

The Accuracy of Computed Tomography in Determining Location and Size of Pelvic Osteolysis Following Total Hip Arthroplasty: A Cadaver Study

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**The Accuracy of Computed Tomography in Determining Location and Size of Pelvic
Osteolysis Following Total Hip Arthroplasty: A Cadaver Study**

Abstract

Introduction: Currently, radiographic evaluation is the standard for monitoring patients with osteolysis following total hip arthroplasty. However, the complex three-dimensional geometry of the pelvis complicates the detection and size determination of pelvic osteolytic lesions on plain two-dimensional radiographs. Three-dimensional imaging techniques, such as computed tomography, could be used to solve the problem if metal implants did not cause artifacts on the computed tomography scans. These streak artifacts prevent accurate assessment of the periprosthetic bone. To address this problem, computer-assisted image processing for computed tomography has been developed. The purpose of our study was to assess, via a cadaver model, the accuracy of computed tomography combined with computer-assisted image processing to determine the location and volume of periprosthetic acetabular osteolysis.

Material and Methods: Four cadaveric pelvises were harvested postmortem and all eight hips received total hip replacement components. The acetabular components then were removed, and sixteen separate bone defects, two per hip, were created in four possible locations: the ilium, ischium, pubis, or at the posterior rim of the acetabulum. We measured the physical volume of the lesions. Next, we reimplanted the cups and acquired a helical, computed tomography scan of the entire pelvis with both hips reduced. We removed the cups two more times. Each time we enlarged the lesions (creating a total of 48 lesions), recorded the volume of each lesion, and obtained new computed tomography scans of the pelvis. To process the acquired computed tomography data, a streak artifact suppression algorithm was used, after which the artifact-suppressed images were processed with a segmentation algorithm. An independent, experienced, musculoskeletal radiologist blinded to location and size of the lesions analyzed the raw and the artifact-suppressed images for the presence of osteolytic lesions and recorded the locations and

volumes of the lesions. We compared the actual locations and volume of the lesions in the cadaver with the locations and volumes determined by the radiologist.

Results: Using computed tomography combined with computer-assisted image processing, the radiologist detected and correctly identified the location of 81% (thirty-nine of forty-eight) of the lesions. The ability to detect lesions was location dependent. Significantly more lesions were detected in the ilium (100%) and at the posterior rim (89%) than in the ischium (78%) or the pubis (50%) ($p=0.007$). The volume of the detected lesions was overestimated by a mean of $0.5 \pm 2.3 \text{ cm}^3$ ($5.6 \% \pm 24.8 \%$). The absolute volumetric error was unrelated to lesion location ($p = 0.25$). However, the relative error in determining lesion volume was dependent on lesion size: the mean percentage error decreased as lesion size increased.

Discussion: Computed tomography combined with this computer-assisted image processing provides a three-dimensional method for reliably detecting pelvic osteolysis, particularly in the posterior column of the acetabulum. Moreover, this method can accurately determine the volume of osteolytic lesions. Consequently, we believe that computed tomography combined with the investigated computer-assisted image processing can become a useful tool in diagnosing and monitoring pelvic osteolysis associated with stable implants to develop effective treatment strategies for osteolysis and to investigate its natural history.

Introduction:

Today, the most common complication threatening the long-term success of total hip arthroplasty is osteolysis^{1,2,3}. In cemented total hip arthroplasty the occurrence of linear osteolysis is related to implant loosening^{4,5,6}. In cementless total hip arthroplasty, the effect of osteolysis on long-term fixation is less predictable. Osteolysis does not necessarily result in component loosening. In fact, expansile osteolysis in the presence of stable cementless implants has been reported commonly^{2,7}. However, knowing the consequences of osteolysis in cemented hip arthroplasty and lacking knowledge about its natural history with cementless arthroplasty, orthopedists remain concerned that osteolysis could result in loosening and failure of cementless implants¹.

Their concern is supported by findings of osteolysis during total hip revision situations. Frequently, surgeons have observed that osteolysis-induced bone loss is more extensive than predicted from preoperative radiographs⁸, or they have found unexpected lesions that were not radiographically evident⁹. This is because the evaluation of two-dimensional radiographs for osteolysis is complicated by the complex three-dimensional geometry of the pelvis. Although radiographic evaluation is the standard for monitoring patients with osteolysis, the problems associated with radiographically identifying and determining the extent of osteolysis, particularly in the pelvis, are becoming more evident as increasing numbers of young patients implanted with cementless components present for long-term follow-up.⁷

Three-dimensional imaging techniques, such as computed tomography or magnetic resonance, could solve the problems regarding the radiographic diagnosis of pelvic osteolysis. However, metal acetabular and femoral implants cause artifacts on the images acquired with both technologies. These streak artifacts originate from the high atomic number and the density of the

metal in the implant^{10,11}. Particularly pronounced with cobalt-chrome components, the streak artifacts prevent an accurate assessment of the bone adjacent to the prosthesis. They also prevent the use of segmentation algorithms, which are applied with computed tomography to perform volumetric measurements. To solve these problems, helical computed tomography with artifact minimization¹² and post-processing software for computed tomography images have been developed to suppress the metal-induced streak artifacts¹³.

Postprocessing artifact suppression software has been used previously by implant manufacturers to develop customized acetabular implants for complicated total hip revision operations involving severe periacetabular bone loss caused by cup loosening. Several authors have reported on the clinical results of these custom-made implants^{9, 14, 15}. However the accuracy of the computed tomography based reconstruction and the actual bone loss *in situ* has been validated only visually by the operating surgeons and not physically. To our knowledge, no study has quantified the accuracy of computed tomography in identifying and sizing periacetabular lesions with implants *in situ* with the objective of investigating its potential as a clinically useful imaging tool for diagnosing pelvic osteolysis with stable acetabular implants.

The diagnostic difficulties and controversial discussion about the treatment of osteolysis with stable implants point to a need for imaging techniques that enable surgeons to diagnose osteolysis and monitor therapeutic efforts^{16, 17, 18}. In this study, we assessed a computer-aided image application for computed tomography that was recently developed for identifying pelvic osteolysis and determining the volume of bone defects in the presence of metal implants. This computer-aided image application processes the original computed tomography images with an algorithm that suppresses streak artifacts. Subsequently, it applies a segmentation algorithm to the artifact suppressed images. Using a cadaver model, we implanted bilateral total hips in

human cadaver pelves and created bone defects in periacetabular locations, based on previous radiographic findings and the senior authors' revision experiences for osteolysis^{19,20}. The purpose of our study was to assess the accuracy of a computer-aided image application for computed tomography interpreted by an experienced radiographic reviewer as a tool to identify and locate pelvic lysis, as well as to determine the volume of the osteolytic lesions in the presence of metal implants.

Material and Methods

Four complete human pelves were harvested postmortem, and all soft tissue was removed. Two orthopedic surgeons implanted cementless, porous-coated total hip replacement components in both hips of each cadaver. Components included a titanium acetabular cup with a shell thickness from 5.8 to 12.4 mm with holes in the surface (Arthropor, Joint Medical Products, Stamford, Connecticut) and a modular, extensively-coated, cobalt-chrome stem (Anatomic Medulary Locking, Depuy, a Johnson and Johnson Company, Warsaw, Indiana) with a CoCr femoral head. CoCr femoral components with CoCr femoral heads were implanted, because they represent a major source of metal streak artifacts for computed tomography. To permit subsequent cup removal without fracturing surrounding bone, when implanting the cups, we reamed the acetabulae line-to-line with the last reamers having the same diameter as the inserted cups. Polyethylene liners were fixed in the cups with two rim screws. We used rubber bands to reduce the implanted cadaver hips and to prevent dislocation during computed tomography scans.

After implanting the components, helical computed tomography scans were performed at the senior author's institution according to the following protocol. The pelvic cadavers were

placed in a box of rice, simulating surrounding soft tissue. Each pelvis was scanned in 1-mm axial slices in standard mode (GE High Speed ADVantage, Waukesha, Wisconsin) with 120 kV and 150 mA and a 1:1.5 pitch. Through further processing, the final computed tomography image recorded each hip separately with a field of view (FOV) larger than 22 cm. To check the technical setting, we acquired a baseline computed tomography scan with the metal implants *in situ* and without bone defects; these scans were not used for comparison purposes in the subsequent assessment of lesions. Computed tomography data were stored on optical disk or on magnetic tape and mailed to the independent radiologist.

Lesion Creation

After the baseline computed tomography scans were made, bone defects to simulate osteolysis were created in the Os ilium, the Os ischium, the Os pubis, or at the osseous posterior rim of the acetabulum, according to the following protocol. First, hips were dislocated, and the polyethylene liners were removed. The position of the cup was marked within the pelvis, so that it could be re-implanted later in the same position. Starting from the marked location of the acetabular shell holes or at the osseous rim of each acetabulum, we created two separate bone defects in two locations in each hip by removing cancellous bone with a curette. Bone defects were filled with a soft-tissue equivalent to simulate the granuloma-tissue content of osteolysis lesions *in vivo*^{21,22}. We reimplanted the cup in its original position, visually ensuring proper seating through the holes in the cup. We then reinserted the polyethylene liner, reduced the hip, and acquired a second computed tomography scan.

We repeated the process of cup removal and reimplantation two more times for each hip. Each time we increased the size of the two lesions and obtained computed tomography scans. A

total of 48 lesions in 8 hips were created and analyzed. To assess the consistency of the reviewer in determining lesion size, we obtained double sets of scans for four lesions. These scans were randomly mixed with the other scans and sent to the independent reviewer for size analysis.

Volume Measurement

After each defect was created, its physical volume was measured by making a mold of the defect with a dental polymer containing methylmethacrylate. Beforehand the walls of the bone defect were lined with petroleum jelly to prevent the polymer from interdigitating with the exposed cancellous bone. Next, the polymer was mixed and finger-packed into the defect while still in a doughy state. The back of the acetabular shell was used to contour the area of the lesion close to the implant surface to create a conforming lesion-cup interface. When the polymer mold was close to being hard, it was removed. After polymerization was completed, the mold was precisely weighed (Ohaus Precision Standard Balance, Ohaus Cooperation, Pine Brook, New Jersey).

To convert the weight of the mold to its volume, the density of polymer had to be determined. Because we prepared the molds individually by mixing the monomer with liquid, each mold required individual calibration of its density. For this, a cylindrical syringe was filled with the polymer used for making a particular mold. When hardened, the plastic mantle of the syringe was removed, and two calibration cylinders were cut from the cylindrical syringe with a water-cooled saw. The length and diameter of each calibration cylinder were measured with digital calipers (Digimatic Caliper, Mitutoyo Corporation, Kanagawa, Japan) to calculate the volume. Each cylinder was weighed, and the density of the polymer was calculated as its weight divided by its volume. The measurements obtained from the two calibration cylinders were

averaged to obtain the mean density for a particular polymer batch. The averaged density (calculated from both calibration cylinders) was used to calculate the volume of the defect mold, based on the weight of the mold.

Computed Tomography Analysis

An independent, experienced, muscular-skeleton radiologist, blinded to the number, location and volume of the lesions, processed the raw computed tomography data of all twenty-four scans (three scans for each of eight hips), using a computer-aided image program (Muscular-Skeleton Analysis Software, Osteolysis Measurement Module, Version 2.0, VirtualScopics, LCC, Rochester, New York)²³. This image analysis program sequentially applies two algorithms. First, the raw computed tomography images are processed with an artifact algorithm to suppress metal-induced streak artifacts. Then, the images are processed with a segmentation algorithm, which enables volumetric measurements by segmenting and classifying the images according to their different statistical properties.

The radiologist reviewed the processed images for the presence of osteolysis. Osteolytic lesions in the computed tomography images were defined as a local lack of trabecular bone with or without sclerotic margins. After identifying the defects, the reviewer then determined their volume using the segmentation algorithm. The results for the identification of the location and the volumetric measurements of the lesions were the furnished back to the senior author's institution for statistical analysis.

Statistical Analysis

Chi squared analysis was used to determine if the percentage of lesions detected with the computed tomography process differed among the four lesion locations. For the detected lesions, we reported the absolute and the relative volumetric error. Absolute error was defined as the difference, in cubic centimeters, between the lesion volume measured in the cadaver and the volume determined by computed tomography. Relative volumetric error was defined as the percent difference between the volume of the lesion determined via computed tomography and the volume physically measured from the cadaver. Using a one sample t-test, we determined if the volumetric errors were statistically different from zero, indicating a bias for one set of measurements to consistently under- or overestimate the other. We used one-way analysis of variance with post hoc Tukey test to determine if a significant difference existed in the mean lesion size or in the mean volumetric error among the four locations. P values less than 0.05 indicated a significant difference.

Results

The reviewer, using the computer-postprocessed computed tomography analysis, detected and correctly identified the location of 81% of the lesions (thirty-nine of forty-eight). The ability to detect lesions was dependent upon the location of the lesions. Lesion identification was easiest in the ilium and most difficult in the pubis. The radiographer detected significantly more lesions in the ilium (100%) and at the posterior rim (89%) than in the ischium (78%) or the pubis (50%) ($p = .007$) (Table 1). Six iliac lesions had a deficient medial wall, which was noted in all cases. Among the nine (19%) undetected lesions, the average volume

was $4.9 \pm 2.7 \text{ cm}^3$, and the lesions were less than 10 cm^3 in size. There was a 100% detection rate for lesions larger than 10 cm^3 .

As measured from the cadavers, the mean volume of the forty-eight periprosthetic lesions was $10.6 \pm 6.7 \text{ cm}^3$ (range, 1.5 to 26.6 cm^3) (Table 1). The mean volume measured from the cadavers of the detected lesions was $12.0 \pm 6.7 \text{ cm}^3$ (range, 1.5 cm^3 to 26.6 cm^3). Measured from the computed tomography scans, the volume of the detected lesions averaged $12.5 \pm 7.4 \text{ cm}^3$ (range, 1.5 cm^3 to 31.1 cm^3). For the detected lesions, the volumetric values from the cadavers correlated highly with the computed tomography values ($r^2 = 0.91$, $p < 0.001$, Fig. 1) and the absolute volumetric error averaged $-0.5 \pm 2.3 \text{ cm}^3$ (range, -4.6 to 6.5 cm^3). This error was not statistically different from zero ($p = 0.18$), indicating that the reviewer did not consistently under- or over-estimate volume. The relative volumetric error was also not significantly different from zero ($p = 0.17$), averaging $5.6 \pm 24.8 \%$. No significant difference existed in volumetric absolute and relative error among the four lesion locations ($p > 0.25$, $p > 0.64$ respectively; Table 2); hence, volumetric error was not related to lesion location.

The relative error in determining lesion volume was, however, related to lesion size. As one might expect, relative error decreased as lesion size increased (Fig. 2). For lesions greater than 10 cm^3 (Fig. 3), the error averaged $1.8 \% \pm 18.1 \%$ ($p = 0.65$, One sample t-test). (Fig 4A and 4B). For the four lesions that were scanned and assessed twice, the mean difference between the first and second volumetric measurements was $9.5\% \pm 11.4\%$.

Discussion

Several long-term studies have demonstrated that the increasing incidence of osteolysis in the presence of stable components is a serious problem in cementless total hip arthroplasty^{2,7}.

At the same time, the treatment for osteolysis with stable components and its timing remains controversial^{16, 17, 18}. Therefore, imaging of pelvic osteolysis is important for the investigation of the natural history of osteolysis and in the development of effective treatment options. Today, plain radiographs are the standard for detecting and monitoring osteolysis. However, the extent of osteolysis usually is underestimated with this method⁹, and the ability to assess radiographs for the presence or absence of osteolysis partially depends on the expertise of the reviewer^{8, 24}.

The ability to image complex objects with three-dimensional imaging techniques, such as computed tomography or magnetic resonance imaging, has been shown to be superior to any two-dimensional technique¹². However, three-dimensional imaging techniques face problems with metal-induced streak artifacts, particularly in areas close to implanted metal components¹⁰. These artifacts can be suppressed by using computed tomography combined with a computer-aided image application; however, the accuracy of computed tomography combined with these post-processing techniques is unknown^{12,13}. For this study we assessed the accuracy of using a computer-aided image application for computed tomography to identify and locate pelvic lysis and to determine the volume of the osteolytic lesions in the presence of metal implants.

In the past, many studies have reported the incidence of osteolysis *in vivo*, based on plain radiographs and more recently on computed tomography¹². However, a true *in vivo* control group has never been available^{2, 3, 7}. Therefore, we created a model for pelvic osteolysis with metal implants *in situ* to assess the accuracy of a reviewer identifying and describing pelvic osteolysis with a computer-aided image application for computed tomography. Lesions were artificially created in predetermined periacetabular locations, based on the concept of the effective joint space. For instance, we considered possible access routes for debris migration, such as holes in the surface of the cup and around the acetabular rim, as starting points for pelvic

osteolytic lesions¹⁹. To produce the most metal artifacts on our images, we implanted bilateral CoCr stems with CoCr femoral heads and first generation titanium cups with thick metal shells. In using these components, we considered our model as representative of a worst case scenario. In this setting, the reviewer, using the computer-aided image analysis, detected and correctly identified the locations of thirty-nine of the forty-eight lesions (81%) in the cadavers. The ability to identify lesions was dependent on lesion location. The 89% detection rate for the ischium and the 78% detection rate for the acetabular rim were encouraging, particularly because the region of the posterior column is difficult to assess with radiographs and represents a crucial area for acetabular reconstruction^{9,25}. Additionally, the radiologist identified all of the iliac lesions with medial wall defects and noted the erosion of the medial cortex from the computed tomography scans. It is of special interest that the detection rate of lesions 10 cm³ and larger was 100% (twenty of twenty), suggesting that for larger lesions detection is independent of location (Fig. 4). All undetected lesions (19% or nine of forty-eight) were smaller than 10 cm³ in size and averaged 4.9 ± 2.7 cm³ in volume.

The reviewer overestimated the volume of the detected lesions by an average of 0.5 ± 2.3 cm³. The relative error - a more critical way to analyze the data, because fairly minor differences in determining the volume of small lesions have a reasonably big influence on the resulting mean and its standard deviation - was $5.6 \% \pm 24.8\%$. Overall, error was independent of lesion location and the relative error decreased with increasing lesion size. For lesions larger than 10 cm³, the mean relative error in estimating volume was 1.8% with a standard deviation of ± 18.1 %. It is important to reiterate that the absolute and relative mean error was for all lesions, rather than a single lesion. However, one should also consider that the standard deviation of the relative error of 24.8% which appears high on the first sight corresponds to an absolute volume of 2.3

cm³ only. Based on our worst-case scenario, we interpret our volumetric measurements as a benchmark, which can be used by future researchers investigating the accuracy of three-dimensional imaging techniques.

We acknowledge that there are limitations to this study. Our conclusions can be applied only to pelvic osteolysis after total hip arthroplasty, because the current version of the computer-assisted computed tomography analysis was developed to assess osteolysis in the pelvis and not in the femur. Secondly, the reviewer identified only 50% of the lesions in the pubis. We believe this is because the streak artifacts from both hip implants overlapped in the pubic region of our model, creating more artifacts there than in other areas of the model.

Despite the study limitations, we are encouraged by the ability to accurately identify and measure pelvic lesions using computed tomography in combination with postprocessing software. Firstly, the scans used in our study represented a worst-case scenario. Secondly, the radiologist was able to assess each set of scans without comparing them to post-implantation scans, which indicates that this level of accuracy could be obtained in the clinical setting without a post-implantation scan, so that patients with radiographically apparent osteolysis can be assessed anytime during their follow-up.

We consider computed tomography combined with the investigated computer-assisted imaging application as one imaging technique of the future that can be used for research studies, as well as in clinical practice. It is unlikely that computed tomography will replace radiographs in routine postarthroplasty monitoring because of the increased irradiation associated with it; however, computed tomography combined with the investigated image analysis represents an accurate imaging technique that can be used once osteolytic lesions are radiographically evident. Radiographic evidence of pelvic lesions implies that osteolytic lesions already are advanced in

size¹². As all lesions bigger than 10 cm³ were identified correctly, and the mean relative error in determining lesion size reached 1.8% ± 18.1 % for lesions bigger than 10 cm³, we conclude that once lesions are radiographically apparent, computed tomography scans can be used to accurately identify lesions and determine their size.

In summary, our study represents the first attempt to design a model for pelvic osteolysis in the presence of total hip arthroplasty components to determine the accuracy of an imaging method. Our data demonstrate that when interpreted by an experienced reviewer, computed tomography combined with the investigated computer-aided image analysis represents a reliable technique to identify pelvic osteolysis. Furthermore, the size of osteolytic lesions can be determined by this method anytime during follow-up without the need for comparison and can be monitored subsequently, if necessary. Clinically, computed tomography combined with the investigated image analysis can be applied to patients with untreated and treated pelvic osteolysis. For patients with either surgically or pharmacologically treated osteolysis, computed tomography can provide an accurate monitoring tool to determine the timing and the effectiveness of osteolysis treatment. For patients with untreated osteolysis, computed tomography can be applied as a three-dimensional imaging method for studying the natural history of osteolysis, particularly the three-dimensional pattern of osteolysis and the three-dimensional development of its size. Furthermore, an understanding of the relationship between the location of pelvic osteolysis and the pattern of bone fixation and remodeling around the acetabular component is of interest, because it can contribute to an understanding about the long-term fate of cementless cups in the presence of pelvic osteolysis.

Table 1: Location and size of all created lesions as measured from the cadaver and the corresponding detection rate of computed tomography

Lesion Location	Mean Lesion Size (cm³) ± Standard Deviation	Number (Percentage) of Lesions Detected by Computed Tomography
Ilium	14.8 ± 7.1*	18/18 (100%) [†]
Ischium	9.0 ± 5.5	7/9 (78%)
Pubis	8.4 ± 5.0	6/12 (50%)
Rim	6.8 ± 5.2	8/9 (89%) [†]
MEAN	10.6 ± 6.7	81.3%
P value	*0.005	[†]0.007

*Lesions of the ilium were statistically larger than lesions in all other groups (one-way ANOVA).

[†]Percentages of lesions detected in the ilium as well as at the rim were statistically greater than the percentages detected in the ischium or the pubis (chi-squared).

Table 2: Location and size of the lesions detected by computed tomography as measured from the cadaver and the corresponding error of computed tomography in determining lesion size.

Lesion Location	Number of Detected Lesions in Cadaver	Mean Lesion Size (cm³) ± Standard Deviation	Absolute Error (cm³) in Assessing Lesion Size (± Standard Deviation)	Relative Error (%) in Assessing Lesion Size (± Standard Deviation)
Ilium	18	14.8 ± 7.1	-1.2 ± 2.1	-9.2 ± 18.4
Ischium	7	9.9 ± 6.1	0.7 ± 3.0	-7.7 ± 39.3
Pubis	6	11.7 ± 4.5	-0.2 ± 2.5	-6.2 ± 20.1
Rim	8	7.5 ± 5.2*	-0.2 ± 1.6	4.6 ± 27.5
MEAN		12.0 ± 6.7	-0.5 ± 2.3	-5.6 ± 24.8
P		*0.05	0.25	0.64

*The mean size of lesions in the ilium was significantly greater than those in the rim but was not different from the mean size of lesions in the ischium or pubis (one way ANOVA).

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Figure Legends

Figure 1: The correlation between lesion volume determined by computed tomography and lesion volume determined from the cadaver for all detected lesions.

Figure 2: The relationship between the volumetric relative error of computed tomography in determining lesion size and the actual lesion size, as measured from the cadaver for all detected lesions.

Figure 3: This left cadaveric hip has a lesion located in the ilium, measuring 9.3 cm^3 in size.

Figure 4A: This right cadaveric hip has a 23.6 cm^3 bone defect in the ilium eroding the medial wall (marked red) and a second 13.9 cm^3 bone defect located at the posterior rim of the cup (marked yellow).

Figure 4B: This is a computed tomography based three-dimensional reconstruction of the right cadaveric hip pictured in Figure 4A. Note the red-colored mold of the lesion and the corresponding bone defect in the ilium with interruption of the medial wall. The lesion size determined by computed tomography is 24.5 cm^3 . Note the yellow-colored mold of a second lesion and the corresponding bone defect at the posterior rim of the cup. The size determined by computed tomography of this lesion is 14.2 cm^3 .