

Periacetabular bone changes after uncemented total hip arthroplasty evaluated by quantitative computed tomography

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Background There are few dual X-ray absorptiometry (DXA) studies on periacetabular bone density changes after cup implantation. This study was designed to analyze the load-transfer mechanism and stress pattern of periacetabular cortical and cancellous bone after implantation of a hemispherical titanium alloy press-fit cup with alumina-alumina pairing in vivo. We introduced a novel method of computed tomography (CT)-assisted osteodensitometry.

Method We investigated 26 hips (26 patients) with osteoarthritis using conventional sequential CT examinations performed within the first 10 days after implantation, and after a mean period of 1.1 years postoperatively. Bone density of full, cancellous and cortical bone (mgCaHA/mL) was measured.

Results At the time of follow-up, the mean bone density values of the cortical bone cranial to the cup increased by 3.6% ($p = 0.03$) while the cancellous bone density decreased by 18%. Cancellous bone loss was greater in the region ventral to the cup (–35%) than in the dorsal region (–30%). Cortical bone density decreased ventral to the cup (–6.4%). All these changes were statistically significant. The bone density changes in the dorsal cortical region were not significant.

Interpretation The method presented is an excellent tool for detailed measurement of bone density changes around the cup after total hip arthroplasty, and allows a thorough assessment of stress shielding phenomena in vivo. The hemispherical titanium alloy press-fit cup is a rigid implant which stress shields cancellous bone and enhances load transfer to the cranial cortical bone. Further investigations will demonstrate the impact these

factors have on the long-term results of the implant, and may allow a type-related predictable prognosis of the longevity of the prosthesis. ■

Compared to numerous investigations of femoral bone stress shielding in total hip arthroplasty, little is known about the load transfer mechanism to periprosthetic pelvic bone after cup implantation.

Finite element analysis of periacetabular stress distribution after total hip arthroplasty has led to postulation of a bone density increase in the cortical bone cephalad to the cup, a decrease in the cancellous bone density in the same region, and extensive attenuation of bone density medial to the cup (Huiskes 1987).

Using DXA, Sabo et al. (1998) analyzed 3 regions of interest (ROI) of periacetabular bone in patients who had received a total hip arthroplasty and found a mean decrease in bone mineral density of –16% for the medial area, of –14% for the cranio-medial area, and of –12% for the cranio-lateral area 2 years after operation. Wright et al. (2001) reported a 20–33% decrease in bone density 1 year after total hip arthroplasty in a CT investigation based on circular cross sections of cancellous bone above the dome of the acetabular component.

We hypothesised that after the implantation of a rigid titanium alloy cup, a marked change in bone density of the pelvis would occur due to an altered load transfer mechanism and stress shielding. This

is the first study to assess stress patterns of periacetabular bone *in vivo* using quantitative CT data with a separate analysis of cancellous and cortical bone structures.

Patients and methods

26 consecutive patients (26 hips, 15 men) with osteoarthritis were operated by one surgeon and analyzed prospectively. An uncemented total hip prosthesis with a titanium hemispherical press-fit acetabular component with alumina-alumina pairing and a tapered stem (Cerafit, Ceraver Osteal, Paris, France) was implanted. The average patient age was 58 (39–65) years. Patients with malignant disease, rheumatoid arthritis and femoral head necrosis were excluded from the study. The study was approved by the local ethics committee. All patients signed an informed consent sheet.

Conventional sequential CT examinations (Somatom Plus 4; Siemens, Erlangen, Germany) were performed. The slice thickness of scans was 2 mm, and the table feed (distance between 2 scans) was 10 mm. A standardized scan mode was used with 140 kV, 206 mA and a field of view of 150 × 150 mm. CT examinations were performed within the first 10 days of surgery and one year postoperatively. Clinical examination was performed using the CART score (Johnston et al. 1990), which was then converted to the Harris hip score.

The patient was placed resting in supine position. On the frontal scout images, pelvic rotation within the axial plane was assessed by analyzing the morphology of the obturator foramen and the alignment between the symphysis pubis and the lumbar spinous processes. For the 1-year control examination, patients were repositioned until the position of the pelvis matched the postoperative analysis. For a better delineation of the prosthesis-bone-interface, an extended CT scale was applied for the reconstruction of the images. This permits the visualization of materials with attenuation values of up to 20,000 Hounsfield units (Kalender 2000).

For calibration and validation of the CT values and for the conversion into hydroxyapatite equivalents, we used a synthetic (anthropomorphic) phantom containing a circular sample with a defined hydroxyapatite (HA) concentration during each

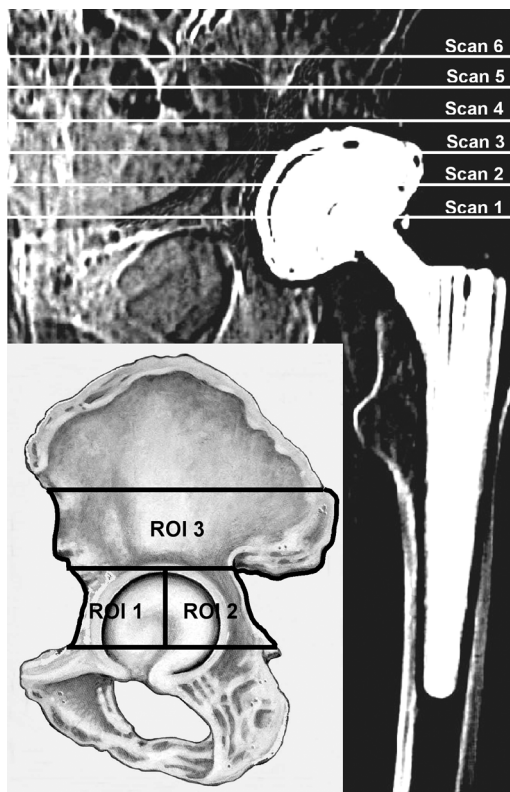


Figure 1. Frontal topogram with CT scan levels. Three scans (Scans 1 to 3) have been performed at the level of the cup (ROI 1 and 2) and three scans (Scans 4 to 6) have been performed above the cup (ROI 3).

examination (Kalender 1992). It was scanned after the patient had been removed from the scanning table to avoid metal artifacts of the implant interfering with the phantom. 3 scans were taken at the level of the acetabular component and three above the dome of the cup, the first of which was 30 mm above the rim of the cup (Figure 1). Corresponding measurements were made of the contralateral side.

We evaluated the data with a special software tool (CAPPapostOP; CAS Innovations, Erlangen, Germany). Cancellous and cortical bone of each scan was segmented manually (Schmidt et al. 2005). After segmentation of cancellous and cortical bone, Hounsfield unit values were given automatically for the defined bone portions. The data were converted into hydroxyapatite equivalents. Bone density (mg CaHA/mL) and area (mm²) of cancellous and cortical bone were analyzed (Figure 2).

The 3 acetabular scans were each divided into a dorsal and a ventral part, which were then summed

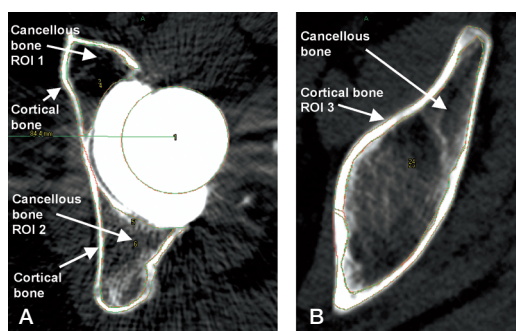


Figure 2. Manual segmentation of the bone structures: ROI 3 is cranial to the cup (A); ROI 1 is the ventral retroacetabular portion, and ROI 2 is the dorsal retroacetabular portion (B).

up to ROI 1 (ventral) and 2 (dorsal). The 3 scans cephalad to the dome of the implant were summarized to a cranial ROI (3) (Figures 1 and 2). Bone density values of ROI 1, 2 and 3 were calculated with consideration given to the area (mm²). According to the following expression, full, cancellous and cortical bone was analyzed separately for each ROI:

$$\text{BD of ROI} = \frac{(a_1 \cdot \text{BD}_1) + (a_2 \cdot \text{BD}_2) + (a_3 \cdot \text{BD}_3)}{a_1 + a_2 + a_3}$$

where a = area (in mm²) of the respective ROI for CT scans 1, 2, and 3, and BD = bone density (mg CaHA/mL) of the corresponding ROI for CT scans 1, 2, and 3.

Statistics

The quantitative measurements are described as mean values (SD). The target measure was intra-individual difference between the postoperative measurement and the 1-year evaluation. We used the Wilcoxon-signed-rank test for comparison of paired data with abnormally distributed differences. P-values equal to or smaller than 0.05 were considered significant. All calculations were made using SPSS version 10.

Results

All 26 hips included in the study were available for investigation at a mean follow-up of 1.1 (1–1.3) years. The mean Harris hip score was 43 (39–65)

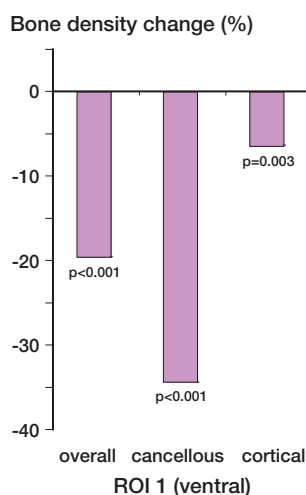


Figure 3. Change in bone density in ROI 1 one year post-operatively compared to baseline values (pairwise differences, Wilcoxon signed-rank test).

points before the index operation and 91 (85–96) points after surgery. The operation reduced pain and increased the function for all patients, who were all satisfied with the outcome. The native radiographs (pelvis anterior-posterior and lateral view of the operated hip) showed no signs of loosening or focal osteolysis in any of the implants. Further subdivision of this group, e.g. on consideration of the cup angle, was not undertaken due to the limited number of hips.

The periacetabular bone, divided into the ventral (ROI 1) and dorsal (ROI 2) portion, showed a significant decrease in cancellous bone density. Cancellous bone loss was greater in the ventral region than in the dorsal sector. Cortical bone density decreased significantly in ROI 1, while little change was observed in ROI 2. Overall bone density was significantly reduced in both ROI 1 and ROI 2 (Figures 3 and 4; Table 1).

1 year after THA, the mean bone density values of the cortical bone cranial to the acetabulum (ROI 3) increased while the cancellous bone density decreased. Overall bone density (cortical + cancellous bone density) decreased (Figure 5; Table 1). No significant changes in bone density were observed for the contralateral side 1 year after THA.

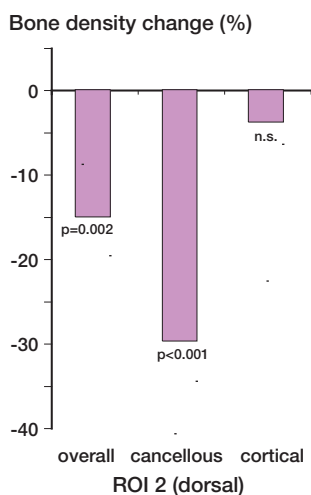


Figure 4. Change in bone density in ROI 2 one year post-operatively compared to baseline values (pairwise differences, Wilcoxon signed-rank test).

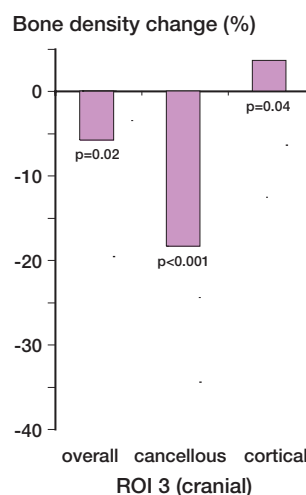


Figure 5. Change in bone density in ROI 3 one year post-operatively compared to baseline values (pairwise differences, Wilcoxon signed-rank test).

Table 1. Description of postoperative/follow-up measurements and pairwise differences

Area	Type of bone	Mean value (mgCaHA/mL)			Changes in percent
		post-operatively	at follow-up	of pairwise differences (SD)	
ROI 1	overall	330	270	-65 (61)	-20
	cortical	630	590	-40 (63)	-6.4
	cancellous	200	130	-67 (55)	-35
ROI 2	overall	280	240	-43 (64)	-15
	cortical	610	580	-23 (84)	-3.8
	cancellous	160	120	-49 (53)	-30
ROI 3	overall	370	350	-21 (47)	-5.8
	cortical	740	760	27 (62)	3.6
	cancellous	200	160	-37 (43)	-18

Discussion

The newly designed CT-assisted method we used aims to quantify overall, cortical and cancellous pelvic bone at the acetabular dome as well as ventral and dorsal to the implant according to 3 defined ROI. By analyzing the bone density changes, we were able to assess the load-transfer mechanism and stress pattern of the pelvis after total hip arthroplasty. Changes in bone density induced by the general catabolic response to trauma, especially of cancellous bone, cannot be excluded fully. We believe this effect to be minute. Our own studies with cemented cups showed a significantly lower cancellous bone density loss compared to press-fit

cups, even though the trauma caused by cement polymerization seems to be potentially higher. After studying the current literature, we expected the insertion of the cup to alter the physiological stress transfer at the level of the ilium, thus leading to marked bone density changes of the pelvis.

ROI 3 (cranial to the cup)

Finite-element studies on stress distribution at the top rim of acetabular implants are controversial. Simulation of metal-backed uncemented components showed stress concentration at the dome of the component with load transfer to the peripheral (cortical) bone cephalad to the acetabulum, and a

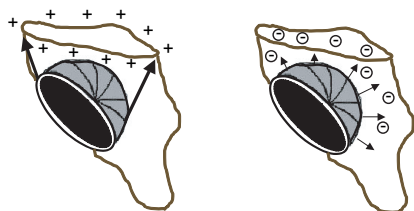


Figure 6. The press-fit cup is a rigid implant which enhances load transfer to the cranial cortical bone (+) and stress shields cancellous bone (-).

decreased stress distribution to the central (cancellous) bone (Huiskes 1987, Huikes et al. 1989). In contrast to the results of these examinations, a finite element model of Levenston et al. (1993) showed little change of the bone mineral density at the ilium in the presence of a metal-backed cup. The authors argued that the implantation of an acetabular component would not alter the basic load transfer mechanism at the level of the ilium. CT investigation of a cancellous iliac bone cylinder, only, above the top rim of the acetabular component showed a decrease in bone density (Wright et al. 2001). In accordance with the finite element analysis of Huiskes (1987), and also with the CT study of Wright et al. (2001), our results suggest a distribution of the bone load to the cortical part and a marked decrease in cancellous bone density (Figure 6). Due to the limited value variability (only overall bone mineral density was measured), the DXA study of Wilkinson et al. (2001) could not show such detailed results. Overall bone mineral density was the only value reported in their study. It increased significantly (by 2.5%) superior to the top border of the cup.

ROI 1 and 2 (ventral and dorsal to the cup)

Analyzing computer modeling techniques, Levenston et al. (1993) predicted extensive attenuation of bone density medial to the cup in uncemented total hip arthroplasty, similar to our ROI 1 and 2. Wilkinson et al. (2001) assessed 4 axial ROI of the acetabular bone by DXA measurements with the implant in the anterior-posterior view. 13 months after total hip arthroplasty, significant decrease in bone mineral density (-4.7%) was observed in the distal medial area adjacent to the acetabular cup. This was also the sector in which we measured the highest loss of cortical, cancellous and overall bone density. In accordance with Wolff's Law, the

reduction of stresses relative to the natural situation causes bone to adapt itself by reducing its mass. Our findings suggest that the metal-backed press-fit cup—with a much higher stiffness than the surrounding bone—redistributed the load away from the central (cancellous) bone to the cranial peripheral (cortical) bone.

Comparison of CT and DXA

In the present 3-D volumetric BD evaluation axial CT-scans were analyzed with a high resolution compared to 2-D low resolution DXA measurements (Gluer et al. 1993, Genant et al. 1996). We could analyse the circumferential structure of cortical and cancellous bone separately, whereas with DXA only single zones of interest in the a.p. view can be evaluated (Engh et al. 1992, Sabo et al. 1998). While the advantages of CT-assisted osteodensitometry over DXA analysis concerning high resolution and accuracy are obvious (Schmidt et al. 2000), the disadvantage of comparatively high radiation (2–4 mSv) must be mentioned. The CT-assisted periprosthetic evaluation of the pelvic bone after total hip arthroplasty by Wright et al. (2001) only measured bone density of the central cancellous bone of the ilium directly cephalad to the press-fit cup. No separate circumferential evaluation of cortical and cancellous bone was undertaken; nor was the bone density measured ventral and dorsal to the cup (Table 2).

Conclusion

While the effect of regional bone density changes induced by surgical trauma must be considered, our study is the first to suggest an altered stress transfer at the level of the ilium after cup insertion *in vivo*, with a differentiated analysis of cortical, cancellous and overall bone density.

The high loss of cancellous bone density is indicative of stress shielding. The load transfer to the cancellous bone is inhibited by the rigid cup. Cortical bone experiences minor loss, no change, or even increase cranial to the cup. This highlights the results of the finite element studies (Huiskes 1987, Huikes et al. 1989) which predicted load transfer from the cup to the cortical bone.

Further investigations are necessary to demonstrate the effect of cup positioning, subchondral bone removal, and different cup designs and mate-

Table 2. Features of different methods used for quantitative periprosthetic osteodensitometry between conventional DXA, vertebral CT-software and the current CT-volumetric study

DXA Wilkinson et al. (2001)	Vertebral CT-software Wright et al. (2001)	CT (CAPPapostOP) (current study)
area densitometry	vol. densitometry	vol. densitometry
2-D measurement	3-D measurement	3-D measurement
low resolution	high resolution	high resolution
low radiation	high radiation	high radiation
ventral and dorsal portions of the acetabulum are not detectable	only bone cranial to the cup is measured	bone ventral, dorsal and cranial to the cup is measured
analysis of single zones of interest	no analysis retroacetabular analysis of only cancellous bone	separate analysis of cortical and cancellous bone
no circumferential evaluation of bone structures	no circumferential evaluation of bone structures	circumferential evaluation of bone structures

rials on stress transfer mechanisms of the ilium after cup insertion. Ultimately, our method should be capable of demonstrating the influence these factors have on the long-term results of the implant. It may also allow a type-related predictable prognosis of the longevity of acetabular components.

Contributions of authors

All authors have participated in the conception and design of this work and its intellectual content. They have all contributed to writing and editing of the manuscript. Analysis of data was undertaken by LAM and AK.

No competing interests declared.

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