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Original Research

# Impact of Acetabular Implant Design on Aseptic Failure in Total Hip Arthroplasty

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ABSTRACT

*Background:* Failure of cementless acetabular osseointegration is rare in total hip arthroplasty. Nevertheless, new fixation surfaces continue to be introduced. Novel implants may lack large diameter, constrained bearings, or dual mobility (DM) bearings to address instability. We compared clinical and radiographic outcomes for acetabular components with differing fixation surfaces and bearing options, focusing on the relationship between fixation surface and osseointegration and the relationship between bearing options and dislocation rate.

*Methods:* We retrospectively reviewed 463 total hip arthroplasties implanted with 3 different acetabular components between 2012 and 2016. Records were reviewed for demographics, clinical scores, and complications. Radiographs were examined for evidence of acetabular osteointegration. Analysis of variance and chi-square tests were used to compare cohorts.

*Results:* All cohorts had 100% survivorship free of acetabular fixation failure with no differences in clinical scores. Dislocation occurred in 1.3% of cases (n = 6). Analysis of the "transition" sizes, for which brand determined the maximum bearing diameter, revealed a significantly higher dislocation rate (3/50, 6%) in implants with limited bearing options. All 4 revisions for recurrent dislocation involved well-positioned components that did not accept large diameter, constrained bearings, or DM bearings, resulting in 3 shell revisions to expand bearing options. Femoral revisions were associated with dislocation risk but did not vary between cohorts.

*Conclusion:* Dislocation was the primary mechanical cause for acetabular revision, while acetabular fixation failure was not encountered. We caution against selecting "new and improved" acetabular components without options for large diameter, constrained bearings, or DM bearings, even when enabling technology makes component positioning reliable.



## Introduction

Cementless acetabular fixation in total hip arthroplasty (THA) has been the fixation method of choice in the United States for decades [1]. Osseointegration occurs reliably with established implants when initial stability is achieved, and subsequent mechanical loosening is rare in the absence of osteolysis due to component wear or other inflammatory processes, such as corrosion or infection [2]. When the surgical technique, the surface of the implant, or the quality of the acetabular bone do not allow for an excellent press-fit, acetabular screws may help provide the necessary initial stability [3,4]. Nevertheless, implant companies continue to design new acetabular fixation surfaces to improve osseointegration. While most new designs have been successful, some have had unanticipated radiographic results [5], and the clinical need for improved surfaces is not well established in outside cases of acetabular bone loss in which primary cementless fixation is less reliable [6,7].

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While early cementless acetabular fixation failure is uncommon in the primary setting, prosthetic hip dislocation remains a leading cause of early revision surgery [2]. In order to accommodate the novel fixation surfaces, some highly porous shells are thicker than established alternatives. This may compromise bearing diameter in specific cup sizes to maintain polyethylene liner thickness. For example, a 46-millimeter shell may accept only a 28-millimeter bearing with a thicker shell but a 32-millimeter bearing with a thinner shell, whereas 32-millimeter bearings may be available for 48-millimeter shells regardless of shell thickness. Smaller bearing diameters in these specific cup sizes may in turn increase the risk of dislocation. Novel acetabular implants may not have constrained or dual mobility (DM) options available to manage instability upon initial clinical release. Furthermore, depending on the implant's market success, such liners may never become available. Therefore, even well-fixed and well-positioned acetabular shells may require revision if recurrent dislocation occurs [5,8]. In settings where constraint is needed despite appropriate positioning, the lack of stable bearing options in the primary shell may result in multiple surgeries to achieve stability because constrained liners are typically avoided in acetabular shell revision because of concern for implant loosening [8].

We sought to compare rates of early mechanical failure between 3 cementless primary acetabular implants with different design features. Maximum bearing diameter for a given acetabular shell diameter varied between implant designs, as did the fixation surface and the availability of DM and constrained bearings during the study period. Endpoints of interest were clinical and radiographic outcomes, with particular attention to acetabular reoperations for mechanical complications including fixation failure and dislocation. Data on femoral complications were also collected to determine if dislocations or other acetabular reoperations were related to femoral complications. We also sought to define the term "transition" cup sizes as acetabular component diameters in which maximum bearing diameter is variable depending on the manufacturer. We hypothesized that the rates of early fixation failure would be low and similar across various fixation surfaces, whereas the availability of large-diameter and DM bearings at the index arthroplasty would be protective against dislocation and acetabular component revision for recurrent dislocation.

## Material and methods

### *Patient selection*

After approval by the governing institutional review board, a retrospective review identified 558 primary or conversion THAs performed by a single surgeon between January 1, 2012, and December 31, 2016. Of these, 482 THAs in 426 patients were performed using one of the 3 cementless acetabular components of interest. Primary and conversion procedures using less commonly used acetabular implants (n = 76) were not included in this review. We excluded patients with conversions to THA from prior open hip surgery (n = 16), severe neuromuscular disease including cerebral palsy and myelodysplasia with neurological deficits (n = 3), and metastatic disease of the hip (n = 1). THAs for treatment of femoral neck fracture (n = 29) and THAs with concomitant procedures, such as open abductor repair (n = 3), removal of loose bodies (n = 1), and excision of myositis ossificans (n = 1), were included. Conversions to THA from percutaneous procedures, such as percutaneous screw fixation of prior femur fracture or slipped capital femoral epiphysis (n = 11), hip arthroscopy (n = 4), and percutaneous core decompression using multiple drilling (n = 2), were also included. This left 463 THAs in 407 patients for analysis.

### *Patient demographics*

In this retrospective nonrandomized cohort study, there were statistically significant differences between cohorts with regard to age, gender, diagnosis, and follow-up time, but not BMI, laterality, or incidence of preoperative abductor deficiency (Table 1).

### *Implants studied*

The hydroxyapatite (HA)-coated Trident cup (Stryker, Kalamazoo, MI) was implanted in 182 THAs in 165 patients. There were 65 hemispherical cups and 117 peripheral self-locking (PSL) cups. Both variants are titanium shells made with identical arc-deposited commercially pure titanium, a HA coating, and a locking mechanism that accepts DM and constrained liner options. Therefore, they were analyzed together. The hemispherical HA-coated cups were underreamed by 1 millimeter and implanted using a press-fit technique. The PSL variant has a 1.8-millimeter peripheral flare designed to enhance press-fit. For the sake of this analysis, PSL cups were classified as being 2 millimeters larger than their nominal diameter to account for peripheral flare, which allowed comparison to hemispherical systems. These implants were reamed to their nominal implant diameter, which is line-to-line at the dome and 1.8 millimeters smaller than the rim diameter. If complete seating was not possible, the mouth of the acetabulum was reamed 1 millimeter larger than the nominal implant diameter, which still imparted a 0.8-millimeter press-fit at the periphery. The HA-coated implants accepted highly cross-linked sequentially annealed polyethylene liners that allow the use of 36-millimeter-diameter bearings in 48-

**Table 1**
Demographics.

| | NHPT, n = 97 | HA-coated, n = 182 | CaP-coated, n = 184 | Total, n = 463 | ANOVA/$\chi^2$ analysis |
|---|---|---|---|---|---|
| Age (years), mean (range) | 56.97 (26-85) | 61.77 (21-92) | 64.01 (38-91) | 61.65 (21-92) | $F(2, 460) = 11.397$, $P < .001$ |
| Gender (male), n (%) | 39 (40.2%) | 70 (38.5%) | 96 (52.2%) | 205 (44.3%) | $\chi^2(2) = 7.797$, $P = .020$ |
| BMI (kg/m2), mean (sd) | 28.7 (6.4) | 29.1 (6.4) | 28.4 (6.7) | 28.8 (6.5) | $F(2, 460) = 0.500$, $P = .607$ |
| Laterality (right), n (%) | 57 (58.8%) | 101 (55.5%) | 94 (51.1%) | 252 (54.4%) | $\chi^2(2) = 1.646$, $P = .439$ |
| Follow-up (years), mean (sd) | 2.1 (1.5) | 1.5 (1.5) | 1.3 (1.3) | 1.6 (1.4) | $F(2, 460) = 8.614$, $P < .001$ |
| Diagnosis, n (%) | | | | | $\chi^2(12) = 21.418$, $P = .045$ |
| OA | 69 (71.1%) | 125 (68.7%) | 148 (80.4%) | 342 (73.9%) | $\chi^2(2) = 7.022$, $P = .030$ |
| ON | 13 (13.4%) | 27 (14.8%) | 13 (7.1%) | 53 (11.4%) | $\chi^2(2) = 5.912$, $P = .052$ |
| Femoral neck fracture | 3 (3.1%) | 11 (6.0%) | 15 (8.2%) | 29 (6.3%) | $\chi^2(2) = 2.794$, $P = .247$ |
| OA in the setting of pediatric hip disease | 7 (7.2%) | 10 (5.5%) | 7 (3.8%) | 24 (5.2%) | $\chi^2(2) = 1.564$, $P = .458$ |
| Rheumatoid arthritis | 4 (4.1%) | 5 (2.7%) | 0 (0.0%) | 9 (1.9%) | $\chi^2(2) = 6.682$, $P = .035$ |
| Nonunion, ON, or OA s/p proximal femur fracture | 1 (1.0%) | 3 (1.6%) | 1 (0.5%) | 5 (1.1%) | $\chi^2(2) = 1.048$, $P = .592$ |
| Synovial chondromatosis | 0 (0.0%) | 1 (0.5%) | 0 (0.0%) | 1 (0.2%) | $\chi^2(2) = 1.547$, $P = .461$ |
| Concomitant abductor ruptures, n (%) | 1 (1.0%) | 1 (0.5%) | 1 (0.5%) | 3 (0.6%) | $\chi^2(2) = 0.280$, $P = .870$ |

ANOVA, analysis of variance; BMI, body mass index; DJD, degenerative joint disease; OA, osteoarthritis; ON, osteonecrosis.

millimeter and larger shells and 32-millimeter-diameter bearings in 44-millimeter and larger shells. Therefore, this cup was classified as allowing the use of large-diameter bearings in "transition" sizes.

The novel highly porous titanium (NHPT) Restoris PST acetabular cup (Stryker, Kalamazoo, MI) was implanted in 97 hips in 89 patients. It is a titanium shell engineered with a porous structure designed to interlock with bone. The manufacturer reports that this cup has 65%-70% of interconnected porosity. The cup's high coefficient of friction and anecdotal reports of difficulty seating the implant when underreamed by 1 millimeter led us to adopt line-to-line reaming, as suggested by the manufacturer. We found that an excellent press-fit was typically achieved without underreaming when using this implant. The implant was only offered with a highly cross-linked vitamin E polyethylene liner. Maximum bearing diameter was 32 millimeters in a 50-millimeter shell and 28 millimeters in a 46-millimeter shell. Therefore, this cup was classified as allowing only small-diameter bearings in "transition" sizes.

The calcium phosphate (CaP)-coated plasma-sprayed titanium Trinity acetabular cup (Corin, Cirencester, UK), was implanted in 184 THAs in 165 patients. There were 177 Trinity cups and 7 Trinity-I cups placed. In both cups, the titanium shell is coated with a rough titanium plasma spray and electrochemically deposited CaP. Both cups were reamed to their nominal diameter because the manufacturer states that the cup is actually 1 millimeter larger than its nominal size when the coating is included. Therefore, in practice, these cups were underreamed by 1 millimeter and implanted using a press-fit technique. These implants offered either a highly cross-linked polyethylene liner or subsequently a vitamin E highly cross-linked polyethylene liner. Maximum bearing diameter for the Trinity cup was 32 millimeters in a 50-millimeter shell and 28 millimeters in a 46-millimeter shell. Therefore, the Trinity shell was classified as allowing only small-diameter bearings in "transition" sizes. When paired with the vitamin E highly cross-linked polyethylene liner, the Trinity-I cups allowed the use of a 36-millimeter bearing diameter in a 50-millimeter shell and a 32-millimeter bearing diameter in a 46-millimeter shell. Therefore, the Trinity-I was considered to allow large-diameter bearings in "transition" sizes. Although a DM liner has been introduced for this acetabular component, it was not available in the United States at the time of the primary surgeries or any subsequent revisions in this series.

### *Implant selection*

Implant selection was multifactorial and determined at surgeon discretion. In some cases, acetabular implant selection was dictated by the technology used, as the robotic arm used in this series supported each of the studied implants at a different point in the study period. The patient's perceived dislocation risk and the femoral component selected also influenced the choice of the acetabular implant. Over time, the surgeon developed a tendency to select the HA-coated shell for patients believed to be at increased risk of dislocation because of the wider variety of available bearing options. Femoral stem choice across the 3 groups was variable and influenced by the patient's bone morphology and bone quality.

Acetabular bearings were also selected at surgeon discretion. Bearing diameter was selected based on perceived dislocation risk, expected longevity, and available options for the acetabular component selected. For the CaP-coated and NHPT cups, the largest available bearing was chosen in all cases, up to a 36-millimeter diameter. For the HA-coated cup, which offered larger bearings in smaller cups, larger bearing diameters were chosen in older patients or when stability was a concern. When smaller bearings were used with the HA-coated cup, the bearing diameter was typically similar to that of those implanted in the comparably sized CaP-coated and NHPT cups. Smaller bearings were selected in some younger patients to optimize polyethylene thickness. Elevated rim polyethylene liners were used in 24.2% of cases, whenever the operating surgeon judged that the patient would benefit from a slight increase in the posterior or superior jump distance based on patient factors or intraoperative assessment. Although such decisions were not recorded prospectively, the surgeon considered switching to an elevated rim, larger diameter, or DM bearing during the index operation if stability was less than optimal, and the option was available for the acetabular shell being used. Lateralized, face-changing, or constrained liners were not used. For 3 patients implanted with polyethylene liners in the HA-coated cup, operative reports did not indicate whether an elevated rim liner was placed. One hip in the HA-coated group was primarily implanted with a DM liner because of intraoperative stability concerns. No other DM liners were implanted. Excluding these 4 cases, there was no significant difference in the use of neutral or elevated rim liners between the 3 acetabular implants ($\chi^2(2) = 0.532$, $P = .767$). This observation was stable to analyses assuming all 4 cases were neutral or had an elevated rim.

Acetabular screws were used in 25.5% of cases, whenever the operating surgeon judged that the patient would benefit from supplemental initial fixation based on perceived bone quality, fixation surface, degree of bone coverage achieved, or quality of the press fit achieved. Fixation was augmented with a single screw in the majority of these cases (72.9%), but up to 3 screws were used at surgeon discretion. Bone screws were more commonly used with the HA-coated cups (38.5%) than with the NHPT (23.7%, $P = .016$) or CaP-coated (13.6%, $P < .001$) cups.

### *Surgical procedures*

Choice of surgical approach (Table 2) for a given case was influenced by case complexity, obesity, and the techniques and technology available at the time and location of surgery. This resulted in

**Table 2**
Surgical details.

| | NHPT, n = 97 | HA-coated, n = 182 | CaP-coated, n = 184 | Total, n = 463 | $\chi^2$ analysis |
|---|---|---|---|---|---|
| Surgical approach | | | | | $\chi^2(4) = 42.434$, $P < .001$ |
| Posterior, n (%) | 85 (87.6%) | 128 (70.3%) | 124 (67.4%) | 337 (72.8%) | $\chi^2(2) = 14.046$, $P = .001$ |
| Anterior, n (%) | 12 (12.4%) | 37 (20.3%) | 60 (32.6%) | 109 (23.5%) | $\chi^2(2) = 16.171$, $P < .001$ |
| Superior, n (%) | 0 (0.0%) | 17 (9.3%) | 0 (0.0%) | 17 (3.7%) | $\chi^2(2) = 27.248$, $P < .001$ |
| Robot-assisted, n (%) | 88 (90.7%) | 67 (36.8%) | 111 (60.3%) | 266 (57.5%) | $\chi^2(2) = 76.258$, $P < .001$ |
| Surgical procedure, n (%) | | | | | $\chi^2(4) = 2.330$, $P = .675$ |
| Primary THA | 92 (94.8%) | 170 (93.4%) | 178 (96.7%) | 440 (95.0%) | $\chi^2(2) = 2.162$, $P = .251$ |
| Primary THA with additional procedure[a] | 1 (1.0%) | 3 (1.6%) | 1 (0.5%) | 5 (1.1%) | $\chi^2(2) = 1.048$, $P = .592$ |
| Conversion | 4 (4.1%) | 9 (4.9%) | 5 (2.7%) | 18 (3.9%) | $\chi^2(2) = 1.233$, $P = .540$ |
| Cases with elevated liner, n (%) | 24 (24.7%) | 40 (22.5%) | 47 (25.5%) | 111 (24.2%) | $\chi^2(2) = 0.487$, $P = .784$ |
| Cases with screw fixation, n (%) | 23 (23.7%) | 70 (38.5%) | 25 (13.6%) | 118 (25.5%) | $\chi^2(2) = 30.015$, $P < .001$ |

[a] Additional procedures included 3 cases with abductor repair, one with synovectomy and removal of extensive synovial chondromatosis, and one instance of resection of myositis ossificans of the gluteus minimus, all of which were performed at the time of index THA.

statistically significant differences between groups. A posterior approach with posterior soft tissue repair was used in 337 hips and was the most common approach regardless of implant group. It was used more commonly in the NHPT group than the HA-coated ($P = .001$) or CaP-coated ($P < .001$) groups. A fluoroscopically guided anterior approach was used in 109 hips and more frequently used in the CaP-coated group compared with the NHPT ($P < .001$) or HA-coated ($P = .009$) groups. Our techniques for these approaches have previously been described [9,10]. A superior approach, similar to the technique described by Barrett et al. [11], was only used in 17 HA-coated cups, not the NHPT ($P = .001$) or CaP-coated ($P < .001$) cups. Robotic-arm guidance was used in 266 hips, more commonly in the NHPT group than in the CaP-coated ($P < .001$) or the HA-coated ($P < .001$) cups. Our technique for use of the robotic arm has also been described [12].

### *Clinical evaluation*

Medical records were reviewed to assess for any complications and reoperations, including the need for revision surgery. Patients undergoing reoperation were included in the clinical evaluation only if the original acetabular component remained in place at the time of their follow-up. Visits subsequent to any acetabular revisions were excluded from the reported duration of follow-up. A total of 275 hips had minimum 1-year follow-up. For these patients, preoperative and most recent modified Harris Hip Scores (mHHS) were calculated if available [13]. Patients undergoing reoperation were included in the mHHS analysis only if all the original components remained in place at the time of their minimum 1-year follow-up visit.

### *Radiographic evaluation*

Radiographic analysis was performed using the most recent plain films for each patient with minimum 1-year follow-up to assess for signs of acetabular loosening, migration, and osseointegration. Radiographs subsequent to any acetabular revisions were not analyzed. Migration was determined using the criteria described by Nunn et al. [14]. Signs of osseointegration were analyzed using the criteria described by Moore et al. [15]. Assessments of migration and osseointegration were performed on anterior-posterior pelvis radiographs by an adult reconstruction fellow under the supervision and training of an attending adult reconstruction surgeon who reviewed and confirmed scoring for the first 20 cases. The attending surgeon also reviewed any subsequent cases for which questions about scoring or classification arose. In cases where the quality or angle of the anterior-posterior pelvis radiograph limited interpretation, lateral radiographs were also reviewed to confirm the proper interpretation. Anteversion and inclination were calculated for patients who sustained at least one dislocation using the technique described by Widmer [16]. These measurements were all individually verified by an attending adult reconstruction surgeon.

### *Data analysis*

The 3 cohorts were compared with regard to clinical outcomes as measured using the mHHS, radiographic outcomes of migration and osseointegration, and complications, including component reoperations, dislocations, fixation failures, fractures, and infections. Our primary outcomes of interest were acetabular fixation failure and dislocation rates. We compared rates of fixation failure between the 3 implant cohorts, each with a different fixation surface. As the various cups allowed similar bearing utilization in most sizes, we focused our dislocation analysis on 46-millimeter and 50-millimeter diameter cups, where the maximum bearing diameter was markedly impacted by implant brand. We defined the term "transition" cup sizes to refer to acetabular shells of these diameters. We analyzed the risk of dislocation in cups with "transition" sizes that allowed only smaller diameter bearings, compared with the remainder of the study population. Finally, we explored the fate of the primary acetabular cup in patients who underwent reoperation, asking whether the metal shell was revised or retained and if a different choice would have been made had the system offered additional modular bearing options.

SPSS version 25 (IBM Corporation, Yorktown, NY) was used to analyze the data. Intergroup comparisons of continuous variables were assessed via a one-way ANOVA and the Bonferroni Post-Hoc analysis. Chi-square tests were used to assess categorical data. Mixed ANOVA was used to assess the mHHS. A Kaplan-Meier test was used to analyze survivorship of the acetabular components. The significance level was set at $P < .05$.

## Results

### *Clinical outcomes*

Preoperative and most recent mHHS were calculated for patients with minimum 1-year follow-up (Table 3). Patients who underwent reoperation were included in this analysis only if they had a 1-year follow-up visit with the original femoral and acetabular implants still in place. Scores after any revision were excluded. Therefore, this included prerevision scores from one patient who underwent staged revision of both components due to indolent infection greater than 1 year after surgery and from one patient who had a femoral revision for thigh pain. Final follow-up for one patient who underwent removal of a femoral cable was also included because the original components remained in place. All 3 groups showed significant improvement in mHHS at 1-year follow-up after THA ($F(1, 154) = 411.574$, $P < .001$), but there was no difference in improvement between the 3 cups ($F(2, 154) = 0.493$, $P = .612$).

### *Radiographic evaluation*

Radiographic data were analyzed for patients with minimum 1-year radiographic follow-up (mean, 2.5 years; range, 1-6.3 years), which included 72 NHPT, 97 HA-coated, and 99 CaP-coated acetabular cups. This included all patients who had their original acetabular component in place at the time of their most recent radiograph, including one patient who underwent removal of a femoral cable for persistent thigh pain, one patient who had his femoral stem revised for thigh pain more than 4 years after index THA, and one patient who had a superficial infection and wound

**Table 3**
Harrris hip scores.

| mHHS | NHPT, n = 54 | HA-coated, n = 45 | CaP-coated, n = 58 | Total, n = 157 | ANOVA |
|---|---|---|---|---|---|
| Preoperative mHHS, mean (sd) | 40.27 (15.22) | 41.12 (15.55) | 47.30 (15.15) | 43.11 (15.53) | $F(2, 154) = 3.490$, $P = .033$ |
| Most recent mHHS, mean (sd) | 78.55 (19.90) | 76.19 (21.87) | 81.62 (21.92) | 79.01 (21.21) | $F(2, 154) = 0.848$, $P = .430$ |
| Change from preoperative to most recent mHHS, mean (sd) | 38.28 (21.75) | 35.08 (20.74) | 34.32 (23.25) | 35.90 (21.97) | $F(2, 154) = 0.493$, $P = .612$ |

ANOVA, analysis of variance.

dehiscence, requiring incision and drainage and placement of a wound vacuum without revision of implants. For one patient who underwent staged revision of both components due to indolent infection slightly greater than 1 year after surgery, the immediate prerevision radiograph was used. At the most recent follow-up, all acetabular cups were found to be osseointegrated, and there was no evidence of loosening or migration. There was 100% survivorship free of the composite endpoint of radiographic evidence of loosening and revision for mechanical loosening for all cementless acetabular cups, regardless of fixation surface.

*Complications and reoperations*

Table 4 shows complications and reoperations. One patient in the HA-coated group had a small nondisplaced intraoperative acetabular fracture; screw fixation was used to augment initial stability. The patient was allowed to bear weight as tolerated and had uneventful bone healing and component osseointegration.

Reoperation occurred in 2.6% of hips, with no difference between cohorts ($\chi^2(2) = 0.241$, $P = .886$). The acetabular cup was revised in 1.3% of hips and did not differ between cohorts ($\chi^2(2) = 1.399$, $P = .497$). There were no reoperations for cementless acetabular fixation failure in any of the 3 cohorts. The occurrence of postoperative infection was 0.9% and did not differ between cohorts ($\chi^2(2) = 0.370$, $P = .831$). While not the focus of this study, early complications associated with cementless femoral fixation, including failure of osseointegration and periprosthetic fracture, occurred in 1.1% of cases. These were the most common indications for reoperation, but did not differ between cohorts ($\chi^2(2) = 0.003$, $P = .999$). One additional patient with a NHPT cup underwent removal of a femoral cable at an outside hospital to address residual hip area pain. The cable had been placed to stabilize a nondisplaced intraoperative calcar fracture and was not prominent or fractured. The femur healed uneventfully after the primary THA with normal osseointegration and no implant subsidence. Another patient, in the HA-coated group, underwent a revision of his well-fixed femoral stem at an outside hospital for thigh pain more than 4 years after THA.

Dislocation occurred in 6 cases (1.3%), and the rate of hips suffering dislocations did not differ between groups ($\chi^2(2) = 1.399$, $P = .497$). Two cases each experienced a single dislocation episode in the early postoperative period. They were treated with closed reduction without subsequent recurrence. The other 4 hips (0.9%) developed recurrent dislocations resulting in revision surgery. These were the only cases requiring isolated acetabular revision; the rate of these revisions did not significantly differ between the cohorts ($\chi^2(2) = 3.318$, $P = .190$). Mean inclination for all 6 dislocations was 42.1 degrees (range = 37.2-46.2 degrees), and the mean anteversion was 21.6 degrees (range = 18.1-24.8 degrees). All acetabular components with dislocations were within the Lewinnek "safe" zone [17]. Four of the 6 patients with dislocations had significant concomitant spinal pathology, including 2 patients with severe multilevel lumbar degenerative disc disease, one patient with a history of multiple spinal procedures, and one patient with a previous compression fracture of T12. The remaining 2 patients with dislocations had mild lumbar degenerative disc disease seen on radiographs, but no documentation of associated clinical symptoms or physical findings. We were unable to compare the incidence of spinal pathology in patients with and without dislocation as data on concomitant spinal disorders were not consistently collected during the study period. Post-hoc analyses showed no association between dislocation risk and age (mean = 56.7 years, $F(1, 461) = 1.048$, $P = .307$), gender ($\chi^2(1) = 0.295$, $P = .698$), BMI ($F(1, 461) = 0.138$, $P = .710$), diagnosis ($\chi^2(6) = 8.842$, $P = .183$), surgical approach ($\chi^2(2) = 2.273$, $P = .321$), or use of robotic assistance ($\chi^2(1) = 1.666$, $P = .247$). We found no increased risk of dislocation in THA for femoral neck fractures ($\chi^2(1) = 1.121$, $P = .323$) or with conversion from percutaneous hip procedures ($\chi^2(1) = 0.246$, $P = 1.000$). It is important to note that this study was not specifically powered for these post-hoc analyses, and therefore, such relationships cannot be excluded.

All 4 revisions for dislocation occurred with components that did not accept DM or constrained liner options. Although this observed trend did not reach statistical significance ($\chi^2(1) = 2.613$, $P = .158$), it did influence the options available at the time of revision surgery. As previously noted, all 4 revisions for dislocation occurred with "well-positioned" acetabular components placed within the Lewinneck "safe zone" [17]. Indeed, all 4 cases would have been treated with shell retention and revision to a constrained or DM liner had the option been available. Instead, 3 well-positioned shells were revised to expand liner options: One received a 40-millimeter bearing (Fig. 1), another received a DM bearing, and the third received a constrained bearing. None of these cases recurred. In one case with preoperative acetabular bone loss, the well-fixed metal shell was retained, and an elevated rim liner was placed along with a longer femoral head. Unfortunately, the hip became infected within 2 months. There was no recurrence of dislocation before all components were removed as part of a two-stage exchange arthroplasty.

Two of the 4 cases of recurrent dislocation resulting in revision developed after reoperations to address femoral complications. One case was a cementless primary THA for osteonecrosis after which the femoral component was revised for subsidence and varus angulation. The other was a cementless primary THA and abductor repair for chronic pathologic fracture of the femoral neck and complete abductor rupture. The femoral component was revised for

**Table 4**
Complications, reoperations, and revisions.

| | NHPT, n = 97 | HA-coated, n = 182 | CaP-coated, n = 184 | Total, n = 463 | $\chi^2$ analysis |
|---|---|---|---|---|---|
| Intraoperative acetabular fractures, n (%) | 0 (0.0%) | 1 (0.5%) | 0 (0.0%) | 1 (0.2%) | $\chi^2(2) = 1.547$, $P = .461$ |
| Acetabular components revised,[a] n (%) | 2 (2.1%) | 1 (0.5%) | 3 (1.6%) | 6 (1.3%) | $\chi^2(2) = 1.399$, $P = .497$ |
| Hips with one or more dislocations, n (%) | 2 (2.1%) | 1 (0.5%) | 3 (1.6%) | 6 (1.3%) | $\chi^2(2) = 1.399$, $P = .497$ |
| Acetabular revisions for recurrent dislocation, n (%) | 2 (2.1%) | 0 (0.0%) | 2 (1.1%) | 4 (0.9%) | $\chi^2(2) = 3.318$, $P = .190$ |
| Acetabular revisions for fixation failure, n (%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | 0 (0.0%) | N/A |
| Reoperations for infection, n (%)[a] | 1 (1.0%) | 2 (1.1%) | 1 (0.5%) | 4 (0.9%) | $\chi^2(2) = 0.370$, $P = .831$ |
| Revision of components for infection, n (%) | 1 (1.0%) | 1 (0.5%) | 1 (0.5%) | 3 (0.6%) | $\chi^2(2) = 0.280$, $P = .870$ |
| Superficial debridement without revision of components, n (%) | 0 (0.0%) | 1 (0.5%) | 0 (0.0%) | 1 (0.2%) | $\chi^2(2) = 1.547$, $P = .461$ |
| Reoperation for femoral fixation failure ± periprosthetic fracture | 1 (1.0%) | 2 (1.1%) | 2 (1.1%) | 5 (1.1%) | $\chi^2(2) = 0.003$, $P = .999$ |
| Reoperation for thigh pain without fixation failure, n (%) | 1 (1.0%) | 1 (0.5%) | 0 (0.0%) | 2 (0.4%) | $\chi^2(2) = 1.666$, $P = .435$ |

[a] Three cases underwent either 1-stage or 2-stage revision of all implanted components. One case had 2 procedures without revision of the components to address a superficial wound dehiscence without deep infection.

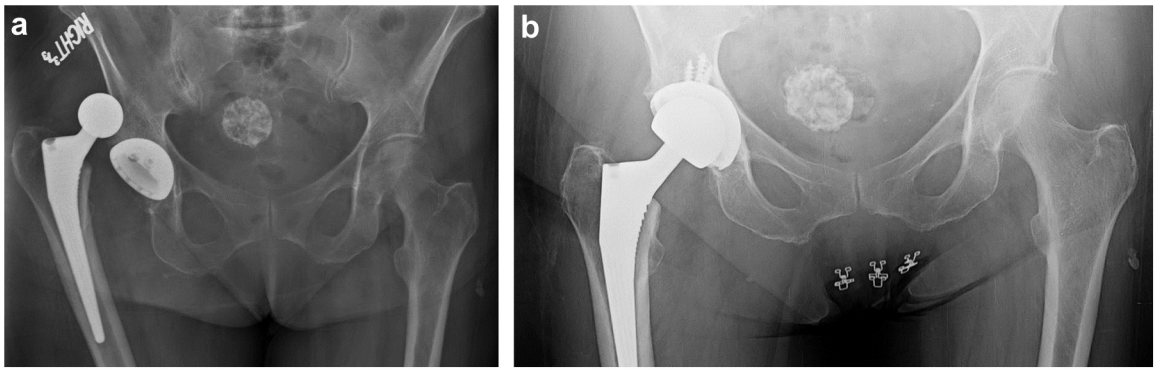


**Figure 1.** Recurrent posterior hip dislocation in a patient with well-positioned implants (a) that did not accept large diameter, dual mobility, or constrained bearings resulted in acetabular component revision (b) to expand bearing options.

subsidence and periprosthetic fracture. Over the entire population, the risk of dislocation subsequent to early femoral revision for fixation failure andperiprosthetic fracture was 2 out of 5 (40.0%) compared with dislocation without any femoral intervention (2 out of 458, 0.4%, $P < .001$). Abductor deficiency resulting in concomitant abductor repair at the time of primary THA was also associated with a risk for dislocation (1 out of 3, 33.3%, ($\chi^2(1) = 24.230$, $P = .038$) and revision for recurrent dislocation ($\chi^2(1) = 37.169$, $P = .026$).

"Transition" cup sizes, which we defined as 46 millimeters and 50 millimeters, accepted bearings of varying diameters depending on the shell selected. For hips implanted with a "transition" size, a small bearing was defined as 28 millimeters in a 46-millimeter cup and 32 millimeters in a 50-millimeter cup. A large bearing was defined as 32 millimeters in a 46-millimeter cup and 36 millimeters in a 50-millimeter cup. Excluding 7 hips with records missing information on cup and bearing diameters, "transition" sizes were used in 19.5% of cases. We classified the one hip with an DM articulation as having a large bearing, based on the outer bearing diameter. However, our statistical findings were unchanged on a confirmatory analysis classifying bearing diameter by femoral head size. Of the 6 hips that sustained dislocations, 3 dislocations occurred in cases where a small bearing was implanted in a "transition" size, resulting in a 4.6% rate of dislocation in patients implanted with a small bearing in a "transition" size. Hips implanted with a small bearing in a "transition" size were significantly more likely to sustain a dislocation than hips in all other patients ($\chi^2(1) = 6.356$, $P = .040$). Fifteen cases implanted with a small bearing in a "transition" size nevertheless had a larger bearing available, implying that the surgeon did not perceive the need for additional stability at the primary surgery. None of these hips dislocated. Furthermore, the incidence of dislocation (3 of 50 hips, 6.0%) was significantly higher for cases implanted with a "transition" cup that would only accept a small bearing than for all other hips (0.7%, $\chi^2(1) = 9.490$, $P = .020$). Conversely, neither head size alone ($F(1, 454) = 0.087$, $P = .768$) nor the ratio of the acetabular cup to the prosthetic head diameter ($F(1, 454) = 0.043$, $P = .836$) was observed to be an independent risk factor for recurrent dislocation across the spectrum of acetabular sizes. There was no difference in dislocation risk with respect to the use of an elevated liner ($\chi^2(1) = 0.187$, $P = 1.000$), the surgical approach ($\chi^2(2) = 2.273$, $P = .321$), or the use of robotic guidance ($\chi^2(1) = 1.666$, $P = .247$).

*Survivorship analysis*

A Kaplan-Meier analysis revealed no difference in survivorship when comparing the 3 acetabular components for rates of revision for all indications ($\chi^2(2) = 1.230$, $P = .541$) (Fig. 2).

## Discussion

Despite differences in demographics, fixation surfaces, and bearing diameters (Table 1), all 3 cohorts had similar clinical results and improvement from their preoperative status in terms of mHHS (Table 4). We were unable to identify any studies directly comparing clinical outcomes with these models of acetabular cups, but comparable clinical outcomes are expected with modern acetabular components when reliable fixation is achieved.

All 3 acetabular cups had 100% 1-year survivorship free of revision for failure of acetabular fixation, and there were no subsequent cases of acetabular loosening. Supplemental screw fixation was used more commonly in the HA-coated group ($P < .001$), so we could not determine whether the 3 surfaces would have been equally effective at achieving fixation without screws. The HA-coated acetabular cup has been available for almost 15 years and has been extensively studied with published results showing 98.5%-100% survivorship free of acetabular loosening at 1-8.8-year follow-up [18-21]. It has also received an Orthopedic Data Evaluation Panel (ODEP) 10A* rating with the current generation of highly crosslinked polyethylene liners [22]. The ODEP is an independent panel of surgeons who evaluate the outcomes of patients undergoing joint replacements for each available prosthesis based on data from the National Joint Registry of England and Wales. The recommendations are regularly updated to evaluate the longevity of each implant [23]. Several studies of THAs performed with the CaP-coated cup have reported outcomes focused on the corresponding femoral stem or the precision of the robotic platform used for acetabular component placement [24-28]. While these studies have not documented unexpected acetabular failure [24-27] and the acetabular implant has an ODEP 7A* rating [29,30], we were unable to identify published studies in the peer-reviewed literature specifically documenting the reliability or durability of the CaP-coated cup's fixation. One study, which used the CaP-coated cup in 189 hips with minimum 1-year follow-up (mean = 37 months), did not report any revisions to the acetabular cup [24]. Two additional studies reported no acetabular failures in 73 patients at a follow-up of 495 ± 281 days [25] and 138 patients with a median follow-up time of 42 months (range, 30-56 months) [26]. One series reported one acetabular revision out of 378 cases at 90-day follow-up [27]. We are aware of one other study investigating the fixation of the NHPT cup, which combined 39 of the cases from the NHPT cohort in this study with other hips from 2 different centers. The study documented reliable fixation of the NHPT cup at short-term minimum 1-year follow-up [31]. Cases included in that series were re-reviewed before inclusion in the current analysis. While all 3 acetabular cups have similarities to previously studied implants,

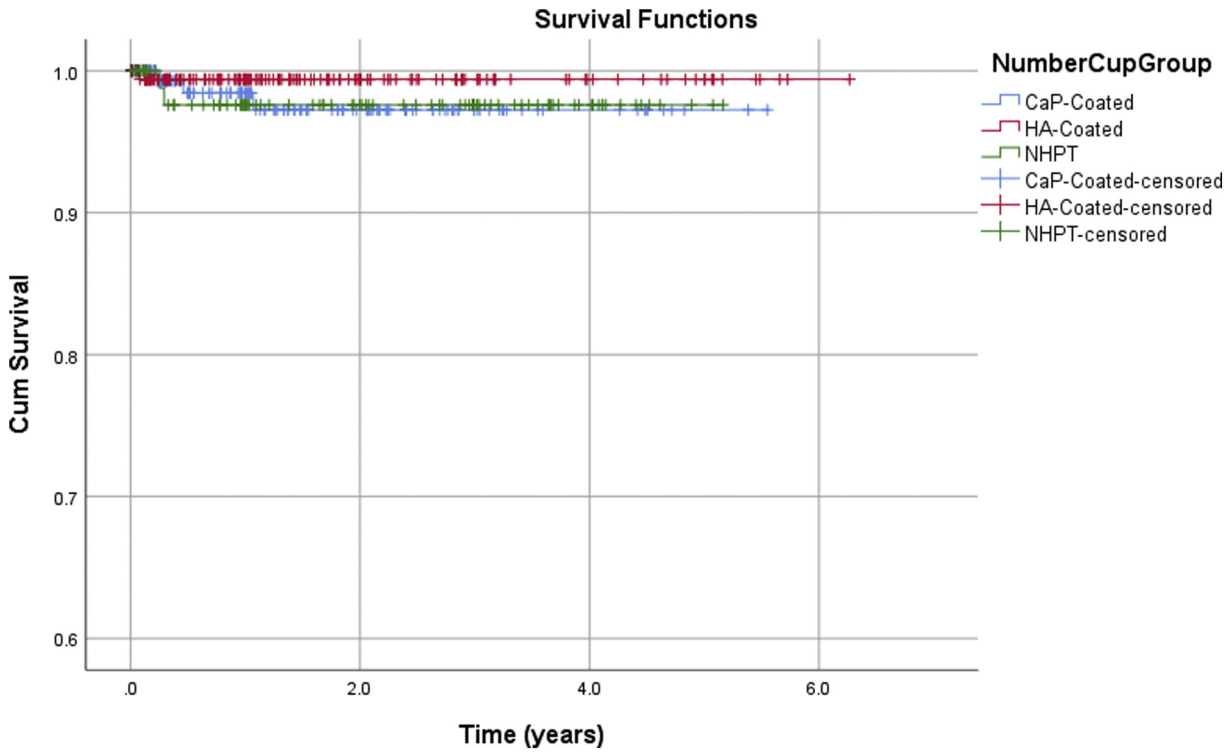


**Figure 2.** Kaplan-Meier curve for acetabular revisions for all indications.

it is impossible to know the true fixation performance of a novel implant without longer term in vivo studies.

Aseptic loosening has been reported to be the most common reason for acetabular revision [32]. However, the majority of such cases may relate to osteolysis, polyethylene wear, or repeat revision surgery, rather than representing failures of established fixation surfaces [33]. Conversely, we are not aware of compelling data suggesting that novel fixation surfaces are sufficient to overcome technical issues with bone preparation or component insertion that result in inadequate stability during primary surgery and subsequent fixation failure. We did not observe failure of acetabular component osseointegration to be a common cause of early mechanical failure. Although the HA-coated acetabular cup has an "ongrowth" rather than "ingrowth" surface, it performed equally to "new and improved" ingrowth acetabular cups with regard to osseointegration. Our results suggest patients undergoing primary or conversion THA in the absence of acetabular bone loss may not gain additional benefit from an acetabular cup with a "new and improved" surface. While patients with significant acetabular bone loss were represented in each of the cohorts studied, they were not separately analyzed or included in quantities sufficient to extrapolate our findings to that population.

Overall, there was a 98.7% acetabular component survivorship, and there was no difference between cohorts ($P = .541$). The only indication for revision of the acetabular component was recurrent dislocation or infection (Table 4). Four hips in the 2 groups without constrained or DM options (NHPT and CaP-coated cohorts) underwent revision surgery for recurrent dislocation. In all 4 cases, the component was well positioned within the safe zone, and a constrained or DM liner revision would have been selected were it an option. Patients were significantly more likely to sustain a dislocation if they previously had a revision of the femoral component for fixation failure and periprosthetic fracture. While this association is consistent with previously published studies, our data suggest a higher risk than that previously reported [34-37]. The low number of femoral revisions makes our estimate of risk imprecise, but this finding may warrant further study.

We defined a new term, "transition" cup sizes, referring to 46- and 50-millimeter diameter cups. In the interest of preserving polyethylene liner thickness, different shell thicknesses at these diameters may influence maximum bearing diameter. Therefore, thicker highly porous cups may only have smaller bearings available than thinner cups that may have an "ongrowth" surface, such as the HA-coated cup. While the maximum head diameter available for a particular cup diameter may influence acetabular component selection, we were unable to find any peer-reviewed literature exploring this concept.

Large-diameter and DM bearings offer the flexibility to address deficient stability at the time of primary THA, and this may reduce the risk of subsequent dislocations. We observed higher rates of dislocation when small bearings were used with "transition" sizes ($\chi^2(1) = 6.356$, $P = .040$), a choice mandated by 2 of the acetabular shells studied and by several highly porous implants on the market. The lowest rate of dislocation was observed with the cup that allowed the use of the largest diameter bearings for a given cup diameter, along with DM and constrained liners. Although this did not approach statistical significance ($\chi^2(2) = 1.399$, $P = .497$), when examined across all implant sizes, the available bearing diameters did not differ in all cup sizes. We therefore focused our dislocation analysis on 46- and 50-millimeter "transition" cups, for which bearing diameters varied between implants. The dislocation rate in "transition" sizes with only small bearings available (6%) was significantly higher than that in the general population (0.7%, $\chi^2(1) = 9.490$, $P = .020$).

Several other studies have documented significant associations between dislocation risk and bearing diameter or ratio of cup to bearing diameter, [38-42] but not all studies have confirmed this observation [43]. Although we did not find a statistically significant association between dislocation risk and bearing diameter, ratio of cup to bearing diameter, or implant brand across the range of

implant sizes, this retrospective study was confounded by selection bias. Patients preoperatively perceived to be at increased dislocation risk preferentially received the brand of implant that allowed the use of a larger bearing in smaller cups, DM, and constrained liners. When multiple bearing diameters were available for a given cup, smaller diameter bearings were used only if intraoperative stability was considered excellent. Indeed, there were no dislocations in 15 cases where the surgeon selected a 32-millimeter or smaller bearing despite the availability of a 36-millimeter or larger head for the acetabular brand and diameter used. The diameter of the largest bearing available for a "transition" size was a better predictor of dislocation risk than was the diameter of the bearing actually implanted. Similar selection bias may also affect other studies retrospectively investigating dislocation risk.

There were no dislocations when the anterior (n = 109) or superior (n = 17) approach was used. Posterior approach cases (n = 337) had a 1.2% dislocation rate after index THA (1.8% when including dislocations subsequent to isolated femoral revision), which is on the lower end of commonly reported range [41,43-47]. Dislocation risk was not significantly associated with surgical approach or with the tools used to guide implant positioning (robotics, fluoroscopy, or manually unguided). Nevertheless, this underpowered analysis should not be taken to say that no such association exists. The lack of such demonstrable associations suggests that the observed association between dislocation rate and available bearing diameter in "transition" sizes was not mediated by these potentially confounding variables. Indeed, the finding remained statistically significant when nonposterior approaches were excluded.

Both our data and published evidence suggest there are risks associated with the use of novel acetabular cups. These risks relate to both unproven fixation surfaces and limited bearing options. While all implants in this study achieved reliable osseointegration, some novel cups have demonstrated higher than expected rates of radiolucent lines or fixation failure [5,20,48,49]. Well-fixed and well-positioned implants that lack constrained or DM liners may require revision to expand liner options in the event of recurrent dislocation. This occurred in 3 patients who required revision for recurrent dislocation. In the remaining case, the surgeon settled for revision to a lipped liner to avoid removing a stable cup placed in the setting of bone loss, even though a bearing with greater stability would have been preferred.

Similar to any retrospective study, our study has other limitations which must be acknowledged. We included only the 3 cementless acetabular implants used most commonly by one surgeon during the study period, which may limit the generalizability of our findings to other implants and to techniques used by other surgeons. However, this should be balanced by the inclusion of multiple surgical approaches and technologies, increasing external validity but decreasing internal validity. Implant selection was not randomized, which may have introduced bias to our analysis. While there were significant differences between implant cohorts with respect to demographics and surgical approach, subsequent analyses showed that these factors were not associated with the risk of postoperative complications or acetabular component survivorship. Incomplete follow-up means we could be missing complications. Mean follow-up of 1.6 years allowed us to assess the incidence of early fixation failure but not late loosening. Additional follow-up will be necessary to assess long-term outcomes. Furthermore, the small number of mechanical failures in each group results in limited power for statistical comparison between groups and leads to imprecision in our estimates of effect size. While recent publications suggest that spinopelvic mobility may play an important role in dislocation risk, routine preoperative assessments of spinopelvic mobility were unavailable during the study period.

## Conclusions

All acetabular revisions for mechanical failure in this series were related to instability, while none were related to acetabular fixation, calling into question the need for novel cementless fixation surfaces in uncomplicated primary THA. Published data support the influence of bearing diameter on dislocation risk, [38-42] and our experience suggests this may be particularly important in "transition" sizes, where bearing diameter may be driven by availability rather than surgeon judgment. Subsequent to this experience and analysis, we are wary to select "new and improved" acetabular cups that do not have options for constrained or DM liners, even when enabling technology makes us confident of safe-zone placement. We further preferentially use acetabular implants that allow the use of large-diameter bearings in "transition" sizes. Finally, the most common causes of reoperation in this cohort were complications related to femoral fixation. Early femoral revision was also a risk factor for subsequent dislocation. Subsequent to reviewing these data, we have increased utilization of cemented femoral stems in osteopenic patients and have begun selectively using collared cementless stems to mitigate the risk of cementless femoral implant subsidence.

## Conflict of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: One or more of the authors has recently performed consulting for Corin U.S.A., Exactech, Inc., and Stryker. One of the authors has recently received institutional and direct research support from Stryker. One of the authors has received or is entitled to receive royalties from Corin U.S.A. and Exactech, Inc.

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