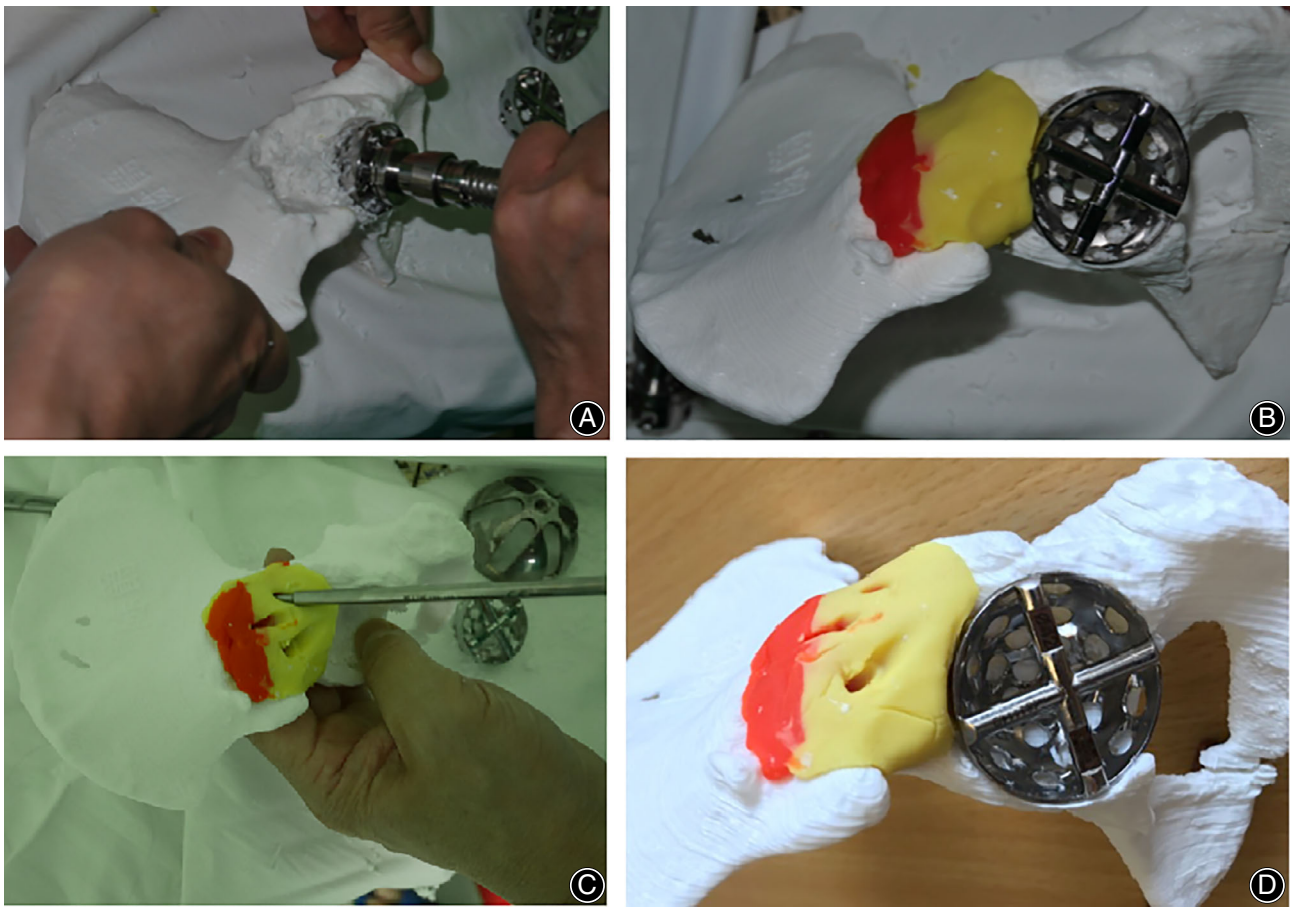

Fig. 1 The preoperative plan and design of 3D printed porous augment. (A) The acetabular cup size and position were designed according to bone volume; (B) the acetabular bone defect was reconstructed by augment made of plasticene; (C) the length and position of screws was designed on the basis of the augment and bone volume; (D) the completed preoperative surgical design

the stress distribution and clinical safety of augments, screws, and bones[10]. And the FEA results showed all the components were intact under single-legged standing model. However, how these 3D printed porous augments perform in patients has not been systemically assessed.

For the first time, the aims of the current study were: (i) to introduce the design parameters and surgical technique of 3D printed porous augments; and (ii) to report the imaging and clinical outcomes of reconstruction of 3D printed porous augments in patients with Paprosky type III acetabular defects.

Materials and Methods

Inclusion and Exclusion Criteria

This retrospective study investigated patients who underwent hip revision surgery in our hospital. Inclusion criteria were as follows: (i) age between 18 and 80 years; (ii) patients with Paprosky type III acetabular bone defects; and (iii) reconstruction surgery with 3D printed porous augments. Exclusion criteria were as follows: (i) follow-up duration was less than 2 years after the reconstruction; (ii) lack of clinical and imaging data; (iii) active infection of the surgical hip; (iv) acetabular bone defects with pelvic discontinuity; and (v) history of radiation exposure in the surgical hip.

This clinical study was approved by the Medical Ethics Committee of the General Hospital of Chinese People's Liberation Army, Beijing, China (ChiCTR-INR-17013267). The study protocol was carefully explained to the participants and their participation was fully voluntary. Written informed consent was obtained from all participants and they agreed to publish their data in this paper.

Design and Fabrication of 3D Printed Porous Augments

Pelvis of each subject was subjected to CT scan to establish a bone defect model. The three-dimensional reconstruction of pelvis and porous Ti6Al4V augment were achieved by using a direct metal laser sintering system (EOSINT M280, Munich, Germany) based on the computer-aided design software package (Mimics Research 20.0, Materialise, Leuven, Belgium). The matching principles was that the 3D printed porous augment was completely matched with three-dimensional structure of the bone defect and closely attached with the acetabular cup according to the acetabular bone volume. This design process should be guided by the surgeon

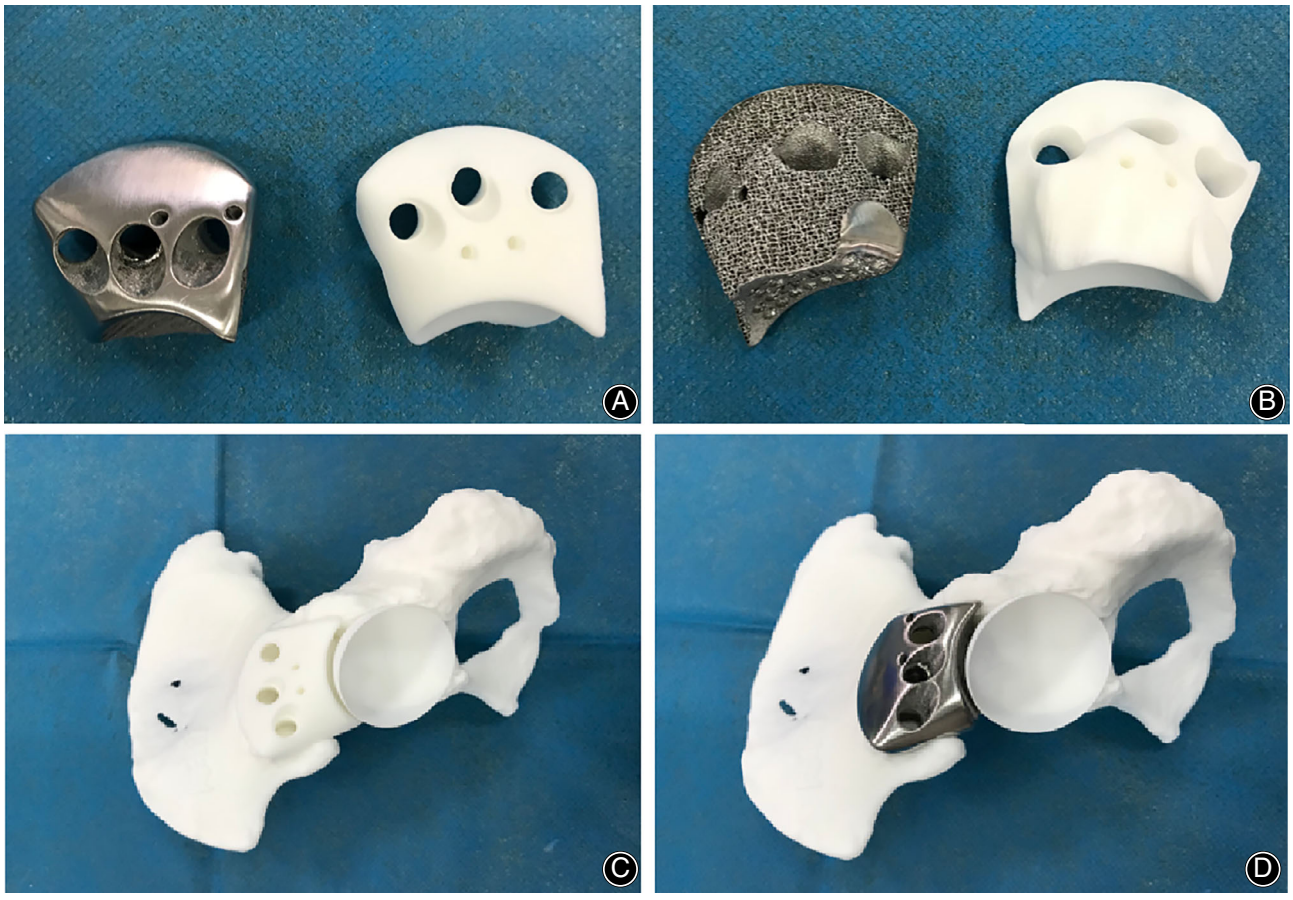

Fig. 2 The material objects of 3D printed augment and pelvis. (A, B) The Ti6Al4V and nylon 3D printed augment; (C, D) the bone defect was well reconstructed by the Ti6Al4V and nylon augment

about the positional relationship of augment, cup, and screws.

Then, a nylon model was printed to simulate operation and to determine the acetabular cup size and the length/direction of screw. This preoperative plan was implemented together with the surgeon. At this time, the 3D printed porous augment was modified on the basis of both the surgeon's suggestions and the design principles (Fig. 1). After that, came to the fabrication of 3D printed porous augments.

Medical Ti6Al4V powder (EOS, Germany) with particles sized from 15 to 53 μm was used. The 3D printed porous augments were fabricated at a scanning rate of 7 m/s and a power of 200 W. The inner pore parameters were designed as follows: cubic-shaped lattice structure with a pore size of 400 μm, a strut size of 200 μm, and a porosity of 60%. The thickness of porous Ti6Al4V coating was 1–2 mm, while the rest of the augment was solid Ti6Al4V. Meanwhile, the position, direction, length and diameter of screws, and Kirschner wires (for temporary intraoperative fixation of the augment) were designed according to the residual bone stock the defective acetabulum. The diameters of screws and K-wires were 6.5 mm and 1.5 mm, respectively. After printing, the 3D printed porous augments were cleaned, polished, sterilized, and then implanted (Fig. 2).

Implantation Surgery of 3D Printed Porous Augment

At the surgical phase of 3D printed porous augment implantation, all procedures were performed with patient assuming lateral decubitus position *via* the posterolateral approach. Exposure and preparation of the acetabulum were the same as the posterolateral THA. Intraoperatively, the acetabulum was trimmed to appropriate size by a reamer. Then the 3D printed porous augment was put on the acetabular defect surface, and two 1.5 mm K-wires were used for temporary fixation. Finally, the 3D printed porous augment was fixed on the defect surface with screws. The augment matched well with the defect in terms of shape and size as observed by naked eyes. After acetabular cup implantation, the gap between cup and 3D printed porous augment was filled with bone cement (Fig. 3A–D).

Outcome Measurements

Data of the patients, including general information, intraoperative findings, postoperative imaging results (Fig. 3E–G), and scores of functional evaluation (Harris hip score, HHS) were analyzed.

Image Evaluation

The limb-length discrepancy (LLD) and vertical HCOR (Fig. 4) were measured by using the Orthoview software

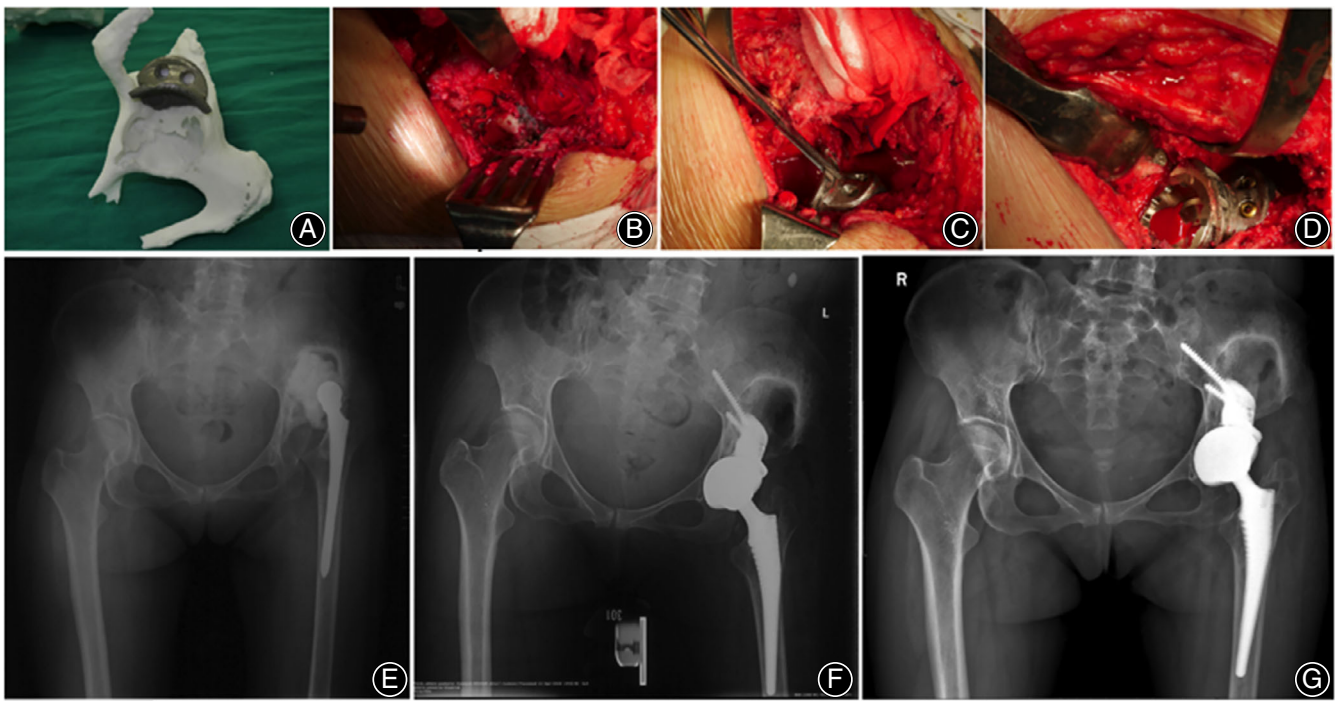

Fig. 3 The 3D printed porous augment was clinically applied in a patient with severe acetabular bone defect. (A) The matching between the 3D printed porous augment and the bone model simulated from a female patient with Paprosky IIIA acetabular bone defect; (B) the acetabular bone defect was detected intraoperatively; (C) the 3D printed porous augment was matched with defect bone surface; (D) the 3D printed porous augment was fixed by two screws and cement between the acetabular cups; (E) X-ray result before operation; (F) X-ray result immediately after operation; (G) X-ray result at the last follow-up (56 months after surgery)

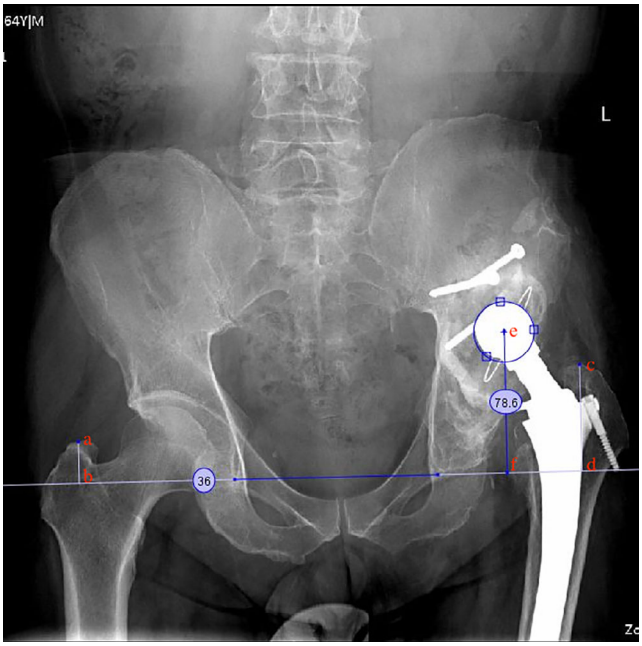

Fig. 4 The limb-length discrepancy (LLD) and vertical hip center of rotation (HCOR) were measured using Orthoview software, and a representative X-ray image is shown. The LLD was discrepancy between line "ab" and line "cd," which was defined as the vertical distance from greater trochanter tip to interteardrop line. The HCOR (line "ef") was defined as the vertical distance from HCOR to interteardrop line. In this case, the LLD and HCOR were 36 and 78.6 mm, respectively

(Materialise, Belgium). The LLD was defined as the vertical distance from greater trochanter tip to the interteardrop line and the HCOR was defined as the vertical distance from HCOR to the interteardrop line. The hip were also radiologically examined to detect radiolucent lines adjacent to the acetabular implant and/or augments by using the methods described by DeLee and Charnley[11].

Functional Evaluation

The HHS was often used to evaluate hip function in adult population preoperatively and postoperatively. The HHS score system mainly includes four aspects as pain, function, absence of deformity, and range of motion. The score standard had a maximum of 100 points (best possible outcome). A total score <70 is considered a poor score, 70–80 fair, 80–90 is good, and 90–100 excellent.

Statistical Analysis

All the statistical analyses were performed using SPSS for Windows (version 18.0, SPSS Inc., Chicago, IL, USA). Gender, type of Paprosky acetabular bone defect, and radiological loosening or radiolucent lines of the acetabular components and augments were of a categorical nature. Age, body mass index (BMI), preoperative laboratory examination, LLD, HCOR vertical position, and HHS were numerical data. Rates were compared by using chi-squared test while numerical data were compared by employing paired sample t test (normal distribution and homoscedasticity) or Wilcoxon rank test. A P value less than 0.05 was considered statistically significant.

Results

General Information

From April 2016 to August 2020, a total of 31 patients received the said reconstructive operation by using 3D printed porous augments in our institution. Among them, 18 (7 males and 11 females) were followed-up for more than 2 years and involved in this current study.

Their mean age was 50.1 ± 3.2 (18–71) years, and the BMI was 25.41 ± 0.99 (16.98–32.39) kg/m^2. The level of serum preoperative C-reactive protein, erythrocyte sedimentation rate, and plasma interleukin-6 were 0.5027 ± 0.1364 (0.05–1.70) mg/dL, 18.56 ± 2.873 (1–49) mm/1 h, and 5.366 ± 1.240 (1.49–23.33) pg/mL, respectively. In terms of the Paprosky acetabular bone defects, 10 were of type IIIA, and eight were of type IIIB.

Among these patients, the operative time lasted for 4.3 ± 0.3 (2.5–6) h, and the intraoperative blood loss was 1736 ± 174.7 (350–3000) mL. The mean diameter of screw-fixed augments was 6.5 mm. The length of screws measured 33.4 ± 1.4 (20–65) mm, and the number of screws was 2.7 ± 0.2 (2–5).

Imaging Outcomes

The preoperative LLD was 31.7 ± 4.2 (3–59) mm while the postoperative LLD was 7.7 ± 1.4 (1–21) mm (t = 5.641, P < 0.0001), with the LLD at the last follow-up being 7.5 ± 1.2 (0–18) mm.

The vertical HCOR from the interteardrop line changed from preoperative 50.7 ± 3.9 (23.3–75.3) mm to postoperative 22.9 ± 1.9 (10.1–40.3) mm (t = 5.576, P < 0.0001), the value being 22.3 ± 1.7 (11.0–40.5) mm at the latest follow-up.

Functional Outcomes

The functional HHS increased from preoperative 40.3 ± 4.5 (10.5–71) to 88.4 ± 1.9 (75–97) at the last follow-up (t = 13.26, P < 0.0001). Collectively, these data suggested that the 3D printed porous augments could achieve good clinical outcomes in our series.

Complications

Follow-up data were available for all the patients, and the mean follow-up time was 33.3 ± 2.0 (24–56) months. There was no periprosthetic joint infection, hip dislocation, fracture, and re-revision for other complications. No radiological loosening and radiolucent lines were observed in the patients.

Discussion

This study examined the performance of the 3D printed porous augments for the reconstruction of Paprosky

type III acetabular defects. The intraoperative findings showed that the 3D printed porous augments matched well with the morphology of bone defects and the acetabular components. In particular, the latest follow-up showed that the imaging and functional outcomes were apparently improved in the patients.

Design Parameters of 3D Printed Augments

The influence of porosity, pore size, and pore shape on the biological behaviors of porous Ti6Al4V prosthesis has been previously investigated[12–15]. Heinl *et al.* demonstrated that three-dimensional structures with a mean interconnected porosity of 61.3% and pore size of 450 μm were suitable for tissue ingrowth and vascularization[12]. Animal experiments exhibited that the 3D printed porous Ti6Al4V scaffold with a total porosity of 58% and a pore size of 500 ± 50 μm possessed mechanical properties close to those of human bone and could promote osseo integration and tissue integration[13]. Wieding *et al.* measured the uniaxial compression, bending, and torsion strength of porous Ti6Al4V scaffold and showed that the pore size of 400 μm was the numerical optimization of porous bone scaffold structures to match the elastic properties of human bone. They also demonstrated that the cubic design had the lowest elastic modulus and could lead to the fastest new bone formation[14]. Another study investigated the influence of the pore shape on mechanical properties and showed that the cubic scaffold was conductive to osseo integration and tissue integration[15]. Considering that the surface of severely defective acetabular bone was not entirely cancellous, the defect surface of many patients receiving revision THA would be partially corticalized due to long-term wear. Therefore, the pore parameters in the present study represented a compromise between mechanical and biological properties, that is, a cubic-shaped lattice structure, a pore size of 400 μm, a strut size of 200 μm, and a porosity of 60%.

Image Evaluation of Acetabular Bone Defect Reconstruction

The primary goal of reconstruction of severe acetabular bone defects was to restore the anatomical position of the HCOR and the LLD[16,17]. In this study, the vertical HCOR from the interteardrop line changed from 50.7 to 22.3 mm at the latest follow-up and the LLD was improved from preoperative 31.7 to 7.5 mm at the latest follow-up. Abolghasemian *et al.* retrospectively studied 34 failed hip replacements revised using a TM acetabular shell and one or two TM augments, and found that the mean vertical HCOR was restored from preoperative 48.5 mm to postoperative 24.8 mm[16]. Banerjee *et al.* conducted a systematic review on the outcomes of acetabular revision with highly-porous metals, and they concluded that the mean vertical HCOR was restored significantly from a mean of 39.2 mm preoperatively to a mean of 24.1 mm postoperatively[17]. The vertical HCOR in our study was restored to 22.3 mm, indicating that functional restoration of the abductors was effectively attained.

Clinical Evaluation of Acetabular Bone Defect Reconstruction

Several studies have reported the short- to middle-term clinical outcomes of TM augments in the reconstruction of severe acetabular bone defects. The average HHS was reportedly increased to 76–84 postoperatively[18,19]. As compared to other reconstruction methods, the jumbo cups and impacted bone grafts for reconstruction of acetabular bone defects scored 72–79 on the HHS scale postoperatively[20,21]. In this study, the mean HHS was improved significantly, from preoperative 40.3 to postoperative 88.4 and the patients were satisfied with the result of surgical treatments and functional recovery of the involved hip joint. The latest X-rays revealed no radiological loosening and radiolucent lines, and that the surrounding bone tissue around the augment was firmly fixed. The aforementioned findings showed that the short-term outcomes of the 3D printed porous augment used for the reconstruction of severe acetabular bone defects was encouraging and the technique had great prospect of clinical application in future.

Limitations

This study had several limitations. First, the study was of retrospective nature and had no control group. Second, the uncontrolled study design prevented us from further proving the superiority of the 3D printed porous augments over other alternatives. However, the positive results in our series preliminarily showed that the 3D printed porous augments are an effective choice for the management of Paprosky type III acetabular defects.

In summary, the 3D printed porous augment in our series morphologically well matched with the defective bone and the acetabular component. Importantly, the latest follow-up showed that imaging and functional outcomes were apparently improved. The technique can not only reduce the mechanical mismatching but also can achieve long-term stability by promoting bone in growth. We are led to conclude the 3D printed porous augment has great potential, as an individualized treatment, to be clinically used in the future.

Acknowledgments

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Data Availability Statement

The datasets supporting the conclusions of this article are included within the article and its supplementary materials.

Conflict of Interest

The authors declare no conflict of interest.

Supporting Information

Additional Supporting Information may be found in the online version of this article on the publisher's web-site:

Table S1. Supporting Information

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