

Original research

Radiolucencies surrounding acetabular components with three-dimensional coatings: artifact or real?

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ABSTRACT

Background: Several 2-dimensional and 3-dimensional surfaces are available for cementless acetabular fixation. Plain radiographs are used to assess osseointegration; however, the radiographs are limited by their inability to capture the bone fixation process occurring over the 3-dimensional cup surface. In this cadaveric study, we compared the bone apposition between 2-dimensional and 3-dimensional cups.

Methods: Both types of cups were implanted in 6 cadavers and pelvic radiographs obtained. Each cup was resected from the pelvis with adequate bone around it, and subsequently embedded in a polymer. Six sections of each cup were obtained to examine the metal and bone interface. Photographs and contact radiograph images were obtained for each section, and these were graded to arrive at percent metal-bone contact values for the cups.

Results: On average, <30% of the cups' areas displayed radiolucencies on the pelvic radiographs for both cup types. For the section images and radiographs, there was about 80% aggregate contact between the cups and surrounding bone in both cup types. In the 3-dimensional cups group, some inconsistencies were found between the section photographs and the corresponding radiograph images. The radiolucencies observed on the section radiograph could not always be correlated with metal to bone gap on the section photograph.

Conclusions: Good metal-bone contact (75% + contact area) was observed on both cup types. The inconsistencies found in the 3-dimensional cup group may be because of the interaction of radiographs with the unique porous cup surface resulting in artifactual radiolucencies.

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Introduction

A variety of 2-dimensional (2D) and 3-dimensional (3D) surface modifications of the acetabular cups are available to surgeons [1,2]. The prime aim of these modified surfaces is to improve the biological fixation between the metallic cup and the surrounding bone. However, evaluating or recognizing true biologic fixation of an acetabular component is not straightforward. Plain radiographs are typically used as an indirect surrogate marker of biological fixation between

the cup and surrounding bone [3-6]. In post-operative plain radiographs, the presence of progressive radiolucent zones of 2 mm or more around the implant in the 3 radiographic zones is reportedly indicative of aseptic loosening [6]. 2D plain radiographs have a limited ability though to quantify the extent of fixation as the biological fixation occurs in 3D space around the entire cup. Only a few researchers have conducted metal-bone contact analysis on retrieved acetabular cups to gain deeper insight into the extent of biological fixation. Engh et al [7] attempted to quantify the biological fixation in retrieved acetabular cups and found that, on average, only 32% of the surface of the cup was in contact with the surrounding bone. In contrast, Bloebaum et al [8] published the results of their retrieval analysis of porous cups and reported an average of 84% bone apposition between the cups and surrounding bone.

In clinical practice, 2D and 3D modified acetabular components have demonstrated good outcomes and survivorship [9-17]. The Trident Primary Acetabular Component (Stryker, Mahwah, NJ) has a

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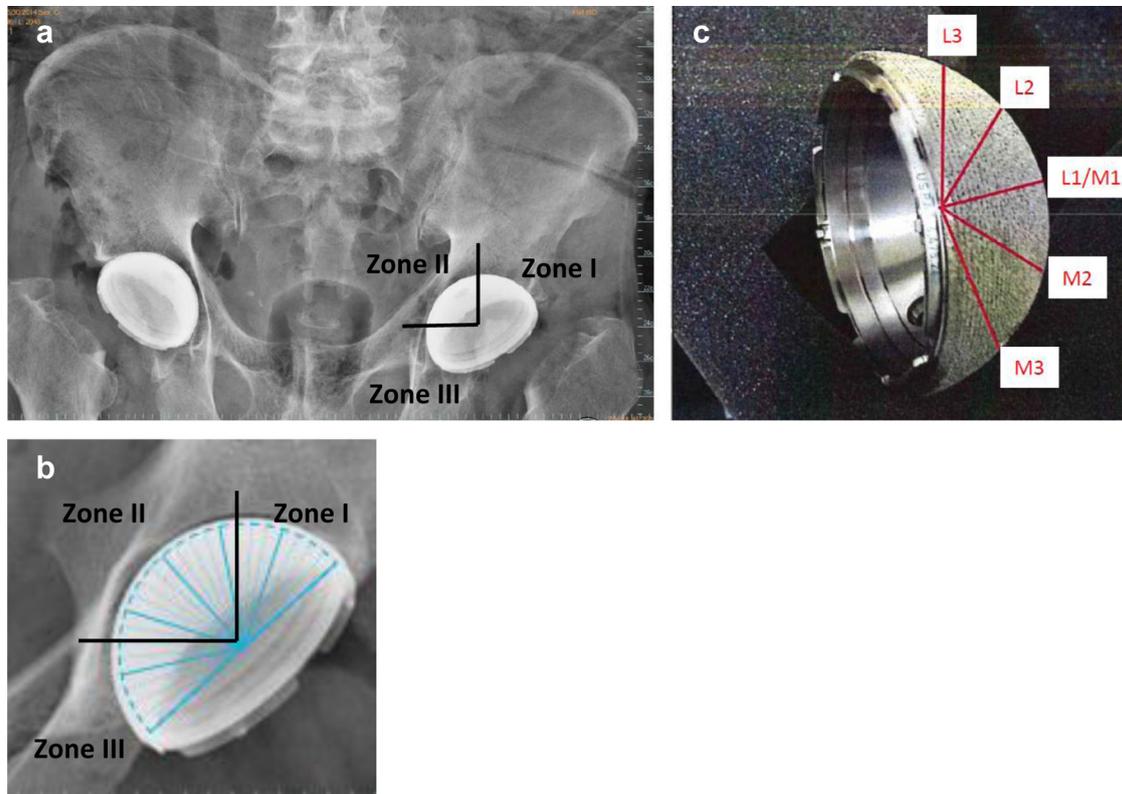


Figure 1. (a) Example of the post-operative pelvic plain radiographs obtained on each specimen. (b) Semicircle grids with 24 subsections measuring 7.5° each were superimposed onto each cup radiograph and divided into 3 zones. (c) Sectioning scheme of the acetabular cup. Six sections were generated from each cup by dividing the cup at 30° intervals (L1, L2, L3, M1, M2, M3). L3 is the lateral most section, while M3 is the medial most section. L1 and M1 are the sections in the central region of the cup; however, they are not exactly the same when we factor in the blade thickness of 0.3 mm. L2 and M2 are between L1 and L3 and M1 and M3, respectively.

2D surface coating of arc-deposited commercially pure titanium. First released in the late 1990s, the Trident has demonstrated long-term clinical success in multiple studies [10–15]. A more recently introduced device with a 3D surface is the Tritanium Primary Acetabular Component (Stryker). The Tritanium porous surface is manufactured by the deposition of commercially pure titanium onto a machined scaffold of reticulated, open cell, polyurethane foam [18]. It is designed to have high porosity and a high coefficient of friction. These properties enhance the biological fixation between the cup and the surrounding bone [19–23]. Short- to medium-term data have shown good clinical performance for this device as well [17,24,25]. However, Carli et al [26] recently reported that over one-third of 121 consecutively implanted Tritanium acetabular components, with an average follow-up of 3.9 years, had associated radiographic lucencies. These authors attributed the radiolucencies to unacceptably large regions of fibrous ingrowth. Nonetheless, in this same study, cup survivorship was an impressive 98.1% at the most recent follow-up. In a separate clinical study, Nandi performed comparative survival analysis of the porous tantalum (Zimmer Biomet, Warsaw, IN) and porous titanium (Tritanium; Stryker) acetabular components in both primary and revision total hip arthroplasty [27]. Their study concluded that there was no difference in likelihood of revision between the porous tantalum and porous titanium cups.

The discrepancy between the imaging findings and clinical results for 3D acetabular cups has not been well researched or explained in the literature. The current cadaveric study was therefore designed to better understand the differences in the radiographic and histologic bone apposition characteristics of 2D (Trident; Stryker) acetabular cups with the recently introduced 3D

(Tritanium; Stryker) acetabular cups. We set out to answer the following questions:

1. Are there radiographical differences between the 2 cup types?
2. Are there differences in bone apposition between the 2 cup types from observation of the physical sections?
3. Are there differences in perceived bone apposition between the physical sections' photographic images and their radiographic images?

Material and methods

Acetabular components were implanted bilaterally in 6 fresh frozen cadavers by a single highly experienced fellowship trained arthroplasty surgeon (P. F. S.). Each specimen was laterally randomized to receive either a 2D (Trident; Stryker) or 3D (Tritanium; Stryker) surface acetabular component. The surgeon utilized a modified anterolateral approach between the tensor fasciae latae and gluteus medius muscles to access the hip joint. The hips were dislocated and an oscillating saw was used for neck resection. Final components were implanted after routine acetabular preparation, including under-reaming the acetabulum by 1 mm (targeting 45° abduction and 20° version). Satisfactory initial stability (the cup did not move when applying a considerable amount of force on the cup inserter, and therefore no need for supplemental screws) of the acetabular component was achieved in all specimens.

Following implantation, all cadaveric specimens were radiographically evaluated with a plain anteroposterior film of the pelvis (Fig. 1a). A large bone defect was found around the cup in 1 cadaver

Table 1
Description of radiolucency zones in cups.

Specimens	Radiolucency zones ^a	%Radiolucency of total contact area
Specimen 1		
2D cup	Zone I (13%) and zone II (87%)	46
3D cup	Zone II (82%) and zone III (18%)	40
Specimen 2		
2D cup	Zone II (100%)	13
3D cup	Zone II (75%) and zone III (25%)	17
Specimen 3		
2D cup	Zone II (67%) and zone III (33%)	26
3D cup	Zone I (60%) and zone II (40%)	21

^a Zone I is lateral, zone II is central, and zone III is medial part of the cup on A-P radiograph.

(a large cavity behind the cup with almost no contact between the cup and the surrounding bone), leaving only 5 complete cadavers for subsequent comparative analysis. The defect was noticed during the procedure as well. We are not sure whether it was iatrogenic or not. Regardless, we removed this sample because the cup-bone contact was visibly minimal due to this defect. Similar to the techniques used by Engh et al [7], a semicircle grid with 24 subsections measuring 7.5° each was then superimposed onto each cup component in the radiograph (Fig. 1b). Component radiolucencies at the bone-implant interface were quantitated for location and length using the 3-zone system described by DeLee and Charnley (zone I = superolateral, zone II = superomedial, zone III = inferomedial) [7]. Subsequently, the acetabular component and surrounding bone were resected from the cadavers. These specimens were placed in 70% isopropyl alcohol for 7 days and then embedded in polymethylmethacrylate. The embedded specimens were then sectioned in 30° intervals in the coronal plane using a diamond saw into 6 sections (Fig. 1c), as recommended by Engh et al [7]. The 6 sections were L1, L2, L3, M1, M2, and M3. L3 was the lateral most section, while M3 was the medial most section. L1 and M1 are the sections in the central region of the cup; however, they are not exactly the same when we factor in the blade thickness of 0.3 mm. L2 and M2 are between L1 and L3 and M1 and M3 respectively as shown in Figure 1.

Two cups during the embedding and sectioning process were determined to have poor bone quality insufficient for evaluation and were subsequently removed from the study. This left us with 3 pairs of acetabular cups: three 2D cups and three 3D cups. Each specimen was microscopically evaluated (10× magnification) by 3 observers for bone apposition (length of bone-implant contact over total length of implant surface) for quantitative analysis.

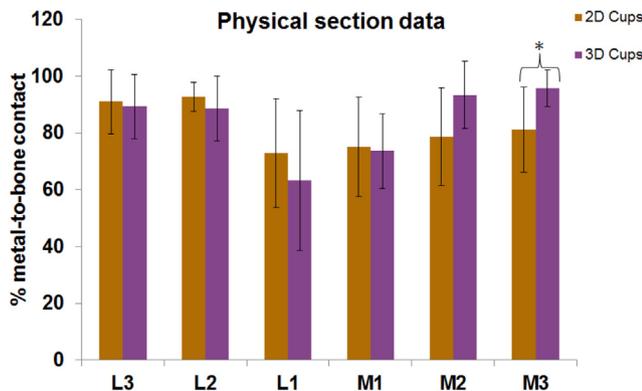


Figure 2. Comparison of metal-bone contact between 2D and 3D cups for physical sections. *Statistical difference.

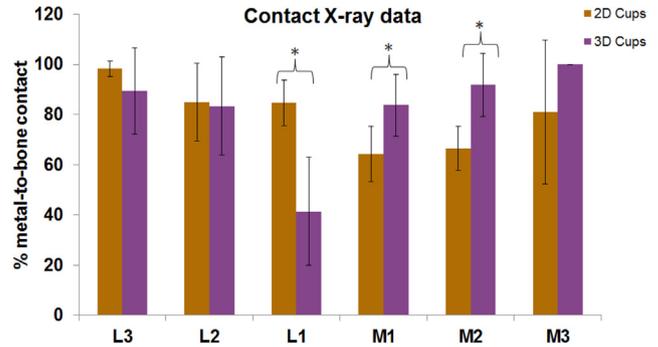


Figure 3. Comparison of metal-bone contact between 2D and 3D cups for contact radiographs. *Statistical difference.

Overhanging parts of the cup implant where no bone contact would be possible were not included in the total length of implant surface. The same analysis was conducted on radiographs of the sectioned specimens obtained by contact radiograph. If radiolucencies were present, it was then determined if the location corresponded with a true implant-bone gap noted during microscopic analysis of the specimens.

Results

The radiographs of the cadaveric specimens implanted with acetabular cups showed some radiolucencies in all cases. Table 1 depicts the presence and percentage of appositional radiolucency along with the zone locations as defined by DeLee and Charnley [6]. On average, 75% of the appositional area in zone II was radiolucent. This percentage was not significantly different between 2D cups (85%) and 3D cups (66%, $P = .30$). Zone III demonstrated an average radiolucent appositional area of 13%. This percentage was also not significantly different between 2D cups (11%) and 3D cups (14%, $P = .81$). Zone I demonstrated an average radiolucent appositional area of 12%, which again was not significantly different between 2D cups (4%) and 3D cups (20%, $P = .49$). Looking at the total bone-metal contact area for all specimens, an average of 27% of the area appeared to be radiolucent on the plain films. 2D cups had an average radiolucent appositional area of 28%, which was not significantly different from the average radiolucent appositional area for 3D cups (26%, $P = .85$).

Figure 2 depicts the bone-metal contact for the various sections in both 2D and 3D cups. The overall average percent bone-metal contact was 81% ± 10% for 2D cups and 84% ± 18% for 3D cups, and these were not statistically different ($P > .05$). Lowest contact was observed on L1 and M1 sections. Between the 2 cups, the

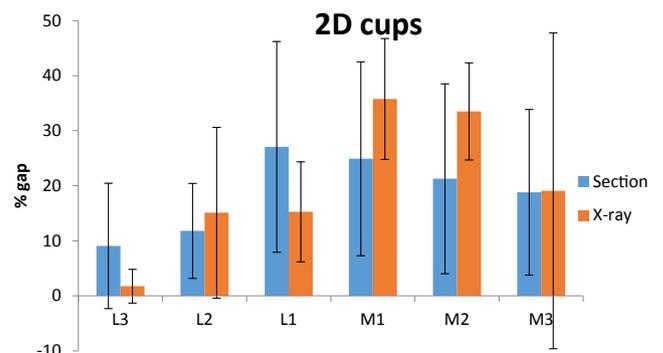


Figure 4. Comparison of gaps between sections and radiographs for 2D cups.

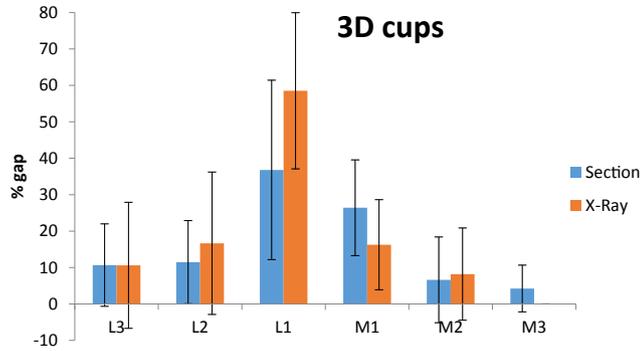


Figure 5. Comparison of gaps between sections and radiograph cups for 3D cups.

average contact values were statistically different ($P < .05$) for the M3 sections only (2D: $81\% \pm 15\%$; 3D: $96\% \pm 6\%$).

Figure 3 depicts the bone-metal contact observed on the contact radiographs of the sectioned specimens of both 2D and 3D cups. The overall average percent bone-metal contact was 80%

$\pm 15\%$ for 2D cups and $82\% \pm 24\%$ for 3D cups, and these were not statistically different ($P > .05$). We observed statistically significant differences in bone-metal contact between 2D and 3D cups in 3 sections: L1, M1, and M2. For the L1 section, bone-metal apposition on the contact radiographs was statistically smaller ($P < .05$) for 3D cups vs 2D cups (3D: $41\% \pm 21\%$; 2D: 85 ± 9). On the other hand, bone-metal apposition on radiograph was statistically higher ($P < .05$) for 3D cups vs 2D cups for the M1 (3D: $84\% \pm 12\%$; 2D: $64\% \pm 11\%$) and M2 sections (3D: $92\% \pm 13\%$; 2D: $66\% \pm 9\%$).

A comparison between the percentage of gaps in the physical sections and radiolucencies in the contact radiographs for 2D cups is depicted in Figure 4. The M1 region demonstrated statistically higher ($P < .05$) gaps in the radiograph ($36\% \pm 11\%$) compared with the physical section ($25\% \pm 18\%$) There was no statistical difference between the physical and radiograph data for the 2D cups in any other region. Figure 5 compares the percentage of gap in the physical sections and radiolucencies in the contact radiographs for 3D cups. No statistical differences between the sections and radiographs were found for 3D cups.

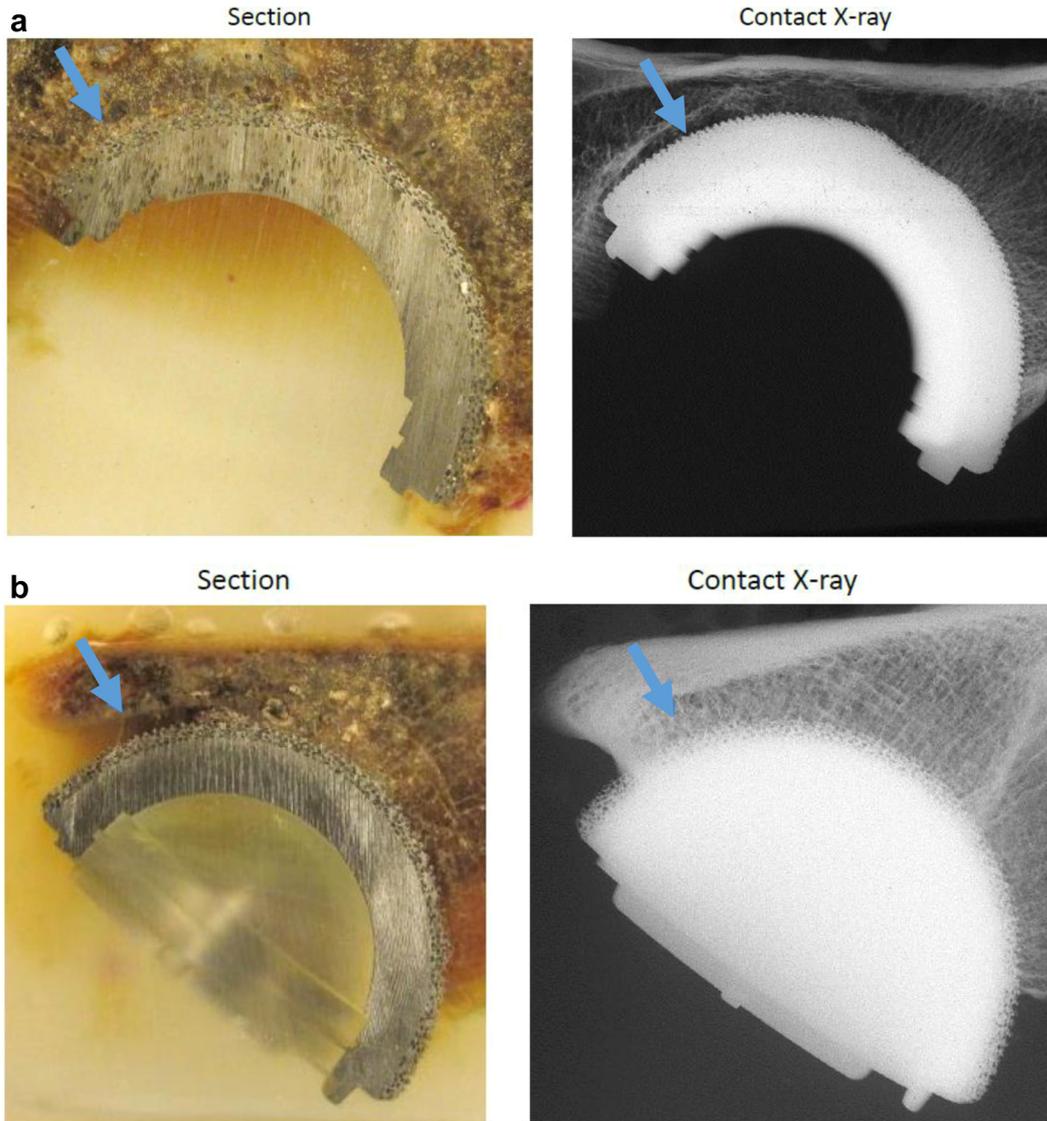


Figure 6. Inconsistencies observed between physical section image and the contact radiograph image. (a) The top images show no gap on the section image; however, the contact radiograph shows radiolucency. (b) The bottom images show that there is gap on the physical section; however, the contact radiograph image does not show that.

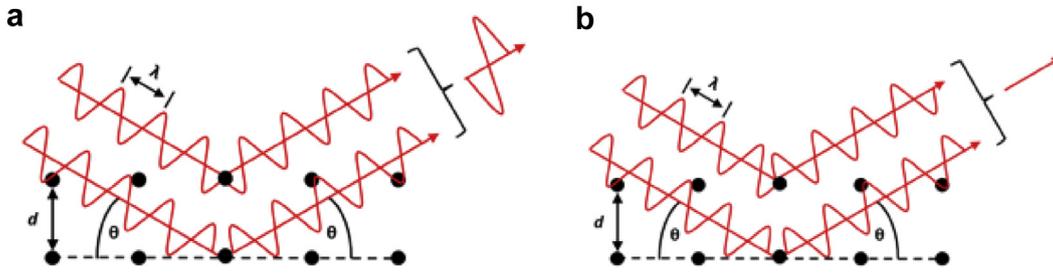


Figure 7. Demonstration of the concept of Bragg's law leading to both constructive (a) and destructive (b) interference. When the resultant phase shift of the deflected radiograph beam is equal to its wavelength or an integer multiple, the 2 beams will be completely in-phase and their waves will be additive (a, constructive). If the deflected radiographs are completely out-of-phase, the summation of their waves will completely cancel out (b, destructive). λ = wavelength of radiation, d = inter-planar distance, θ = angle between the incident radiation ray and relevant crystal planes.

Discussion

Porous coated uncemented acetabular components are commonly used in total hip arthroplasty with good long-term survival [9-13,16,17,25]. Conversely, retrieval studies have shown that bone fixation occurs on a relatively small percentage of the available porous surface and fibrous growth is commonly present on many acetabular implants with porous surfaces [9,28].

Radiolucency on the radiograph may be indicative of a true gap or presence of fibrous growth. It has been proposed that regions of fibrous ingrowth create channels for particulate debris to reach bone, and may ultimately allow for osteolysis and cup loosening [29]. In a comprehensive retrieval review of multiple cementless acetabular cup surfaces, Swartz et al [9] found correlation between the surface type (eg, bead size, material, etc.) and biological fixation. The amount of biological fixation, based on visual scoring, varied with the cup type and the median values ranged from approximately 5% to 45%, suggesting that a variety of factors including the surface design, time in situ, and occurrence of infection can influence the biological fixation.

Radiolucent lines on the radiographs may also be due to incomplete seating of the cups. This may be the reason why we observed zone II radiolucencies in the cadaver radiographs. In a clinical study, Springer et al [30] have studied the fate of zone II radiolucencies in much detail. Based on the review of 343 cases, they concluded that "Incomplete seating of press-fit acetabular components is safe and effective in achieving initial and long-term fixation. Zone II lucencies when present initially are not associated with increased failure risks."

In the current cadaveric study, we sectioned the acetabular cups to evaluate the metal-bone interface. This technique provides greater detail than an anteroposterior radiographic view, which provides

information only in a single plane. Sectioning the cups yielded 6 semicircular sections from each cup, which was then analyzed to understand the contact between the metal and bone through multiple planes. This exercise enabled us to visualize 6 times the area that we could visualize on the plain radiographs obtained post-op, thereby allowing us to do detailed analysis over the entire cup surface. In general, we found that intimate metal-bone contact exists over the entire surface of both 2D and 3D cups (average 80% + contact on both sections and contact radiographs). This illustrates that initial metal-bone contact, while sometimes invisible on the radiograph, exists in both cup designs. This is corroborated by the good long-term and short-term clinical successes of the 2D and 3D cup designs respectively [10-13,16,17,24,25,31].

Further analysis of the sections and the contact radiographs yielded interesting results. Overall, we found that the gap values correlated well between the physical sections and the corresponding contact radiographs, except for one region in the 2D cup group where the radiograph showed a significantly higher gap value. Examination of individual specimen sections yielded more interesting findings. In a few cases, inconsistencies between the physical section and the contact radiographs were observed. Notably, there were 2 types of inconsistencies as shown in Figure 6. The first one was the presence of radiolucency on the contact radiograph image, but no corresponding gap was observed on the physical section (Fig. 6a). In contrast to the first type, the second type of inconsistency was characterized by visual physical gap on the section but no corresponding radiolucency on the contact radiograph (Fig. 6b). These inconsistencies occurred in only a few cases of the 3D cup group (2 of 18 sections total) and may be associated with the manner in which a radiograph beam interacts with the cup surface. The physics of radiograph diffraction which may be the underlying cause of the inconsistencies is described below.

Radiograph crystallography is an established technique used to determine the atomic structure of crystals [32,33]. Radiographs can be considered waves of electromagnetic radiation and atoms in a crystal, or any structure, can scatter or diffract the waves into new directions. When multiple radiation waves are deflected off a crystal surface, they can interfere constructively or destructively depending on the amount of phase shift which occurs in each wave, which correlates with the incident angle and the lattice spacing on the surface in accordance with Bragg's law (Fig. 7). This interference may result in increased intensity of deflected radiographs when the radiographs interfere in a constructive manner. On the other hand, the interference may result in decreased intensity of the deflected radiographs when the radiographs interfere destructively. In theory, the phenomenon described by Bragg may be applied to radiograph images of acetabular cups, particularly those with crystalline surface modifications, such as the 3D Tritanium cup. This may elucidate some of the bone-metal appositional

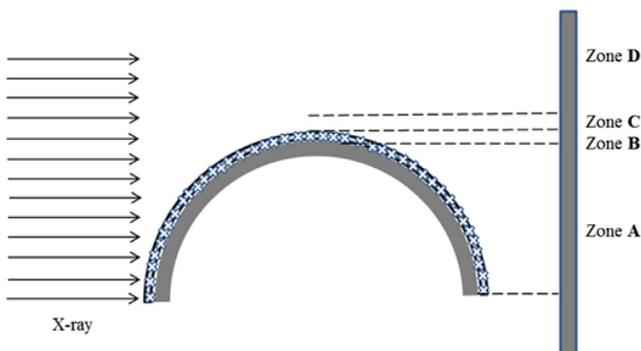


Figure 8. Illustration of various zones with potentially different radiograph intensity during imaging of acetabular cups.

inconsistencies observed in our study. We have attempted to explain this phenomenon in Figure 8. Multiple zones are shown when radiographs fall on the film. Zone A represents low radiation as most of it is blocked by the metal cup. Zone B has more radiation than zone A as some radiation can pass through the coating. Zone C is interesting because it consists of radiation passed through bone plus the radiation which could have been deflected off the cup coating. Finally, zone D represented the radiation which passed through bone and soft tissues. We postulate that the total radiographs may either increase or decrease in intensity in zone C, depending on whether they are interfering constructively or destructively. This is why we sometimes observed radiolucency or lack thereof on the radiograph images that did not correspond to the observation on the physical sections. This phenomenon may be influenced by the orientation of the crystal planes and the angle of the incident radiographs.

There are limitations to our study. We started with 6 cadavers; however, the final analysis was completed on only 3 cadavers and therefore the sample size is small. The inconsistencies were only observed in 2 of 18 sections, indicating that it occurs under certain conditions which we were unable to fully explain. Also, this is a cadaveric study, therefore no actual bone ingrowth could be observed on the cups. A similar study on retrieved cups may be able to shed more light on this topic. Nevertheless, our study was able to show the rare occurrence of the inconsistencies between the radiograph images and physical sections with 3D surface.

Conclusions

In summary, both 2D and 3D cups had equivalent mean metal-bone contact. Artifactual radiolucencies were found in the contact radiograph images of the 3D cups. The clinicians should be aware that artifactual radiolucencies may give a false impression of aseptic loosening. As reported by Sundfeldt et al [29], the causes of aseptic loosening are complex and multifactorial and many factors affect the stability and longevity of the device.

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