

Review Article

Three-Dimensional Printed Patient-Specific Implants in Complex Acetabular Reconstruction

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Abstract

Background: Massive acetabular bone loss from aseptic loosening, pelvic discontinuity, or peri-acetabular tumour resection remains one of the most demanding problems in hip surgery, and conventional jumbo cups, cup-cage constructs, and structural allografts have inconsistent fixation in the most severe defects.

Objective: To synthesise evidence on three-dimensional (3D) printed patient-specific acetabular implants, their design-and-manufacturing workflow, and outcomes relative to conventional reconstruction.

Methods: Narrative review of clinical series, systematic reviews, and biomechanical studies of additively manufactured triflange, monoblock, and hemipelvic implants.

Findings: Custom triflange and porous monoblock implants achieve implant survivorship of 90-100% at intermediate follow-up with radiographic osseointegration exceeding 90%, comparing favourably with jumbo cups (95.0%) and trabecular titanium revision cups (92.5%).

Conclusions: Patient-specific 3D-printed implants provide reliable fixation for Paprosky III defects, pelvic discontinuity, and tumour resection where conventional options fail, though cost, lead time, and long-term data remain limiting factors.

Keywords: Acetabular reconstruction; Three-dimensional printing; Patient-specific implant; Pelvic discontinuity; Revision total hip arthroplasty

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Introduction

Massive acetabular bone loss is among the most technically demanding problems facing the revision hip surgeon. Aseptic loosening with progressive osteolysis, chronic pelvic discontinuity, infection, and resection of peri-acetabular malignancy can each leave a defect in which the native columns and posterior wall no longer provide a stable bed for a hemispherical cup [1]. The Paprosky classification, based on the degree of superior migration, ischial and teardrop lysis, and Köhler-line

violation, remains the standard framework for staging these defects and anticipating which reconstructions will provide durable host-bone contact [1]. Type IIIA and IIIB defects, and defects complicated by pelvic discontinuity, are precisely the group in which conventional options - jumbo cups, cup-cage constructs, and structural allografts - show the least predictable survivorship, since each depends on a hemispherical or graft-bone interface that assumes a degree of residual columnar support the defect may no longer provide.

Additive manufacturing has changed what is technically achievable in this setting. Computed-tomography-derived, patient-specific titanium implants can be designed to match the residual host bone geometry, incorporate a porous osseointegrative surface analogous to trabecular bone, and distribute fixation across multiple flanges or a monoblock shell rather than relying on a single hemispherical interference fit [2]. This review synthesises the published literature on 3D-printed patient-specific acetabular implants: their design and manufacturing workflow, clinical and radiographic outcomes in Paprosky III defects and pelvic discontinuity, their extension to peri-acetabular tumour resection, and how their outcomes compare with jumbo cups, cup-cage constructs, and structural allografts.

Indications and the Paprosky Framework

The Paprosky classification stratifies acetabular defects from Type I (minimal rim loss) through Type IIIB (severe bone loss with likely pelvic discontinuity), based on plain radiographic and, increasingly, CT criteria [1]. Type IIIA defects retain enough host bone to support a jumbo cup or cup-cage construct with adjunct augmentation, whereas Type IIIB defects and chronic pelvic discontinuity generally lack sufficient contiguous host bone for reliable ingrowth with an off-the-shelf hemispherical component. Patient-specific implants are

indicated in this most severe subgroup, and in the analogous problem of a large, irregular defect created by resection of a peri-acetabular sarcoma or metastasis, where no standard implant geometry can match the residual bone stock [3].

Design and Manufacturing Workflow

The workflow begins with thin-slice pelvic CT, from which a three-dimensional bone model is segmented and the defect margins delineated. Implant geometry is designed around the residual ilium, ischium, and pubis, with fixation flanges or screw trajectories planned against a virtual bone model to maximise purchase in dense host bone while avoiding neurovascular structures [2]. The implant is manufactured in titanium alloy by powder-bed additive processes such as electron-beam or selective-laser melting, which allow a solid structural shell to be printed in continuity with a graded, trabecular-like porous surface engineered for bone ingrowth [4]. Porosity, pore size, and strut thickness can be varied continuously across the implant to approximate the stiffness of adjacent trabecular bone and mitigate stress shielding, a property difficult to achieve with subtractively manufactured components [4]. Finite-element analysis of split-type and monoblock triflange designs has been used preoperatively to estimate interfacial micromotion under simulated gait and stair-climbing loads, informing postoperative weight-bearing protocols, since micromotion above roughly 150 micrometres is associated with fibrous rather than osseous fixation [5]. A patient-specific drill guide is frequently produced alongside the implant to reproduce the planned screw trajectories intraoperatively, shortening operative time and reducing the risk of malpositioned fixation relative to freehand screw placement in a distorted pelvis. Manufacturing lead time typically spans several weeks from imaging to delivery, which restricts the technique to planned revision or oncological resection rather than acute trauma or an

actively infected field, and multidisciplinary planning between the surgeon and the manufacturing engineer is required to finalise flange position, screw length, and liner orientation before printing.

Custom Triflange and Monoblock Implants: Clinical Outcomes

Custom triflange acetabular components, the most established patient-specific design, use three flanges fixed to the ilium, ischium, and pubis with multiple screws to achieve fixation independent of the deficient acetabular floor. Early clinical series in catastrophic bone loss reported implant survivorship above 90% at short- to mid-term follow-up [6,7]. A systematic review of 1218 patients across multiple triflange series confirmed favourable pooled survivorship with re-revision predominantly due to infection and dislocation rather than aseptic loosening [8], corroborating an earlier systematic review of survivorship and clinical outcomes in this population [9]. Minimum 5- and 10-year follow-up series have since extended this durability signal, with implant survival maintained and functional scores sustained beyond a decade [10,11,12]. A prospective series of 50 hips reconstructed with a custom triflange implant for large defects and pelvic discontinuity reported good clinical results at 2 years with low re-revision rates (Table 1) [13], and survival analysis restricted to severe pelvic discontinuity has confirmed durable fixation in this specific subgroup [14].

Monoblock and porous augment designs represent a parallel evolution. Custom 3D-printed monoblock implants for acetabular reconstruction achieved 100% cumulative implant survivorship at a median of 53 months, with Oxford Hip Score improving from 8 to 32 and radiographic bone integration in 92% of patients at one year or later [15]. A finite-element-validated split-type triflange design for Paprosky IIIB defects produced comparable functional gains, with Harris Hip Score

improving from 31.9 to 82.9 and stable fixation in all cases at mid-term follow-up [5]. Custom porous titanium augments used adjunctively with standard revision cups for Paprosky III defects have likewise reported encouraging early clinical and biomechanical results [16]. Even in the less severe primary-arthroplasty setting, personalised porous monoblock cups have restored acetabular bone stock with reliable fixation [17], consistent with the durable fixation reported for a 3D-printed trabecular titanium acetabular cup at minimum 2-year follow-up in 92 consecutive primary arthroplasties [18], and standard versus custom-made implants comparisons suggest custom implants offer an advantage specifically once host bone loss exceeds what standard hemispherical or augmented constructs can reliably engage [19].

Table 1: Selected clinical series of 3D-printed patient-specific acetabular implants reviewed here [2,6,13,10,15,14,5,8].					
Study	Design	n	Indication	Follow-up	Key outcome
Berasi 2015	Custom triflange	78	Catastrophic bone loss	Mean 5.4 years	Survivorship >90%
Citak 2018	3D-printed monoblock	13	Extensive defects	Mean 2.2 years	No aseptic loosening
Scharff-Baauw 2021	Custom triflange	50 hips	Large defects, pelvic discontinuity	2 years	Low re-revision rate
Alexander 2023	Custom triflange	68	Catastrophic bone loss	Minimum 5 years	Survivorship maintained
Di Laura 2023	3D-printed monoblock	26	Severe bone loss	Median 53 months	100% survivorship; 92% integration
Alvarez Valdivielso 2024	3D-printed acetabular implant	Not stated	Severe pelvic discontinuity	Mid-term	Durable fixation
Guo 2025	Split-type triflange	14	Paprosky IIIB	Mid-term	HHS 31.9 to 82.9
Broekhuis 2023 (meta-analysis)	Custom triflange	1218 (pooled)	Large defects	Variable	Favourable pooled survivorship

Osseointegration and Comparison with Conventional Reconstruction

Osseointegration, judged by absence of radiolucent lines, trabecular bridging, and stable component position on serial imaging, has been reported above 90% across custom triflange and monoblock series (Figure 1) [15,20]. A multicentre series of a 3D-printed fully porous monoblock cup with a cemented liner reported 97.5% osseointegration at one year and all-cause revision-free survival of 92.0% at four years in complex primary and revision arthroplasty [20], figures that sit alongside the 92.5% survival reported for trabecular titanium revision cups more generally [21] and the 95.0% re-revision-free survivorship reported for conventional jumbo cups at a mean 9.3 years (Figure 1) [22].

Conventional alternatives remain reasonable options for less severe defects but show greater variability once bone loss is extensive (Table 2). Jumbo cups achieve good mid-term survivorship overall, but dislocation (5.9%) is their most frequent complication, with aseptic loosening (3.0%) and infection (2.1%) less common (Figure 2) [22]. Cup-cage constructs, designed specifically for pelvic discontinuity, achieve union across the discontinuity in most series and comparable survivorship in systematic review and meta-analysis, though dislocation and cage fracture remain recognised modes of failure [23,24]. Structural allografts restore bone stock but are limited by resorption and nonunion, and a recent systematic review and meta-analysis found less favourable pooled survivorship than metal-augment-based reconstructions for massive defects [25]. Trabecular titanium revision cups, whether off-the-shelf or custom, show comparable dislocation and infection rates to jumbo cups but a modestly lower aseptic loosening rate (Figure 2) [21].

Table 2: Comparative characteristics of reconstruction options for complex acetabular bone loss [22,23,24,25,21,15].

Technique	Typical indication	Fixation principle	Reported survivors hip	Principal failure mode
3D-printed custom triflange/monoblock	Paprosky IIIB, pelvic discontinuity	Multi-flange/porous ingrowth matched to host bone	90-100%	Infection, dislocation
Jumbo cup	Paprosky IIIA	Press-fit hemispherical, host-bone contact	95.0%	Dislocation (5.9%)
Trabecular titanium revision cup	Paprosky IIIA/IIIB	Porous hemispherical +/- augments	92.5%	Dislocation (3.4%)
Cup-cage construct	Chronic pelvic discontinuity	Ilio-ischial cage bridging discontinuity	Comparable to triflange	Dislocation, cage fracture
Structural allograft	Segmental bone loss	Graft incorporation and remodelling	Lower than metal augments	Resorption, nonunion

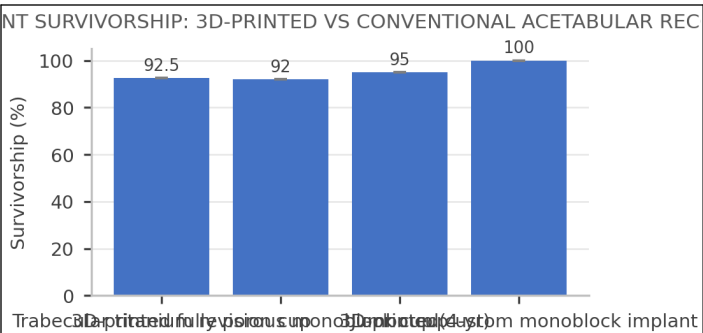


Figure 1: Mid-term implant survivorship reported for 3D-printed and conventional acetabular revision reconstruction techniques: custom 3D-printed monoblock implant at median 53 months [15], 3D-printed fully porous monoblock cup at 4 years [20], trabecular titanium revision cup [21], and jumbo cup at mean 9.3 years [22].

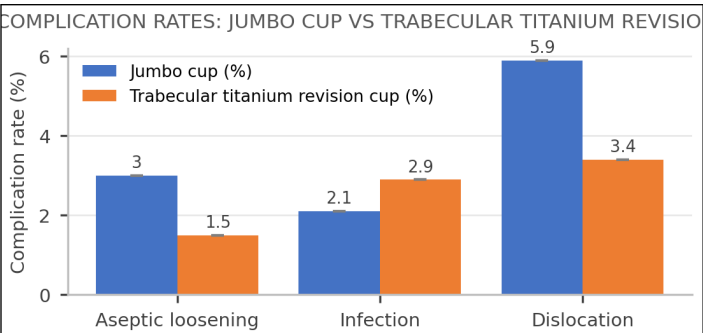


Figure 2: Complication rates reported for jumbo cup versus trabecular titanium revision cup reconstruction of acetabular defects, from two systematic reviews [22,21].

Application in Peri-Acetabular Tumour Resection

The same design-and-manufacturing principles have been extended to reconstruction after resection of peri-acetabular and sacroiliac tumours, where the residual defect is even less standardised than in revision arthroplasty. Patient-specific modular hemipelvic implants incorporating the sacroiliac joint have restored pelvic ring continuity and hip function after tumour resection [3], and custom hemipelvic prostheses incorporating auxetic, negative-Poisson's-ratio porous structures have achieved successful osseointegration in all cases with substantial improvement in Musculoskeletal Tumor Society score and pain scores at intermediate follow-up [26]. These oncological applications underscore that the principal advantage of additive manufacturing - the ability to match an arbitrarily irregular bone defect with a mechanically and biologically appropriate implant - applies equally whether the defect arises from loosening, discontinuity, or resection. Image-guided navigation and patient-specific cutting or drilling guides have further improved the accuracy of tumour margin resection and implant seating in this setting, reducing reliance on intraoperative freehand judgement when normal anatomical landmarks have been destroyed by the tumour itself.

Conclusion

Three-dimensional printed patient-specific implants have matured from isolated case reports into a reproducible reconstruction option for the most severe acetabular defects, achieving implant survivorship and osseointegration rates comparable to, and in several series exceeding, jumbo cups, cup-cage constructs, and structural allografts, while directly addressing the geometric mismatch that limits off-the-shelf components in Paprosky IIIB defects, pelvic discontinuity, and peri-acetabular tumour resection. Design-and-manufacturing advances - graded porosity,

finite-element-validated flange geometry, and patient-specific drill guides - have paralleled these clinical gains. The principal remaining barriers are cost, manufacturing lead time unsuited to acute trauma or infection, and a continued shortage of long-term (>10-year) comparative data against contemporaneous jumbo cup, cup-cage, and allograft cohorts rather than historical controls; addressing these, alongside standardisation of design software and postoperative loading protocols across centres, should further define the role of patient-specific implants within the broader reconstructive algorithm for complex acetabular bone loss.

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