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Measurement of Bone Defects Adjacent to Acetabular Components of Hip Replacement

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Computed tomography can assist in the detection of periprosthetic osteolysis, but it has not been used to measure the actual volume of bone defects adjacent to hip replacement components because of the scanning artifact caused by metal. The aim of the current study was to develop a spiral computed tomography technique that provides precise and reliable volumetric measurement of bone defects adjacent to uncemented metal-backed acetabular components. Computed tomography scans were taken of small and large defects of known volume created in the ilium in a bovine hemipelvis and a pelvis from a cadaver. Scans were analyzed by two independent observers. The computed tomography operating conditions were determined that enabled volumetric measurements and that were accurate to within 96% for small and large defects and precise to greater than 98% for small and large defects. This computed tomography technique has the capability to measure accurately and precisely the volume of bone defects in the ilium adjacent to metal-backed acetabular components. This technique has clear advantages over plain radiographs. It will allow investigation of the natural history of osteolytic lesions, enhance preoperative planning, and improve monitoring of the outcomes of treatments of osteolysis.

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Although the middle to long-term clinical results of total hip replacement using uncemented metal-backed acetabular components are promising, loss of bone from around these prostheses, termed periacetabular osteolysis, remains a significant concern.[8,9,13,15,22,23] These acetabular components may remain well-fixed in the presence of progressive osteolysis even while the patient is asymptomatic.[22] This may result in prosthesis loosening, for which the patient requires complicated and expensive revision surgery, or major bone grafting before loosening. Although it is recommended that patients with these hip replacements be monitored closely to identify bone loss, there are currently no reliable techniques available to measure the amount of bone loss.

Early identification and quantification of periprosthetic osteolysis using plain radiographs is often difficult or inaccurate.[10] A study by Robertson et al[19] reported that plain radiographs can underestimate bone loss by at least 20%. Computed tomography (CT) scans can reveal osteolysis that is not detectable on plain radiographs and also gives much more information about the extent and anatomic localization of the osteolytic lesions.[19] Computed tomography scanning is used for preoperative planning[3,4,6] and is used as a diagnostic tool to measure volumetric changes of musculoskeletal and other tumors.[25] However, attempts to extend this application of CT scanning to the measurement of osteolytic lesions around total hip replacement prostheses have been limited because of the artifact produced by the metallic components of total hip replacement or the screws used to fix the components.[14,20]

Metal artifact reduction software is available with spiral CT scanning, but, although the advantages of spiral CT scanning in identifying osteolysis have been described,[19] the accuracy of the technique in measuring the volume of osteolytic lesions has not been reported. Therefore, the aim of the current study was to develop a technique using spiral CT scanning that allows precise and reliable measurements of the volume of osteolytic lesions in the bone adjacent to uncemented metal-backed acetabular total hip replacement components.

MATERIALS AND METHODS

Because of the limited availability of pelves from cadavers, the initial development and validation of the CT scanning technique was done using a bovine hemipelvis containing a unilateral total hip replacement prosthesis. Additional validation of the technique was done in a pelvis from a cadaver, into which unilateral and bilateral acetabular components were implanted consecutively.

It has been reported that most osteolytic lesions adjacent to metal-backed acetabular components of total hip replacement are periacetabular, and lesions commonly occur in the ilium in association with fixation screws.[22] Therefore, the current authors examined CT measurements of simulated acetabular bone defects in the ilium in the presence of the acetabular component and the fixation screws.

Specimens

A fresh-frozen hemipelvis from a bovine, comparable in size to an acetabulum in a human, was defrosted from $-20°$ C to room temperature. The bovine acetabulum was orientated in the same anatomic orientation as in the human, and the specimen was mounted in a table vice and the acetabulum was prepared. The acetabulum was reamed initially using a 44-mm outer diameter reamer, followed by 54-, 55-, 56-, and 57-mm outer diameter reamers (Zimmer Inc, Warsaw, IN) to accept a 58-mm outer diameter TiA1V Trilogy fiber metal-coated shell with three screw holes (Zimmer Inc). The acetabular component was implanted into the acetabulum of the specimen in 40° operative inclination and 25° operative anteversion[17] and rotated so that one screw hole was superior, one screw hole was posterosuperior, and one screw hole was anterosuperior. A Kirschner (K) wire was placed through the superior screw hole into the ilium and oriented with its axis parallel to the longitudinal axis of the specimen. After marking the position of the cup on the reamed surface of the acetabulum, the cup was removed. A large, 40-mm deep cylindrical defect was created by drilling over the K wire with a 12-mm cannulated drill. The axis of the large simulated defect was parallel to the longitudinal axis. The procedure was repeated in the posterosuperior screw hole to create a small 25-mm deep cylindrical defect, orientated posterosuperiorly, using a 9-mm cannulated drill (Fig 1).

The volumes of the simulated defects were determined by filling with water and measuring three times using a 0.01-mm graduated 1-mL syringe. The acetabular component was reimplanted using an impactor-positioner (Zimmer Inc). A 30-mm long, 6.5-mm diameter TiA1V self-tapping bone screw (Zimmer Inc) was inserted into the superolateral screw hole so that it engaged in 5 mm of bone distal to the created defect. A 25-mm long similar screw was inserted through the superomedial screw hole with no defect. A Trilogy polyethylene liner (Zimmer Inc) was inserted into the com-

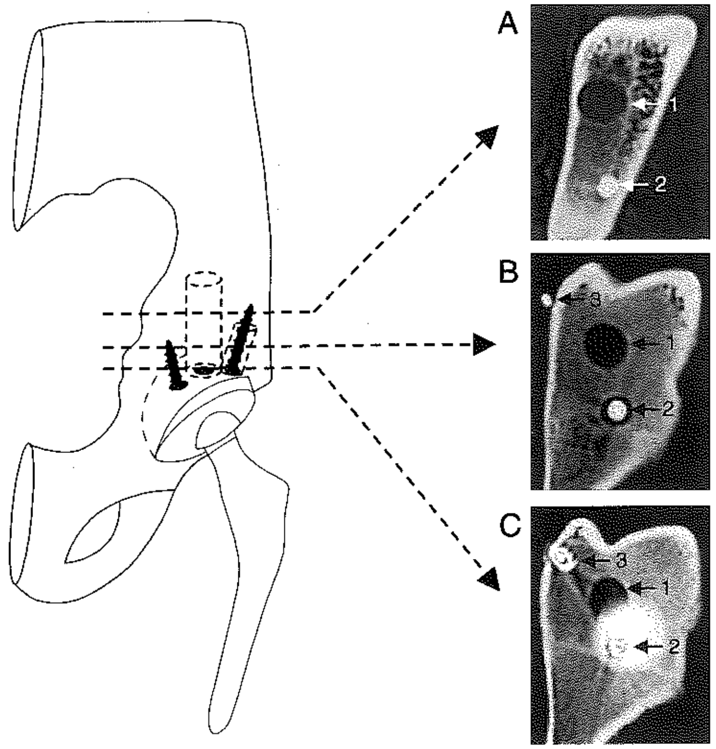

Fig 1. A bovine hemipelvis total hip replacement model is shown. The diagram shows the large bone defect adjacent to the acetabular component and the small defect around a lateral fixation screw. Computed tomography scans at several levels show the following defects: (A) 1, large bone defect; 2, lateral screw; (B) 1, large bone defect; 2, bone defect around lateral screw; 3, tip of medial screw that penetrated medial cortex; and (C) 1, large bone defect; 2, lateral screw with artifact interference from top of acetabular component; and 3, medial screw.

ponent. The specimen was placed into a plastic container and orientated so that its longitudinal axis was parallel to the midline of the container and its sagittal plane was perpendicular to the base of the container. The proximal aspect of the specimen was fixed to the vertical wall of the container with three screws. The ischium was rested on the base of the container and was fixed with one screw. A cementless PCA CoCr alloy femoral stem (Howmedica International, Ltd, Rutherford, NJ) and 28-mm diameter CoCr alloy head (Howmedica International) were positioned into the liner.

An intact pelvis with L4 and L5 vertebra and femoral bones was retrieved from the cadaver of a 70-year-old man. The specimen was defrosted from $-20°$ C to room temperature and the muscles and the hip capsules were removed. The right acetabulum was prepared in the same manner as that for the acetabulum from the bovine, except that 46-mm, 48-mm, 50-mm, and 51-mm outer diameter reamers were used consecutively.

For the human pelvis, one acetabular defect in the ilium was created. A 52-mm outer diameter Harris-Galante-II (Zimmer Inc) uncemented, metal-backed acetabular component was implanted in 40° operative inclination and 25° operative anteversion.[17] The component was fixed with two self-tapping TiA1V screws 6.5-mm diameter and 30-mm long (Zimmer Inc). A polyethylene liner (Zimmer Inc) was inserted into the component. An uncemented Versys fiber metal midcoat femoral stem (Zimmer Inc) was implanted into the right femur, using a standard uncemented technique. A 28-mm CoCr femoral head (Zimmer Inc) was inserted. The pelvis was placed in a supine position so that the spinous tubercles of the sacrum and posterior-superior spines of the ilium rested on the base of a container. The line joining the midpoints of the symphysis pubis and the L5 vertebra was represented as a longitudinal axis of the specimen and was oriented parallel to the midline of the container in the coronal plane. The pelvis was fixed to the container using plastic ties. Both specimens were covered with tap water, which was used to simulate soft tissues during scanning.

To investigate the effects on CT scanning caused by a contralateral total hip replacement, an uncemented metal-backed Trilogy acetabular component (Zimmer Inc) and a cementless PCA CoCr alloy femoral stem (Howmedica International, Inc, London, United Kingdom) and 28-mm CoCr head (Howmedica, International, Inc) were implanted into the contralateral hip and the CT scans of the original study hip were repeated.

Quantitative Computed Tomography

Computed tomography scanning was done using a Picker PQ6000 spiral CT (Picker International Inc, Cleveland, OH) scanner with Voxel Q FALCON metal artifact reduction software (Picker International Inc). Computed tomography scans were taken at 120 kV and 200 mA to maximize the resolution and contrast of the trabecular and cortical bone. To allow standardization of measurements, the top of the sacroiliac joint was used as the anatomic reference point and scans were taken to the end of the ischium. A metal pin was inserted into the ilium of the bovine hemipelvis to mark the reference point.

The simulated bone defects were measured in consecutive CT slices displayed on the computer screen by tracing the inner border of the defect using a computer mouse. Volume measurement was done using algorithms coded into the commercial image-analysis software (PQ6000 Voxel Q FALCON, Picker International Inc).

To determine the optimal CT scanning operating conditions for measuring the volume of bone defects adjacent to metal-backed acetabular components, two parameters were investigated in the cow hemipelvis model. These were the angle of the CT beam, +25° (cephalad), 0° and −25° (caudad), and the two thicknesses of CT slice routinely used in clinical practice, 3 and 4 mm.

Once the protocol and operating conditions were determined, the impact of metal artifact using this protocol then was examined by comparing volumetric measurements of the large defect from CT scans taken with and without the prosthesis in situ. The radiodensity of the bovine bone was markedly higher than that of the bone from an elderly man. The operating conditions and protocol tested in the bovine hemipelvis model therefore were investigated again using the human pelvis model implanted with a unilateral total hip replacement prosthesis and containing a large superior defect adjacent to the acetabular component. To examine the interference effect of a contralateral total hip replacement prosthesis on the volumetric measurements, scans were repeated on the human pelvis after implantation of a total hip replacement prosthesis on the contralateral side.

Statistical Analysis

The accuracy of the volumetric measurements from the CT scans was determined by calculation of the percent error between the manual measurement of the simulated defects, done using water and a syringe and the measurements from the CT scans. Volumetric measurements from the CT scans were repeated five times in each instance by two observers, an orthopaedic research registrar and a research officer. The reliability of the quantitative measurements was determined by calculation of the intraobserver and interobserver errors. The intraobserver error was reported as the percent coefficient of variation and the interobserver error was measured by the percent variance.

Interferential analysis was done using analysis of variance (ANOVA) and the Fisher's least-significant-difference test. Data summary statistics were calculated using Microsoft Excel (Microsoft Corporation, Redmund, WA) and interferential analyses were done using the SAS statistical software package (SAS® System for Windows™ Release 6.12 1989–1996, SAS Institute Inc, Cary, NC). A probability value less than 0.05 was considered to indicate statistical significance.

RESULTS

Bovine Acetabulum Study

The actual volume of the large simulated acetabular defect adjacent to the component, measured using a syringe and water, was 5.03 mL (standard deviation, 0.04 mL). The actual volume of the small defect around the lateral screw was 1.24 mL (standard deviation, 0.02 mL).

The estimated volumes of the large simulated defect measured from each of the CT scans taken using the different operating conditions are shown in Figure 2. There was a significant effect of beam angle and slice thickness on the volumetric measurement of the large defect ($p < 0.0001$). The most accurate measurement of defect volume was obtained using a beam angle of 0° and a slice thickness of 3 mm (error, −1.7%). The volume was significantly greater than the volumes measured from scans taken with a beam angle of +25° and −25° ($p < 0.0001$) and significantly

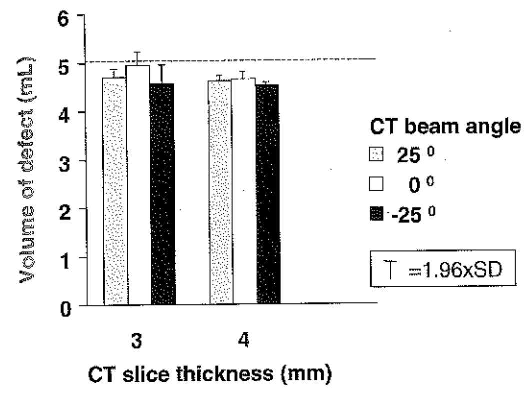

Fig 2. This graph shows the effect of beam angle and slice thickness on the volume of a large acetabular defect measured from CT scans in a bovine hemipelvis model. The dashed line indicates the defect volume measured using water and a syringe. SD = standard deviation.

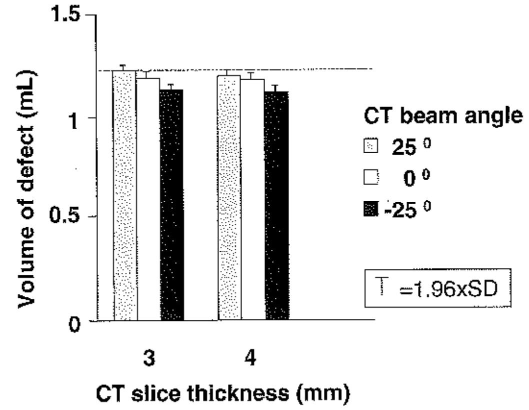

Fig 3. The effect of beam angle and slice thickness is shown on the apparent volume of a small defect around a fixation screw measured from CT scans in a bovine hemipelvis model. The dashed line indicates the defect volume measured using water and a syringe. SD = standard deviation

greater, and closer to the true volume, than that determined from scans taken using a slice thickness of 4 mm and a beam angle of 0° ($p < 0.0001$). The intraobserver error and interobserver error of the volume measurements of the large defect were 2.27% and −2.73%, respectively, using the operating parameters of 3-mm slice thickness and a beam angle of 0°. Using a scan thickness of 3 mm and a beam angle of 0°, there was no significant difference between the volumes measured from the scans taken with and without the prosthesis in situ ($p = 0.944$).

For the small simulated defect around the lateral screw, measurement of the CT scans taken using a beam angle of +25° gave significantly more accurate measures of volume than when using scans taken at 0° ($p < 0.0001$) (Fig 3). The CT scan taken using a beam angle of −25° resulted in the least accurate measurement of volume. There also was a significant difference in the volumes measured from the CT scans taken at 3- and 4-mm slice thickness ($p = 0.0072$). The mean intraobserver and interobserver errors of the volume measurements of the small defect were 0.62% and 0.9%, respectively, using the operating parameters of 3-mm slice thickness and a beam angle of 0°.

Cadaver Study

The actual volume of the simulated acetabular defect adjacent to the component, measured using a syringe and water, was 3.42 mL (standard deviation, 0.03 mL). There was a significant effect of beam angle ($p < 0.0001$) but no effect of slice thickness ($p = 0.647$) on the volume of the defect measured when a unilateral total hip replacement prosthesis was implanted (Fig 4). With a 3-mm slice thickness, the most accurate measurements of the defect volume were obtained with scans taken using a beam angle of 0° (error, −1.9°) and +25° (error, −2.5%), which were both significantly more accurate than measurements taken using a beam angle of −25° ($p = 0.0005$). The intraobserver and interobserver errors for the scans taken at 0° were 2.8% and 2.15%, respectively.

With bilateral total hip replacement prostheses implanted, the volumetric measurements taken using a slice thickness of 3 mm and a beam angle of 0° were less accurate (error, −4.2%) than when a unilateral total hip

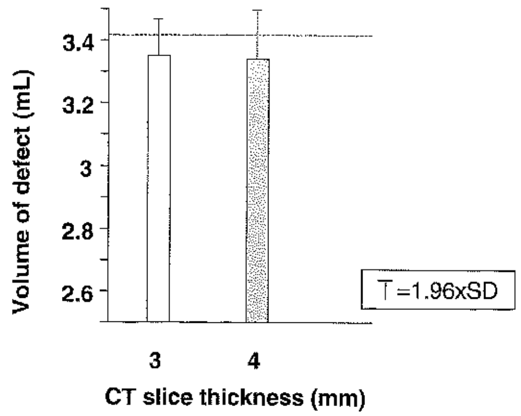

Fig 4. The effect of slice thickness is shown on the volume of bone defect adjacent to the acetabular component measured from CT scans in a pelvis from a cadaver. The beam angle was 0°. The dashed line indicates the defect volume measured using water and a syringe. SD = standard deviation

replacement prosthesis alone was implanted (error, −1.9%) (Fig 5). The difference in the measured volume of the defect in the acetabulum when bilateral total hip replacement prostheses were implanted was not statistically significant ($p = 0.164$) to that measured when

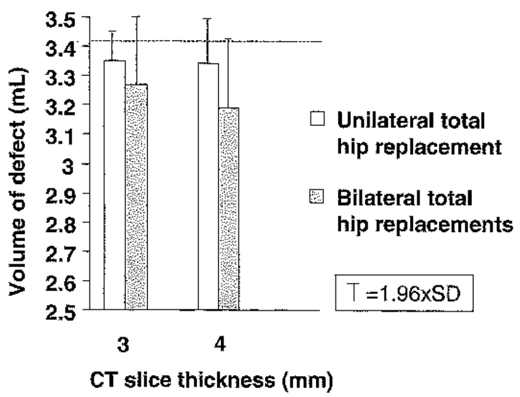

Fig 5. The effect of bilateral total hip replacement is shown on the volume of bone defect adjacent to the acetabular component measured from CT scans of a pelvis from a cadaver. The beam angle was 0°. The dashed line indicates the defect volume measured using water and a syringe. SD = standard deviation

only unilateral total hip replacement prostheses were implanted. The intraobserver (4.2%) and interobserver (−2.3%) errors were similar to those obtained for the unilateral total hip replacement model.

DISCUSSION

In the current study, spiral CT scanning was able to accurately and reliably measure small and large bone defects in the ilium adjacent to Ti metal-backed acetabular components implanted in a bovine hemipelvis and a pelvis from a cadaver. Volumetric measurements of simulated defects were accurate to within 96% for small and large defects and precise to 99% and 98% for small and large defects, respectively. There was a small loss of accuracy in the estimate of the volume of the acetabular defect when a contralateral total hip replacement prosthesis was present, but this was unlikely to be clinically significant. This small loss likely was caused by the artifact from the opposite acetabular component.

The findings described here show that, in experimental models of total hip replacement-associated bone loss, it is feasible to use CT scanning to measure the volume of defects in the cancellous bone superior to metal-backed acetabular implants. Using the scanning parameters that were determined, including CT slice thickness and beam angle, together with metal artifact reduction software, accurate and reliable volumetric measurements can be obtained. The ability to accurately measure different types of defects in the current study of a large acetabular defect adjacent to the component and a small defect around a fixation screw, is likely to be useful in measuring and monitoring similar types of osteolytic lesions in humans.

There were differences in the accuracy of volumetric estimation between CT scans taken with different angles of the gantry. The likely explanation of this is the angle of the gantry. The CT volume measurement of the large defect using a 0° angle of beam had better accuracy than that using +25° or −25°. This was

probably because the longitudinal axis of the large defect was parallel to the longitudinal axis of the specimen resulting in more of the large defect being seen by the axial view at 0°.

The CT volume measurement of the small defect using a +25° angle of beam had better accuracy than that using 0° or −25°. That was probably because the longitudinal axis of the small defect was orientated posteriorly from the tip of the acetabular component. In this position, most of the small defect could be detected only by a posteriorly tilted CT beam, which was +25° cephalad.

This CT technique is likely to be superior to anteroposterior radiographs of the pelvis in measuring osteolysis around total hip replacement acetabular components. Studies using plain radiographs have been restricted to using two-dimensional measurements of osteolysis[16,24] or volumetric measurements using planimetric measurements and mathematic formulas assuming ellipsoidal cavities.[7] Because of the recognized limitations of plain radiographs for identification and localization of osteolytic lesions,[5,12,19,26] these techniques will remain, at best, semiquantitative. Computed tomography scanning, using the techniques described, offers significant advantages and, if the level of accuracy in vivo approaches that in vitro, it will allow definitive studies of the cause and outcomes of treatment of osteolysis.

A criticism of the current study is that simulated defects were used to investigate the usefulness of CT scanning in this application. Osteolytic defects may be filled with granulomatous tissue and fluid and therefore the fluid-filled defects in the current study may not exactly represent the clinical situation. Preliminary studies in patients, however, have resulted in similar CT images as seen in the current model. Clearly this is an area for additional study.

Other imaging methods currently available cannot be used to determine the volume of osteolytic defects adjacent to metallic components of total hip replacement prostheses, but dual energy xray absorptiometry (DEXA)[1,2,11,18] can be used to assess overall bone density. It will be of interest to apply DEXA in parallel with CT scanning to investigate associations between CT measurements and overall bone density measurements. This would be of particular interest in exploring the potential benefit of pharmacologic treatment of osteolysis, including the use of bisphosphonates, in which treatment would be expected to influence bone density generally, and inhibit bone resorption at the specific site of bone loss.

A precise and reliable CT quantitative method for measuring the volume of periprosthetic osteolytic lesions has been described. Although currently a research tool, it is proposed that this technique could be further developed to allow assessment of osteolysis, monitoring of the natural history of periprosthetic osteolysis and its relationship to wear, and the potential benefits of surgical treatment, including bone grafting without prosthesis removal,[21] or pharmacologic treatment.

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