Can the Volume of Pelvic Osteolysis be Calculated without Using Computed Tomography?

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Published online: 27 September 2008
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Abstract The most common method to diagnose and monitor osteolysis is the standard anteroposterior radiograph. Unfortunately, plain radiographs underestimate the incidence and extent of osteolysis. CT scans are more sensitive and accurate but also more expensive and subject patients to more radiation. To determine whether the volume of pelvic osteolysis could be accurately estimated without a CT scan, we evaluated the relationships between CT volume measurements and other variables that may be related to the size of pelvic osteolytic lesions in 78 THAs. Only the area of pelvic osteolysis measured on radiographs, heavy patient activity level, and total volume of wear were associated with the pelvic osteolysis volume measured on CT in the context of the multivariate regression analysis. Despite a strong correlation ($r = 0.93$, $r^2 = 0.87$) between

these three variables and the volume of pelvic osteolysis measured on CT, estimates of pelvic osteolysis volume deviated from the actual volume measured on CT by more than 10 cm^3 among eight of the 78 THAs in this study. CT images remain our preferred modality when accurate assessments of pelvic osteolysis volume are required.

Level of Evidence: Level III, diagnostic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Periprosthetic osteolysis adjacent to an acetabular cup is typically asymptomatic. With time, it can contribute to cup loosening and acetabular fracture [1, 4, 10, 22]. Osteolysis can also increase the complexity and compromise the effectiveness of revision surgery [2]. Currently, the most common method in clinical practice to diagnose and monitor the progression of osteolysis is the standard anteroposterior (AP) pelvic radiograph, occasionally in concert with other views. These radiographs can be used to measure polyethylene wear and the 2-D area of osteolytic lesions. Unfortunately, plain radiographs tend to underestimate the incidence and extent of osteolysis [5, 14, 16, 21, 25]. Lytic lesions in front of or behind the acetabular implant relative to the xray beam source can be obscured by the prosthesis. The 2-D nature of plain radiographs also makes it impossible to directly assess the volume of an osteolytic lesion or the total surface area of the cup that has lost bony contact.

Clinical studies using conventional radiographs have demonstrated patients with high polyethylene wear rates are prone to develop osteolysis [6, 18–20]. However, similar studies using 3-D CT methods have yielded

The Anderson Orthopaedic Research Institute has received funding from Inova Health System and from a cooperative agreement awarded and administered by the US Army Medical Research & Materiel Command (USAMRMC) and the Telemedicine & Advanced Technology Research Center (TATRC) to support this study. Two of the authors (CAE and CAE, Jr.) receive royalties from DePuy, a Johnson & Johnson company. One author (CAE, Jr.) serves as a consultant for DePuy and another author (CAE) owns Johnson & Johnson stock.

Each author certifies that his or her institution has approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

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conflicting results. Looney et al. [16] and Howie et al. [11] reported periacetabular osteolytic volume correlated directly with polyethylene wear. In contrast, Puri et al. [21] found no correlation between osteolytic volume and linear polyethylene wear.

Stulberg et al. [25] has recommended CT as part of an algorithm for evaluating the presence and extent of osteolysis based on age, activity level, wear, and presence of osteolysis on standard radiographs. Having observed in our own clinical practice that not all patients with high wear developed radiographic evidence of osteolysis and not all patients with low wear are free of this complication, and taking into account the underestimation of pelvic osteolysis on standard radiographs, we have routinely recommended CT scans of our THA patients after the fifth postoperative year. CT scans, however, are over 10 times more expensive than an AP pelvis combined with an iliac oblique, require more sophisticated analysis techniques to interpret, and subject patients to over 10 times the radiation of an AP pelvic radiograph. Although the radiation exposure associated with a pelvic CT is considered minimal, it is equivalent to several years of exposure to natural background radiation [24, 27]. Therefore, more investigation is needed to elucidate the role of routine CT scans after total hip arthroplasty.

We hypothesized large osteolytic lesions could be reliably detected on radiographs and that other radiographic, patient- and implant-related factors could be used to accurately calculate the lesion volume in the absence of a CT scan.

Materials and Methods

We analyzed data prospectively collected and stored in our database coupled with a retrospective analysis of routine radiographs and CT scans. The study population was identified by querying our institutional database for all patients with a Duraloc[®] 100 cup, a porous-coated stem, and a conventional Enduron[™] polyethylene liner (DePuy Orthopaedics, Warsaw, IN). A CT scan at least 5 years after surgery and a followup AP radiograph within 3 months of the CT scan were also required as study inclusion criteria. CT images had to be of sufficient quality to enable the assessment of pelvic osteolytic lesions. Radiographs had to be of sufficient quality to assess both pelvic and femoral osteolysis. To measure polyethylene wear, we further restricted the study population to cases with at least three annual followup AP pelvic radiographs (in addition to an immediate postoperative radiograph nominally taken 6 weeks after surgery) with a minimum of 2.5 years between the first and final followup radiographs. The presence or absence of osteolysis was not a selection

criterion for this study. The database supplied all patient demographics (Table 1) and implant characteristics (Table 2). Radiographic factors (Table 3) and CT data were obtained by three independent reviewers as subsequently described. The mean time interval between surgery and the CT scan for the 78 hips (71 patients) that comprised the study population was 7.7 ± 2.2 years (range, 5–14.4 years). We had prior IRB approval for our study.

Radiographic reviews were performed by two independent reviewers: one to analyze AP radiographs for femoral and pelvic osteolysis and component stability (CCP) and one to measure wear (SEB). The reviewer who analyzed the radiographs for osteolysis had prior experience interpreting both CT and radiographic images. A third independent reviewer (HE) evaluated the CT scans. Each reviewer was blinded to the results of the other two reviewers.

Acetabular and femoral fixation were assessed on radiographs using established criteria [7, 8, 17]. Osteolytic lesions were also defined as previously described [9] and, when present, were measured using Martell's Hip Analysis Suite software (University of Chicago Medical Center, Chicago, IL). Depth of seating of the acetabular component to the medial wall was measured by drawing a line perpendicular to the interteardrop line adjacent to the medial edge of the cup and another line adjacent to the lateral side

Table 1. Patient characteristics

Parameter	Value
Gender	
Female	42
Male	36
Preoperative diagnosis	
Osteoarthritis	62
Osteonecrosis	11
Developmental hip dysplasia	2
Posttraumatic arthrosis	2
Inflammatory arthritis	1
Age at surgery (years)*	57.5 ± 12.2 (36–92)
Height (m)*	1.71 ± 0.099 (1.52–1.93)
Weight (kg)*	79.9 ± 17.1 (49.4–147.4)
Body mass index (kg/m ²)*	27.3 ± 5 (19.3–48.5)
Physician-assessed activity level	
Heavy	14
Moderate	46
Light	13
Semisedentary	5

* For continuous variables, the data are expressed as mean $\pm$ standard deviation, with range in parentheses.

Table 2. Implant characteristics

Parameter	Value
Duraloc [®] 100 cup design	78
Enduron [™] polyethylene liner material	78
Polyethylene liner geometry	
4 mm lateralized	62
Standard	13
10° lip	3
Terminal sterilization	
Gas plasma	63
Gamma-in-air standard dose	11
Gamma-barrier standard dose	3
Gamma-barrier low dose	1
Shelf storage duration (years) for 11 gamma-in-air sterilized liners*	1.5 ± 1.5 (0.05–4.9)
Femoral head material	
Cobalt-chrome	70
Ceramic	8
Femoral head diameter	
32 mm	3
28 mm	71
26 mm	3
22 mm	1
Cup outer diameter	
48 mm	2
50 mm	1
52 mm	19
54 mm	18
56 mm	15
58 mm	15
60 mm	5
62 mm	1
64 mm	2
Hole eliminator	
Plug with positive stop	54
Plug without positive stop	15
Not used	9
Porous-coated stem fixation	78

* For continuous variables, the data are expressed as mean ± standard deviation, with range in parentheses.

of the radiographic teardrop, measuring the distance between these two lines, and adjusting for the magnification factor based on the diameter of the femoral head.

The wear measurements and the determination of the polyethylene wear rate and volume were carried out on the serial AP radiographs, which had all been taken with the beam centered over the pubic symphysis while the patient was supine with their legs internally rotated. The volumetric wear associated with the 2-D head penetration

was determined for each followup radiograph relative to the immediate postoperative view with the Hip Analysis Suite software [12]. Using at least three serial AP pelvic radiographs taken at least 0.75 years postoperatively, a least-squares linear regression was used for each hip to determine the slope of the line that best fit the relationship between the volumetric wear and the time in situ [13, 26]. The slope of the linear regression represented the volumetric wear rate of the polyethylene. Total volumetric wear at the time of the CT scan was calculated by multiplying the volumetric wear rate with the followup interval when the CT scan was obtained. Linear wear rates and total linear head penetration were calculated for each hip in the same fashion using the linear head penetration data derived from Hip Analysis Suite.

Helical CT scans were performed at 140 kV (GE LightSpeed[®] VCT, General Electric Co, Waukesha, WI; and Siemens Somatom[®] Sensation 4, Siemens AG, Munich, Germany) and thin axial images (1–3 mm) were reconstructed from raw data. The DICOM-formatted image data were transferred to a personal computer for analysis using a computer-aided imaging program (Muscular-Skeleton Analysis Software, VirtualScopics, Rochester, NY). An automated segmentation algorithm based on a Hounsfield threshold was used to identify the implant. A single observer then traced the boundaries of acetabular osteolytic defects slice by slice. Osteolytic lesions were defined as any demarcated area adjacent to the acetabular component without trabecular bone [16, 21]. The volume of pelvic osteolysis was computed by the software application based on a summation of the user-segmented regions.

To compare the agreement between radiographic and CT findings, sensitivity and specificity were computed for the radiographic interpretation of pelvic osteolysis using the CT findings as a gold standard. Univariate correlations were evaluated to determine the association of pelvic osteolysis volume on CT with each of the patient, implant, and radiographic parameters. A multivariate regression analysis with stepwise variable entry was also performed to determine to what extent any combination of patient, implant, and radiographic factors could be used to estimate the volume of pelvic osteolysis. Patient-related factors considered in our analysis included gender, preoperative diagnosis, age at surgery, height, weight, body mass index, and physician-assessed activity level (Table 1). Implant factors included polyethylene liner geometry and terminal sterilization technique, femoral head material, femoral head diameter, cup outer diameter, and hole plug usage (Table 2). Factors derived from measurement of the radiographs included volumetric wear, volumetric wear rate, linear wear, linear wear rate, cup abduction angle, depth of acetabular seating, femoral osteolytic area, and pelvic osteolytic area (Table 3). Categorical variables were incorporated in the regression

Table 3. Radiographic parameters

Parameter	Value
Time between surgery and CT (years)	7.7 ± 2.2 (5–14.4)
Volumetric wear (cm ³)	1.04 ± 0.66 (−0.33–2.58)
Volumetric wear rate (cm ³ /year)	0.136 ± 0.082 (−0.051–0.335)
Linear wear (mm)	1.86 ± 1.09 (−0.31–4.51)
Linear wear rate (mm/year)	0.24 ± 0.13 (−0.05–0.54)
Number of followup radiographs used to compute wear rate for each hip	6 ± 2.8 (3–21)
Cup abduction angle (°)	39.5 ± 7.6 (22–58)
Depth of acetabular seating (cm)	2 ± 2.8 (−8.2–8.1)
Time between radiographs and CT (days)	10 ± 24 (−71–84)
Femoral lysis area (cm ²) among 45 THAs with femoral osteolysis	1.71 ± 1.85 (0.14–7.96)
Pelvic lysis area (cm ²) among 36 THAs with pelvic osteolysis	3.98 ± 4.04 (0.07–18.47)
Total lysis area (cm ²) among 48 THAs with pelvic or femoral osteolysis	4.59 ± 4.21 (0.07–18.72)

All data are continuous variables and are expressed as mean ± standard deviation, with range in parentheses.

analysis using dummy coding (0, 1) [23]. When coding for parameters such as femoral head diameter that included three or more categories, the THAs in each category were compared to all other THAs in the remaining categories (ie, THAs with 32-mm heads were coded as 1 and all other THAs, including those with 22-, 26-, and 28-mm heads, were coded as 0). Interaction terms were created to accommodate the potential influence of shelf storage after gamma irradiation in air.

The magnitude of each factor's effect was based on the best-fit regression model accounting for the largest portion of the variance in the volumetric pelvic lysis. Because approximately 25 predictor variables were incorporated, an inclusion *p* value of 0.002 (0.05/25) was used for the regression analysis. The amount of variance of the criterion variable (pelvic osteolysis volume measured on CT) that could be accounted for by the predictor variables was characterized by the coefficient of determination, *r*². The equation resulting from the multivariate analysis was then used to calculate a lesion volume for each hip and compared to the volume measured on the CT scan. Limits of agreement using the technique described by Bland and Altman [3] were then calculated to quantify the agreement between CT interpretation of pelvic osteolysis and the estimation of pelvic lysis volume using the optimal regression equation. While the multivariate analysis evaluates how strongly the independent factors are related to

the dependent variable (pelvic osteolysis on CT), the limits of agreement assess how accurately the regression equation estimates the pelvic osteolysis volume for individual cases. Statistical analyses were performed with SPSS (SPSS Inc, Chicago, IL).

Results

Among the 78 THAs included in this study population, 40 had evidence of pelvic osteolysis on CT. The mean pelvic osteolytic lesion volume among these 40 THAs was 19 ± 20.8 cm³ (standard deviation) (range, 0.2–73.1 cm³). Nine hips had pelvic osteolytic lesion volumes of less than 2.5 cm³, 11 had lesions between 2.5 and 10 cm³, 10 had lesions between 10 and 30 cm³, and 10 had lesions greater than 30 cm³. All cups and stems were radiographically stable. Periacetabular osteolysis was identified on plain radiographs in 31 hips of the 40 hips with pelvic osteolysis on CT. Using the CT presence of osteolysis as the gold standard, the interpretation of standard AP pelvis radiographs yielded a sensitivity of 77.5%. Of the nine THAs with osteolysis on CT not identified on radiographs, three hips had defects less than 1 cm³ and the largest lytic defect had a volume of 4.3 cm³. Pelvic osteolysis was read on the radiographs of five THAs without evidence of pelvic osteolysis on CT; thus, the interpretation of standard AP pelvis radiographs yielded a specificity of 86.8%. The areas of the lesions identified on standard radiographs but not identified on CT were all less than 4 cm²; three of these measured less than 1 cm².

For the multivariate analysis, only the area of pelvic osteolysis measured on radiographs (*p* = 4 × 10^{−18}), heavy patient activity level (*p* = 0.00003), and total volume of wear (*p* = 0.002) were associated with the pelvic osteolysis volume measured on CT (Table 4). The single most important factor was the area of pelvic osteolysis (which accounted for 80% variance in the pelvic osteolysis volume, *r* = 0.89, *r*² = 0.80). When combined with heavy patient activity as assessed by the surgeon and total volume of wear, these three factors accounted for 87% of the variance in the pelvic osteolysis volume (*r* = 0.93, *r*² = 0.87). The volumes calculated by the equation based on the multivariate regression were within 5 cm³ of the actual CT volume for 50 hips (64%), between 5 cm³ and 10 cm³ for 20 hips (26%), and more than 10 cm³ for eight hips (10%) (Fig. 1). The limits of agreement between the calculated volume and the actual volume of pelvic osteolysis measured on CT were ± 12.5 cm³, meaning the volume estimation based on the regression equation was within 12.5 cm³ of the volume measured on CT in 95% of cases.

Table 4. Association of pelvic osteolytic lesion volume on CT with patient, implant, and radiographic parameters

Factor	Univariate analysis		Multivariate analysis	
	Correlation coefficient (r)	p value	Incremental r^2	p value
<i>Patient factors</i>				
Gender (male = 1, female = 0)	0.28	0.01		0.60
Preoperative diagnosis				
Osteoarthritis	0.11	0.36		0.24
Osteonecrosis	−0.09	0.41		0.78
Developmental hip dysplasia	0.02	0.86		0.39
Posttraumatic arthrosis	−0.08	0.50		0.33
Inflammatory arthritis	−0.009	0.94		0.45
Age at surgery	−0.14	0.22		0.19
Height	0.09	0.44		0.65
Weight	−0.10	0.40		0.65
Body mass index	−0.17	0.14		0.74
Physician-assessed activity level				
Heavy	0.54	0.000003	0.05	0.00003
Moderate	−0.20	0.08		0.40
Light	−0.22	0.06		0.37
Semisedentary	−0.11	0.32		0.97
<i>Implant factors</i>				
Polyethylene liner geometry				
4 mm lateralized	−0.003	0.98		0.05
Standard	0.06	0.61		0.08
10° lip	−0.11	0.35		0.52
Terminal sterilization				
Gas plasma	−0.37	0.0008		0.18
Gamma-in-air standard dose	0.48	0.00001		0.02
Gamma-barrier standard dose	−0.07	0.56		0.29
Gamma-barrier low dose	−0.06	0.62		0.74
Shelf storage duration for gamma-in-air liners	0.38	0.0007		0.09
Femoral head material (ceramic = 1, CoCr = 0)	0.07	0.54		0.74
Femoral head diameter	0.15	0.19		0.25
Cup outer diameter	0.19	0.10		0.23
Hole eliminator				
Plug with positive stop	−0.25	0.03		0.84
Plug without positive stop	0.17	0.14		0.90
Not used	0.14	0.21		0.67
<i>Radiographic factors</i>				
Years between surgery and CT	0.50	0.000003		0.94
Volumetric wear	0.51	0.000002	0.02	0.002
Volumetric wear rate	0.31	0.005		0.19
Linear wear	0.53	0.0000006		0.84
Linear wear rate	0.30	0.007		0.21
Number of followup radiographs used to compute wear rate for each hip	0.42	0.0001		0.08
Cup abduction angle	−0.18	0.12		0.45
Depth of acetabular seating	0.11	0.34		0.33
Days between radiographs and CT	−0.21	0.06		0.59
Femoral lysis area on radiograph	0.16	0.15		0.74
Pelvic lysis area on radiograph	0.89	4×10^{-18}	0.80	4×10^{-18}

Fig. 1 Among the 78 THAs included in this study, we found a strong correlation ($r = 0.93$, $r^2 = 0.87$) between the actual volume of pelvic osteolysis measured on CT and the calculation of lysis volume derived by multiplying the area of the pelvic defect on radiographs measured in cm^2 by 3.95 (95% CI, 3.46–4.45), adding the volume of wear measured in cm^3 by 4.08 (95% CI, 1.59–6.57), adding 9.56 (95% CI, 5.31–13.81) for patients with heavy activity levels and subtracting 3.49 (95% CI, –6.25 to –0.73) for all hips. However, the calculated values still deviate from exact agreement with the CT volumes (solid dark-gray line), and the limits of agreement are $\pm 12.5 \text{ cm}^3$ (dashed light-gray lines). As a consequence, CT images remain our preferred diagnostic modality when accurate assessments of pelvic osteolysis volume are required.

Discussion

A method to accurately determine the volume of osteolysis is a desirable tool given the potential consequences of large osteolytic lesions. Currently, CT scans are the most sensitive method for diagnosing the presence of osteolysis [5, 14, 21] and the most accurate method for measuring its volume [14, 21]. While large osteolytic lesions can be reliably detected on radiographs, we found that areas of osteolysis measured on the AP radiograph can not accurately estimate the volume of pelvic osteolysis even in concert with other radiographic and patient- and implant-related factors.

One limitation of this study is that biologic and genetic factors that may influence osteolysis were not included in this analysis. More research is needed to identify these factors and quantify their effects. Another major limitation of this study is that although we included a spectrum of defect sizes among our study population, we did not analyze a consecutive series of THAs. We routinely recommend CT scans for all patients, but those with radiographic evidence are more likely to pursue this recommendation. As a consequence, although almost $\frac{1}{2}$ of the hips (38/78) in this study did not demonstrate evidence of osteolysis on CT, the mean defect volume among the 40 THAs with pelvic lysis was 19 cm^3 . This average defect volume is substantially higher than that of several other

published studies (Puri et al. [21], 4.9 cm^3 ; Howie et al. [11], 10.3 cm^3 and 13.3 cm^3 ; Looney et al. [16], 3 cm^3). In addition, results of this analysis are specific to the Duraloc[®] 100 cup with conventional polyethylene.

When we compared estimates of the 3-D CT volume based on the 2-D radiographic area, patient activity and implant wear with the actual CT volume in this study, we found the limits of agreement ranged from -12.5 to 12.5 cm^3 , indicating that the estimates were within 12.5 cm^3 of the actual volumes for 95% of the cases. Using only the radiographic area of the osteolysis, Kitamura et al. [14] reported limits of agreement of -14.6 cm^3 to 18.7 cm^3 . The improvement in agreement in this study can be attributed to the increased sensitivity (77.5% versus 66.7%) and specificity (86.8% versus 72.4%) of the radiographic review (radiographic findings being the most important factor in estimating osteolysis volume) as well as the inclusion of the volumetric wear and activity level as predictor variables. The increased sensitivity and specificity of the radiographic review in the current study is likely due to the larger average defect size (19 cm^3 versus 12.1 cm^3).

Like Looney et al. [16] and Howie et al. [11], we also found the total wear volume was associated with the pelvic lysis volume. This finding supports the recommendation that patients demonstrating substantial radiographic evidence of head eccentricity should also be considered candidates for CT scans to rule out the presence of osteolysis, even when the radiographs appear to be negative.

Our analysis also supports the surveillance algorithm proposed by Stulberg et al. [25]. Patients with evidence of pelvic osteolysis on plain radiographs, those with high wear, and those with heavy physician-assessed activity levels are more likely to demonstrate larger osteolytic lesions on CT scans than sedentary patients with little wear and no obvious radiographic evidence of osteolysis. Unfortunately, however, our analysis results could not accurately estimate the volume of an individual osteolysis lesion.

Because we have been unable to accurately determine the volume of pelvic osteolysis without a CT scan, we would recommend a CT scan whenever the volume of osteolysis needs to be precisely known. We consider a CT scan essential for preoperative planning to definitively evaluate the location and extent of the osteolysis and any cortical perforations, the bony support available to the cup, and the amount of bone graft material necessary to fill the defect (if grafting is planned). A CT scan can be used to confirm the extent of the osteolysis when a lesion appears on radiographs and is especially useful if a surgeon has a threshold for intervention based on lesion size, location, or growth rate. Because some large osteolytic lesions can be missed with standard radiographs, a CT scan may also be

useful in the evaluation of unexplained pain in an active patient with high wear—for example, we have used CT to diagnose pelvic fractures that were not apparent on radiographs. CT scans are also useful for routine followup intervals (every 5 years, for example) if the patient received a new (or novel) bearing surface or implant. These images would allow the surgeon to characterize the outcome associated with new implants more completely [15]. A large archive of CT images could also enable the collection of more detailed data to guide clinical decision making (such as what types of lesions may predispose a patient to pelvic fracture or cup loosening). Currently, the relationships among lesion volume, location, cortical perforation and pelvic architecture and their effect cup loosening and periprosthetic fracture are unknown. Further research is required in this area.

In summary, a CT scan is recommended whenever the exact size, location, and surface area involvement of a lesion is of interest. We continue to recommend routine CT scans to our patients at 5-year intervals to obtain information that can improve followup and clinical decision making. Routine use of CT allows us to identify small lesions, avoid missing large lesions, and more closely follow the 3-D progression of the osteolysis.

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