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Original Research

The Fate of Zone 2 Radiolucencies in Contemporary Highly Porous Acetabular Components: Not All Designs Perform Equally

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ABSTRACT

Background: The enhanced frictional resistance of modern ultraporous acetabular components can impede complete seating; however, surgeons expect the enhanced ingrowth surface to resolve polar (zone 2) gaps over time via osseointegration. This study characterized zone 2 radiographic osseointegration in 3 acetabular component designs: 2 highly porous ingrowth and one traditional ongrowth.

Methods: A consecutive cohort of primary total hip arthroplasties was reviewed which utilized 3 different acetabular cup designs: ongrowth titanium with hydroxyapatite (HA), highly porous titanium with machined radial grooves (MRG), and dual-porous titanium substrate with micropore (MP). Radiographic analysis was performed using accepted measurement criteria with particular attention to radiolucent lines.

Results: Seven hundred ninety cases were available for analysis. Initial 1-month radiographs revealed 43.2% of HA, 78.2% of MRG, and 81.0% of MP cups exhibited zone 2 radiolucencies, consistent with incomplete seating. At 1 year, all HA radiolucencies resolved, whereas 46.2% and 34.7% of radiolucencies remained in MRG and MP cups, respectively ($P \leq .005$). At minimum 2 years, a significant proportion of zone 2 radiolucencies remained in 46.0% of MRG compared with 23.9% of MP cups and 3.0% of HA cups ($P \leq .007$).

Conclusion: The resolution of zone 2 radiolucencies at 1-year and minimum 2-year follow-up signified osseointegration for nearly all HA and most MP cups. Highly porous titanium cups with machined radial grooves demonstrated persistent zone 2 radiolucencies at 1 year and beyond. Given reports of early loosening with this particular acetabular implant, further follow-up is warranted as this study highlights that not all contemporary highly porous metal acetabular components perform equally.

Level of Evidence: III.

Introduction

Modern total hip arthroplasty (THA) typically uses cementless acetabular components, with implantation occurring via an interference fit (or press-fit) technique to create mechanical stability of the outer porous surface against native bone. Contemporary acetabular component surfaces have evolved to now include highly porous metals of either titanium or tantalum in hopes of enhancing osseointegration thereby minimizing the incidence of aseptic loosening and extending implant longevity. A desired characteristic of highly porous metal surfaces is the increased coefficient of friction [1,2], which optimizes the interference fit and subsequent mechanical stability against host bone; however, increased frictional resistance may create difficulty fully seating the hemispherical implant depending on the degree of interference fit or manufacturer tolerance between the reamer and final implant. Incomplete seating of the acetabular component and its resultant lack of apposition with host bone is particularly prevalent at the apex of the hemispherical cup known as zone 2 in the DeLee and Charnley radiographic classification [3].

The initial presence and eventual resolution of polar zone 2 gaps around acetabular cups have been documented with earlier generation cementless designs in which porous titanium and porous tantalum cups have reported good to excellent stability and bony osseointegration [4-10]. These data have provided reassurance when

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leaving a small in vivo polar gap and to avoid overimpacting which can cause deleterious peri-prosthetic acetabular fracture [11]. However, for contemporary, ultraporous titanium acetabular designs, there is a paucity of data on radiolucent line resolution, partially because long-term data are not yet available for many of these modern designs. Consequently, it is important to evaluate short-, mid-, and long-term results to clinically validate adoption, which is currently based largely on successful biomechanical and basic science studies [1,2,12-17]. The purpose of this study was to characterize zone 2 osseointegration via radiographic analysis in 2 highly porous ingrowth and one traditional ongrowth acetabular component designs.

Material and methods

A retrospective review of 888 primary THAs was performed with institutional review board approval. All THAs were performed between August 2010 and November 2018 by a single surgeon. Ninety-eight cases were excluded because of potential confounds: acetabular protrusion (11 cases), surgery performed for fractures around the acetabulum (5 cases), acetabular deformity or excessive hardware removal around acetabulum (5 cases), dysplasia (28 cases), avascular necrosis (7 cases), patients with known recurrent instability or dislocations (2 cases), prior osteotomy (1 case), arthrogryposis (1 case), direct anterior approach (2 cases), cases which required a deep irrigation and debridement with component retention or resection after the index primary (16 cases), younger than 18 years (3 cases), surgery required hardware that obstructed the view of the bone implant interface (6 cases), resulted in aseptic revision of acetabular component within 1 year of index case because of component not growing into fragmented acetabulum (1 case), dislocation requiring revision (2 cases), deaths unrelated to surgery within 1 year of surgery (1 case), and no radiographs at 1 month (7 cases) resulting in a final sample size of 790 cases for analysis.

Surgical technique

All THAs were performed by a single fellowship-trained, high-volume surgeon at an academic destination center for hip and knee arthroplasty. The posterolateral approach was used in all cases with the patient in a lateral decubitus position. All acetabular components were of hemispherical, modular design and implanted with a consistent surgical technique. An initial reamer of size 5 mm smaller in diameter than the anticipated acetabular implant size was chosen based on preoperative templating. The acetabulum was reamed with progressively larger reamers until an odd numbered diameter reamer removed sufficient bone to visualize punctate bleeding in the subchondral bone. This enabled an anticipated 1-mm interference fit between the reamed acetabular diameter and the actual implant. However, if the cup was unable to be seated to within 1 mm of full seating as visualized through the dome hole, the acetabular cup was removed, and an identically size reamer to the implant was used in a “line-to-line” fashion to allow full seating of the implant against host bone at the dome of the component as visualized through the dome hole. Manual force of the acetabular component insertion handle was used to ensure mechanical stability of the implant, and if judged suboptimal because of inadequate press-fit or poor bone quality, 2 divergent cancellous screws were placed to provide adjuvant fixation. Furthermore, if a polar gap occurred but the cup was mechanically stable with extreme leveraging force required for attempted cup removal that bent the insertion handle, the cup was left implanted assuming the cup position was acceptable. Over time during a learning curve, it was discovered that the MP acetabular component was best implanted with a “line-to-line” reaming technique which predictably allowed more complete seating, as well as enhanced mechanical stability, in the majority of these particular implants. Highly cross-linked polyethylene liners were used in all acetabular components. Target acetabular component position was 45° abduction and 25° anteversion.

Data collection

Demographic data of age, sex, height (in cm), weight (in kg), and body mass index (BMI, in kg/m^2) were recorded from our institution’s internal medicine specialist’s history and physical note whose practice focuses exclusively on total joint arthroplasty patients. Surgical details including acetabular cup type and size; femoral head size; and use of acetabular screws were recorded from the electronic medical record via scanned documents of the implant manufacturer labels after each case.

Radiolucent lines were recorded at 1 month, 1 year, and at a minimum of 2 years by a single rater within a digital radiograph database (Synapse, Fujifilm Medical Imaging, Tokyo, Japan). All radiographs were taken by a trained radiology technician using an identical protocol. Radiolucent lines were categorized using DeLee and Charnley zones [3] on anteroposterior view pelvic radiographs. In particular, radiolucent lines in zone 2 of the DeLee and Charnley classification were recorded as a percentage of each zone, and the thickness measured in millimeters as previously reported in the orthopedic literature [18,19]. A digital ruler was calibrated within the radiograph system using the known size of the femoral head to ensure accurate linear measurement of the radiolucent line dimensions. If the radiolucent line was too small to accurately measure the thickness, it was recorded as “less than 1 mm.” Radiolucent lines were then categorized into “yes” (ie, presence of a zone 2 radiolucent line) or “no” (ie, no zone 2 radiolucent line) categories regardless of size or percentage for data analysis.

Data analysis

Minitab 19 (State College, PA) was used for statistical analyses. Means of 2 groups were compared with an unpaired 2-sample *t*-test (t), while means of 3 or more groups were compared with a one-way analysis of variance (ANOVA, F). Pearson’s Chi-Square (χ^2) test was used to evaluate the independence among categorical variables with a significance level of 0.05, and Fisher’s *P* reported for 2 × 2 contingency tables. If cell counts were low, Yates’ correction was used. Multivariate analysis was attempted but was unable to be performed because of quasi-complete separation of data. A significance level of 0.05 was used for all statistical analyses.

Results

The cohort was 53% (421/790) female with mean age and BMI of 63.1 years (standard deviation 11.8, range 18.1 to 89.9) and 30.7 kg/m^2 (standard deviation 6.3, range 14.5 to 53.7), respectively. Acetabular bone screws were used in 18% (145/790) of cases. Femoral head sizes ranged from 22 mm to 44 mm, and acetabular cup sizes ranged from 46 mm to 64 mm. THAs were categorized by acetabular component type as follows (Fig. 1; top to bottom): 44 (5.6%) ongrowth porous titanium cups with hydroxyapatite coating (“HA”; Trident, Stryker, Mahwah, NJ), 377 (47.7%) highly porous titanium cups with machined radial grooves (“MRG”; Tritanium, Stryker, Mahwah, NJ), and 369 (46.7%) dual-porous titanium cups with micropore (“MP”; FMP, DJO Global, Vista, CA).

The mean age did not differ between the 3 acetabular component types (Table 1; $P = .226$). Mean BMI was significantly higher for MP than for MRG cups only (Table 1; 31.3 vs 30.2 kg/m^2, $P = .030$). While the difference was statistically significant, the mean difference was only 1.1 kg/m^2 and therefore did not

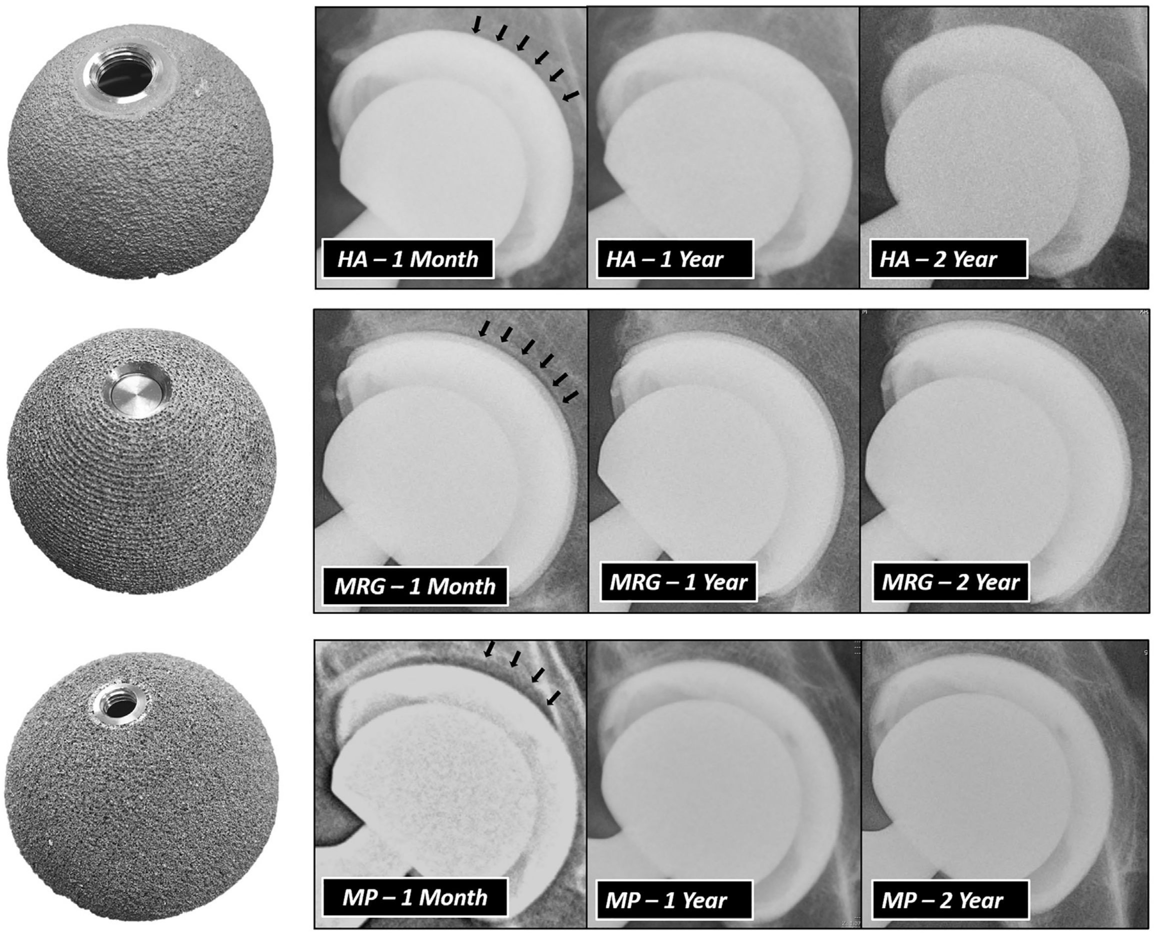

Figure 1. (Left panel) Three modern acetabular cup designs with different osseoconductive materials and manufacturing processes. (Top to bottom) HA – highly-porous titanium with HA coating, MRG – highly-porous titanium with machined radial grooves, and MP – highly-porous titanium substrate with titanium micropores. (Right 3 panels) Evolution or disappearance of radiolucent lines in the same patient for the 3 cup designs.

represent a clinically meaningful difference. Furthermore, BMI did not have an effect on the presence of radiolucent lines at 1 month, 1 year, or minimum 2 years ($P \geq .143$). As expected, there was a significantly higher proportion of females for the HA cup group (Table 1; $P < .001$) than for both MP and MRG cups as this design accommodates smaller cup sizes and therefore smaller acetabula (ie, typically female patients). However, there was no difference in the proportion of zone 2 radiolucent lines between females and males at 1 month, 1 year, or minimum 2 years ($P \geq .267$) and therefore can be determined that the difference in gender proportion among cup designs did not influence the presence of zone 2 radiolucent lines.

MP cups used significantly less acetabular screws than both MRG and HA cups (Table 1; $P < .002$) because of the surgeon's evolution of avoiding adjuvant screw fixation with highly porous metal fixation. While cups with acetabular bone screws had significantly less zone 2 radiolucent lines than the group without acetabular bone screws at 1 month ($P = .002$), there was no difference in the proportion of radiolucent lines between these groups at 1 year or minimum 2 years ($P \geq .328$).

Table 1
Acetabular cup design comparison.

		MRG	MP	HA	Test statistic	*P*
N		377	369	44	–	–
Age (years)		62.4	63.9	63.2	F = 1.5	.226
BMI (kg/m^2)		30.2[a]	31.3[b]	30.5[ab]	F = 3.5	**.030**
% Female		53%[b]	49%[b]	91%[a]	$\chi^2 = 28.0$	**<.001**
Use of screws		26%[a]	7%[b]	43%[c]	$\chi^2 = 63.8$	**<.001**
Zone 2 radiolucent lines	N	MRG	MP	HA	Test statistic	*P*
One mo	790	78.2%[a]	81.0%[a]	43.2%[b]	$\chi^2 = 32.6$	**<.001**
One y	608	46.2%[a]	34.7%[b]	0.0%[c]	$\chi^2 = 33.1$	**<.001**
Min. 2 y	406	46.0%[a]	23.9%[b]	3.0%[c]	$\chi^2 = 34.7$	**<.001**

χ^2, chi-square test; BMI, body mass index; F, ANOVA test.
Bold *P* values indicate statistical significance below .05. Groups that do not share a superscript letter are significantly different.

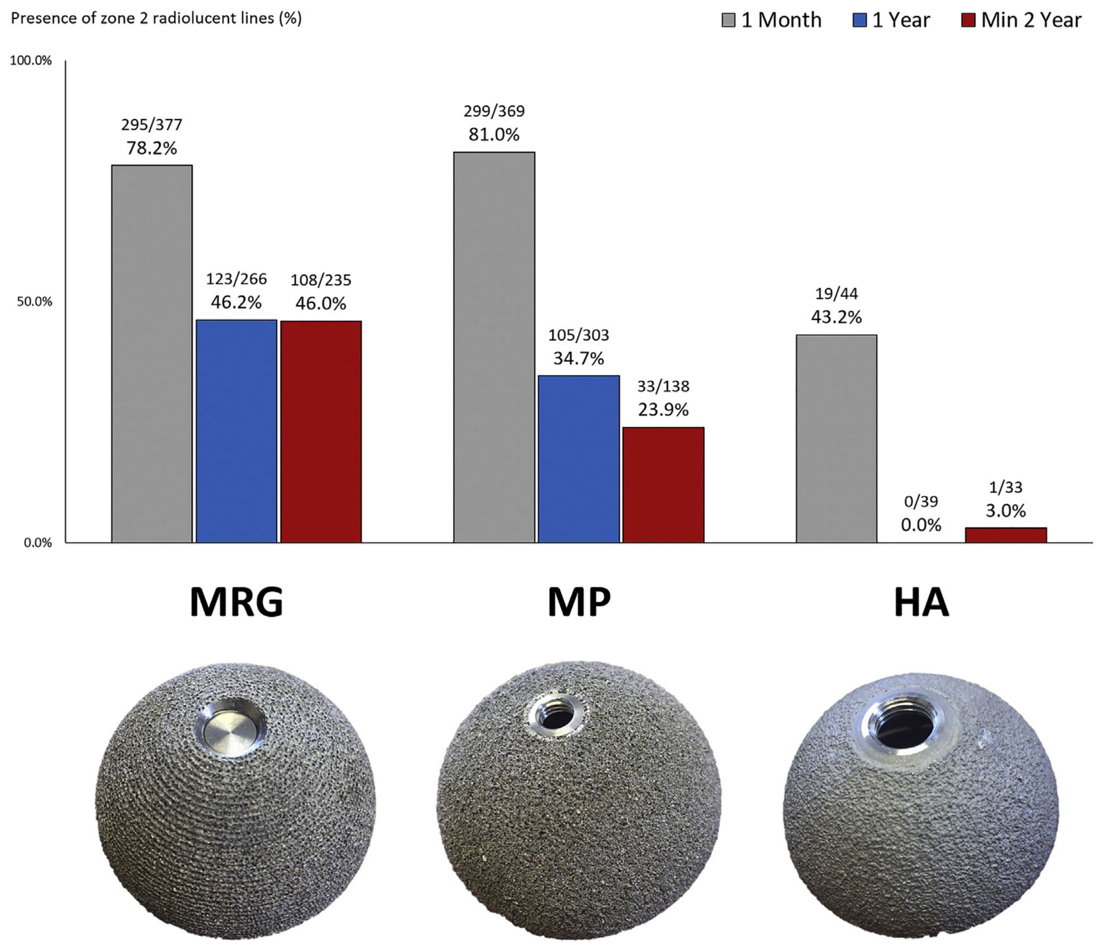

Figure 2. Proportion of zone 2 radiolucent lines at one-month, one-year, and minimum two-years. At one-year and minimum two-year follow-up, all three cup designs exhibited significantly different proportions of zone 2 radiolucent lines.

One-month results

Seven hundred ninety cases obtained 1-month radiographic follow-up and were analyzed. Overall, 77.6% (613/790) of cups showed a zone 2 radiolucent line of any dimension at 1 month. Of all, 43.2% (19/44) of HA cups, 78.2% (295/377) of MRG, and 81.0% (299/369) of MP had a zone 2 radiolucent line (Fig. 2). HA cups had a significantly lower proportion of zone 2 radiolucent lines than MRG and MP cups (Fig. 2; $P < .001$); however, MRG and MP cups did not differ significantly in the proportion of zone 2 radiolucent lines at 1 month (Fig. 2; $P = .346$).

One-year results

At 1 year, 608 cases obtained 1-year radiographic follow-up. All 3 acetabular cup design groups showed a decrease in the proportion of zone 2 radiolucent lines from 1 month (Fig. 2). Overall, 37.5% (228/608) of cups showed persistent zone 2 radiolucent lines of any dimension at 1 year. Of all, 46.2% (123/266) of MRG, 34.7% (105/303) of MP, and 0.0% (0/39) of HA cups had zone 2 radiolucent lines at 1 year (Fig. 2). All 3 cup designs were significantly different from one another with respect to the proportions of zone 2 radiolucent lines at 1 year (Fig. 2; $P \leq .005$).

Minimum 2-year results

At minimum 2 years, 406 cases obtained minimum 2-year radiographic follow-up. Overall, 35.0% (142/406) of cups showed persistent zone 2 radiolucent line of any dimension at minimum 2 years. Of all, 46.0% (108/235) of MRG, 23.9% (33/138) of MP, and 3.0% (1/33) of HA cups had zone 2 radiolucent lines at minimum 2 years (Fig. 2). All 3 cup designs were significantly different from one

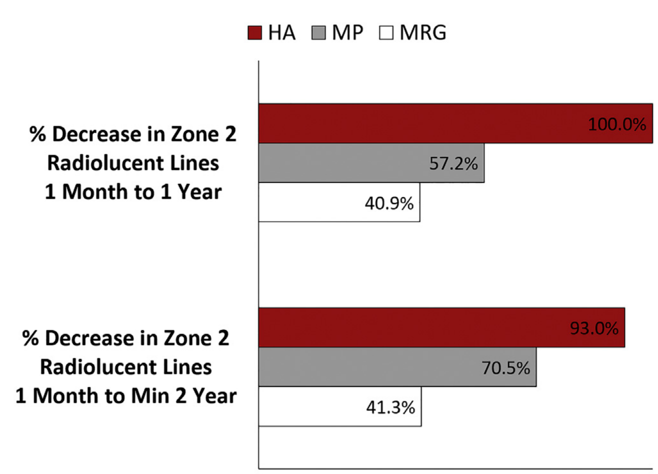

Figure 3. Nearly all zone 2 radiolucent lines resolved or remained resolved for HA cups at one-year and minimum two-years, 57.2% resolved for MP, and 40.9% resolved for MRG cups between one-month and one-year. Between one-month and minimum two-years, 70.5% resolved for MP, and 41.3% resolved for MRG cups.

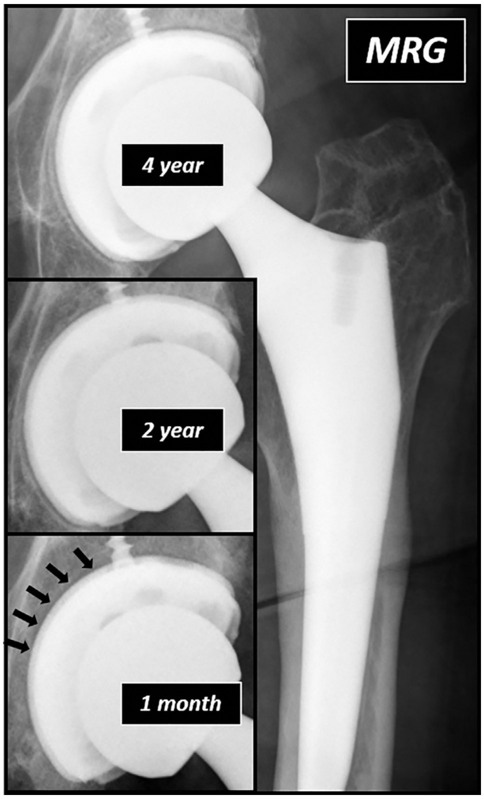

Figure 4. MRG cups showed radiolucent lines at one-month followed by the formation of radiosclerotic lines at two-years and four-years. The evolution of radiosclerotic lines was apparent for a majority of MRG cups possibly signifying the lack of osseointegration.

another with respect to the proportion of zone 2 radiolucent lines at minimum 2-year follow-up (Fig. 2; $P \leq .007$).

Furthermore, 100% of zone 2 radiolucent lines resolved by 1 year, and only 1 case developed a zone 2 radiolucent line at minimum 2 years for HA cups (Fig. 3). For MP cups, 57% of zone 2 radiolucent lines resolved by 1 year, and 71% of all zone 2 radiolucent lines present at 1 month resolved by minimum 2-year follow-up (Fig. 3). For MRG cups, 40.9% of zone 2 radiolucent lines resolved by 1 year, and only 41.3% of all zone 2 radiolucent lines present at 1 month resolved by minimum 2-year follow-up (Fig. 3).

Radiographic appearance of acetabular components with persistent and sustained zone 2 radiolucent lines was consistent for MRG cups. A series of radiographs of an initial zone 2 radiolucent line at 1 month and the continued development of radiosclerotic lines at 2 and 4 years postoperatively (Fig. 4) are shown as a characteristic example of similar cases in this series. Figure 1 (right 3 columns) also shows a representative case of each design for the progression or resolution of zone 2 radiolucent lines from 1 month to minimum 2 years.

There were 2 revisions in the inclusion cohort for aseptic loosening of the acetabular component at 2.2 and 5.4 years postoperatively (2 MRG cups). The cases exhibited symptomatic pain with activity and persistent radiolucent lines in all 3 acetabular zones on serial radiographs and were both in very active 43- and 56-year-old males, respectively. Intraoperatively, the acetabular components were fibrous ingrown and removed easily with the explant device. Upon removal, the acetabular implants were covered with fibrous tissue and without visible bone ingrowth. The patients are currently at 4 and 2 years after revision and are both asymptomatic with complete resolution of pain.

Discussion

Ultraporous surfaces have been rapidly adopted for acetabular fixation in cementless THA. However, the enhanced frictional interference fit can impede complete seating, resulting in radiolucent lines at the dome (zone 2) of the acetabular component. Radiolucent lines in traditional porous titanium cups have been described, [4-9] and while the majority have been reported to resolve, data on contemporary highly porous titanium acetabular components are lacking. In the quest for the best long-term results and survivorship during implantation of cementless acetabular components, surgeons technically address the balance between optimal mechanical stability and maximal apposition against viable host bone. Contemporary highly porous (or “ultraporous”) cementless acetabular components were designed to enhance both mechanical stability via increased frictional resistance and osseointegration via optimal biologic ingrowth into 3-dimensional microporous and macroporous structures. Therefore, it has been postulated that modern highly porous acetabular components will have a “factor of safety” and achieve maximal osseointegration even in the setting of incomplete seating that may occur because of the inherent frictional resistance, as evidenced by resolution of zone 2 polar gaps over time.

Highly porous titanium cups in the present study showed acetabular cups with machined radial grooves (MRG, 46%) had the highest proportion of radiolucent lines remaining at 1 year, compared with no radiolucent lines in traditional porous titanium cups with HA coating and 35% of radiolucent lines in highly porous titanium substrate cups with titanium micro beads (MP; Fig. 2). Similarly, at minimum 2 years, a significantly higher proportion of zone 2 radiolucent lines was observed for MRG cups (46%) while a significantly lower proportion was observed for porous titanium substrate cups with titanium micro beads (MP, 24%) and even lower for traditional ongrowth cup which only had 1 cup develop a zone 2 radiolucent line (HA, 3%).

MRG cups had the highest proportion of persistent radiolucent lines at 1 year and minimum 2 years and demonstrated a consistent and specific radiographic pattern over time. MRG cups followed a distinct evolution of radiolucent lines, with zone 2 radiolucent lines visible at 1 month worsening to circumferential or radiosclerotic lines at 2 years and further worsening out to 4 years (Fig. 4). These circumferential radiosclerotic lines were apparent only in the MRG cups and not in the MP or HA cups. These radiosclerotic lines could be interpreted as a lack of osseointegration possibly because of increased micromotion at the bone-implant interface or the uniform distance between radially machined grooves which is greater than the reported osteoblast jump distance (800 μm to 1 mm) [20,21]. This suggestion is consistent with published data comparing radiolucent lines in the same MRG acetabular components [22]. In 109 porous titanium cups with machined radial grooves (Tritanium; Stryker), 30% had radiolucent lines in 2 or more DeLee and Charnley zones at 1-year follow-up, with 37% at 2 years and 40% at 5 years and beyond [22]. By comparison, 100 matched porous titanium PSL cups with HA coating (Trident; Stryker) were 1%, 0%, and 0%, respectively [22]. Two titanium cups with machined radial grooves and zero porous titanium PSL cups with HA coating were revised for aseptic loosening [22]. In a recent retrospective cohort study, Yoshioka et al. [23] reported on 130 consecutive highly porous titanium cups (Tritanium, Stryker) vs 130 traditional ongrowth HA cups (Trident; Stryker). Radiolucent lines increased in the Tritanium group (36.1% at 3 months and 60.7% at final follow-up), whereas radiolucent lines decreased in the Trident group (2.5% at 3 months and 0.8% at final follow-up) [23]. Furthermore, in a recent Finnish Registry study, Palomäki et al. [24] investigated the survival of 6,080 primary MRG cups compared with 25,670 conventional cups and found the 5-year Kaplan-Meier survivorship of the MRG cup was inferior to that of the conventional cup group (94.7% vs 96.0%). In addition, the risk for revision due to aseptic loosening was found to be higher for the MRG cup at early (0 to 2 years) and mid-term (>2 to 4 years) time points with hazard ratios of 3.80 and 11.2, respectively [24]. These reports support our findings in the present study with regard to the persistence of zone 2 and circumferential radiolucent (or radiosclerotic) lines which may lead to an increased risk for aseptic loosening for a 3-dimensional highly porous titanium acetabular component with machined radial grooves (Tritanium; Stryker). In addition, to further corroborate our findings, a recent case report identified 5 cases in which this particular acetabular component with radially machined grooves demonstrated circumferential radiolucent lines and subsequent revision in all 5 cases due to aseptic loosening even with screw augmentation [25].

Adjuvant screw fixation may provide additional mechanical stability in acetabular components and would theoretically mitigate the risk of ingrowth failure, which is why many surgeons use supplemental screws in practice. The HA cup group used the most acetabular screws and had the lowest proportion of radiolucent lines at 1 month (43%), 1 year (0%), and minimum 2 years (1 cup, 3.0%) compared with MRG cups which used the second most acetabular screws and had the highest proportion of radiolucent lines at 1 year and minimum 2 years (46%). The correlation of acetabular screw use and significant differences in zone 2 radiolucent lines may imply the manufacturing process with radially machined grooves may hinder osseointegration of this particular highly porous surface, regardless of adjuvant screw fixation [25]. Interestingly, MP cups used significantly less acetabular bone screws than MRG cups and demonstrated a significantly lower proportion of zone 2 radiolucent lines at 1-year (35%) and minimum 2-year follow-up (24%). Again, this may imply the manufacturing process with radially machined grooves may hinder osseointegration of this particular highly porous surface.

Our observations of nearly no radiolucent lines at 1 year or beyond in ongrowth titanium cups with HA coating are consistent with existing reports. The HA ongrowth cups are thinner than the highly porous cups, which makes it more flexible. In addition, the surface coating of the HA cup has a smaller coefficient of friction. Both of these material characteristics allow the cup to fully seat more predictably and maximize the surface area in contact with host bone. A similar study of 613 hips reported no radiolucent lines and no revisions for aseptic loosening in this cup at minimum 2-year follow-up [26]. In a prospective multicenter study, Capello et al. [27] reported no radiolucent lines or osteolysis in any zone with the arc-deposited hydroxyapatite-coated acetabular component at 4- to 7-year follow-up.

Our observations should be considered in the context of study limitations. First, this study was conducted in a retrospective manner which can introduce selection bias; however, the cohort for this study was a consecutive series of primary THAs. Second, these results represent the experience of a single high-volume surgeon and may not be applicable to other settings. Third, zone 2 radiolucent lines on postoperative radiographs were recorded by a single rater; however, it has been recommended that single experienced observers be used to evaluate radiolucencies because of higher intra-rater agreement than inter-rater agreement [28]. Furthermore, zone 2 radiolucent line measurements were categorized into discrete groups (yes vs no) for data analysis to minimize the effect of a single radiographic rater.

Conclusions

Our early radiographic results imply that not all modern, ultraporous acetabular cup designs perform equally. We interpret our data as indicative of (a) excellent osseointegration for ongrowth titanium HA cups, (b) great osseointegration for titanium dual MP, and (c) poor and worrisome osseointegration for porous titanium MRG cups at short-term follow-up. Although the short-term revision rate for aseptic loosening of acetabular components in our series was very low (2 MRG cups), we believe it is important to follow this series for long-term assessment and imperative to clinically monitor patients with porous titanium MRG cups, as a greater than expected number of implants may be fibrous ingrown rather than the preferable osseointegrated. Finally and most importantly, despite the theoretical advantages and “factor of safety” anticipated with the advent of modern highly porous metal acetabular components and based on these data, we now ensure that acetabular components are fully seated with minimal to no polar gaps via direct visualization through the dome hole and do not accept any measurable lack of contact between implant and host acetabular bone.

Conflict of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Please see attached conflict of interest forms.

Acknowledgments

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