Proximal humeral fractures: Regional differences in bone mineral density of the humeral head affect the fixation strength of cancellous screws

Markus J. Tingart, MD,[a] Janne Lehtinen, MD,[b] David Zurakowski, PhD,[cd] Jon J. P. Warner, MD,[b] and Maria Apreleva, PhD,[a] *Boston, MA**

The purpose of this study was to investigate the 3-dimensional trabecular bone mineral density (BMD) in the humeral head and determine the effects of trabecular BMD on the pullout strength of cancellous screws. Five regions of interest (ROIs) were defined in the humeral head (superior- anterior, superior-posterior, central, inferior-anterior, and inferior-posterior). The trabecular BMD of each ROI was determined by use of peripheral quantitative computed tomography. Cancellous screws were inserted in each ROI and cyclically loaded. The superior-anterior ROI had a lower trabecular BMD than all other ROIs (P $<$ .001). The central ROI had a higher trabecular BMD than the inferior-anterior ROI (P $<$ .01), whereas no differences were found between the inferior-posterior, superior-posterior, and central ROIs. Pullout strength was lower in the superior-anterior ROI compared with all other ROIs (P $<$ .01). The trabecular BMD and pullout strength were significantly correlated (P $<$ .01). Placement of screws in regions with a higher trabecular BMD may help to prevent implant loosening and may improve patient outcome. (J Shoulder Elbow Surg 2006;15:620-624.)

Fractures of the vertebrae, distal radius, proximal femur, and proximal humerus in elderly patients are often a result of osteoporotic bone changes. Proximal humeral fractures account for 5% of all fractures.[2,7,9]

From the [a]Orthopaedic Biomechanics Laboratory, Beth Israel Deaconess Medical Center, Harvard Medical School, [b]Department of Orthopaedic Surgery, Massachusetts General Hospital and [c]Departments of Orthopaedic Surgery and [d]Biostatistics, Children's Hospital.

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Reprint requests: Maria Apreleva, PhD, Orthopaedic Biomechanics Laboratory, Beth Israel Deaconess Medical Center, Harvard Medical School, 330 Brookline Ave, RN 115, Boston, MA 02215 (E-mail: *Maria.Apreleva@gmx.net*).

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In the United States alone, 300,000 fractures of the proximal humerus occur annually.[7,8] Of these fractures, 80% can be treated conservatively with early physical therapy, whereas 60,000 displaced fractures require surgery.[7] Different techniques are used for internal fixation of displaced proximal humeral fractures. They can be stabilized with tension bands, K-wires, screws, and plates.[5] Independent from the method chosen for fracture repair, reduced bone mass and bone quality of the humeral head complicate internal fixation. Inadequate implant fixation may result in implant loosening, fracture redisplacement, and poor patient outcome.[4–7,13]

Little is known about the relationship between bone mineral density (BMD) and the strength of internal fixation of proximal humeral fractures. Williams et al,[13] investigated the effect of BMD, determined by dual-energy x-ray absorptiometry (DXA), on the strength of figure-of-8 wire alone or wire supplemented with Ender rods. In their study, tension banding combined with Ender rods showed that maximum load was increased 15-fold compared with that without the rods, whereas no correlation was found between total BMD and fixation strength.[13]

The 2-dimensional DXA technique does not allow for assessment of spatial distribution of bone mass and separation between trabecular and cortical BMD. However, trabecular BMD may be particularly important for fixation strength of implants such as cancellous screws, because the humeral head mainly consists of trabecular bone and has only a thin cortical shell.[3] Therefore, a more systematic analysis of trabecular BMD might be required to identify regions within the humeral head that may provide higher pullout strength of cancellous screws.

The objectives of this study were (1) to investigate the 3-dimensional distribution of trabecular BMD in the humeral head by use of peripheral quantitative computed tomography (pQCT) and (2) to determine the effects of trabecular BMD on the pullout strength of cancellous screws.

We hypothesized that a higher trabecular BMD is associated with a higher pullout strength of cancellous screws. This study will help identify bone loca-

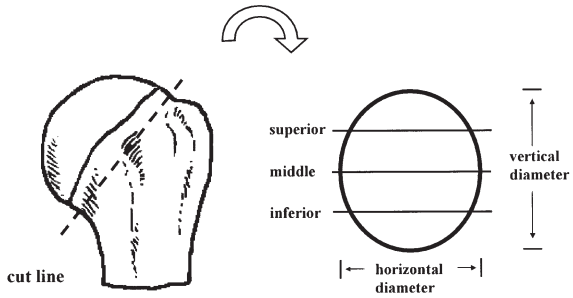

Figure 1 The proximal humerus was cut at the anatomic neck to separate the humeral head. The vertical and horizontal diameters were measured, and the superior, middle, and inferior levels were defined.

tions that provide a stronger fixation for implants and, thus, reduce the risk of implant loosening and fracture redisplacement.

MATERIALS AND METHODS

Specimen selection and preparation

Eighteen unpaired human humeri were harvested fresh and stored frozen at a temperature of −20°C. Specimens were thawed at room temperature for 24 hours before testing. After thawing, specimens were dissected free of all soft tissue, and biplanar radiographs were used to detect any bone abnormalities of the proximal humerus. Specimens having previous proximal humeral fractures, other underlying pathologic changes, or surgical intervention were excluded from the study. Of the specimens, 2 did not meet the inclusion criteria and 16 (12 male and 4 female, mean age, 71 years [range, 59–88 years]) were included.

Measurement of trabecular BMD

The humeral head was cut off of the proximal humerus at the anatomic neck with a band saw (Figure 1) and vertical (50.1 ± 3.6 mm) and horizontal (45.1 ± 3.5 mm) diameters were measured with a digital caliper (Mitutoyo Co, Tokyo, Japan), (error, ±0.02 mm). The superior, middle, and inferior levels were defined on the cut surface of the humeral head by dividing it into 3 equivalent regions (Figure 1). Trabecular BMD was determined at each level by use of pQCT (XCT- 960A, Norland/Stratec, Fort Atkinson, WI). For pQCT scanning, the humeral head was fixed horizontally in a custom-made jig, and axial scans were obtained perpendicular to the surface (pixel size, 0.59 mm, slice thickness, 2.5 mm) (Figure 2). On the pQCT scans at the superior and inferior level, trabecular BMD was determined independently for the anterior and posterior part of the humeral head

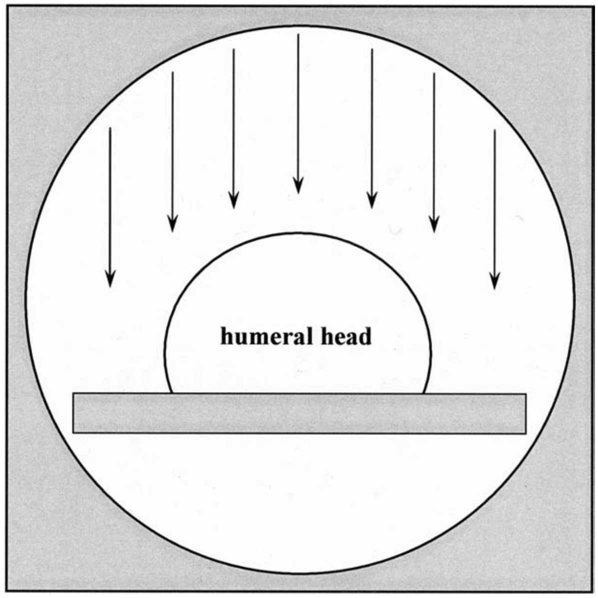

Figure 2 Axial pQCT scans of the humeral head were performed at the superior, middle, and inferior levels to determine trabecular BMD.

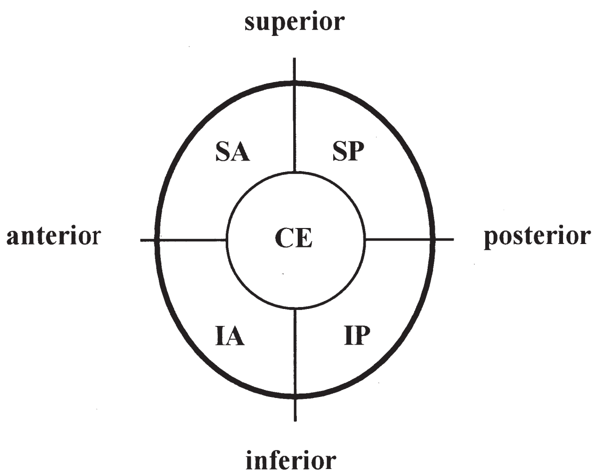

Figure 3 Cancellous screws were placed in 5 different ROIs of the humeral head.

(superior-anterior [SA] superior- posterior [SP], inferior-anterior [IA], and inferior-posterior [IP]), whereas at the central level, trabecular BMD was calculated for the middle third of the humeral head cross section (central [CE]) (Figure 3).

Pullout tests of cancellous screws

The cut surface of the humeral head was divided into 4 quadrants of the same size by a horizontal and vertical line, running through the center of the surface. Overall, 5 regions of interest (ROIs) were defined for

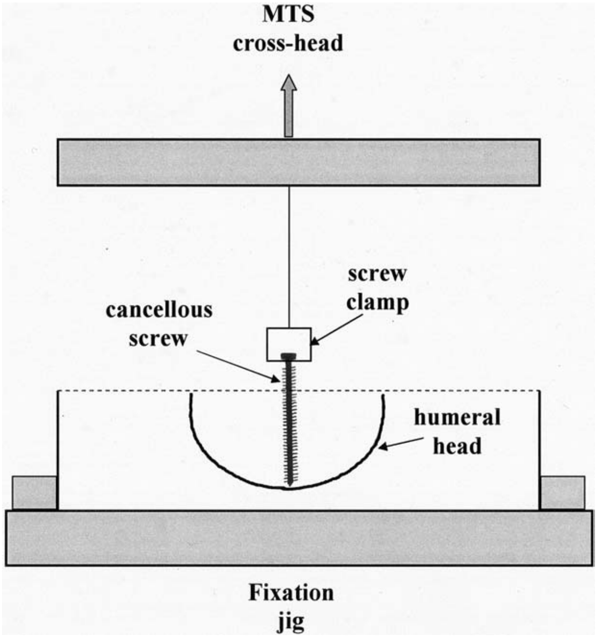

Figure 4 The humeral head was fixed horizontally in a custom-made jig and connected to the material testing machine (*MTS*) for cyclic pullout testing of cancellous screws.

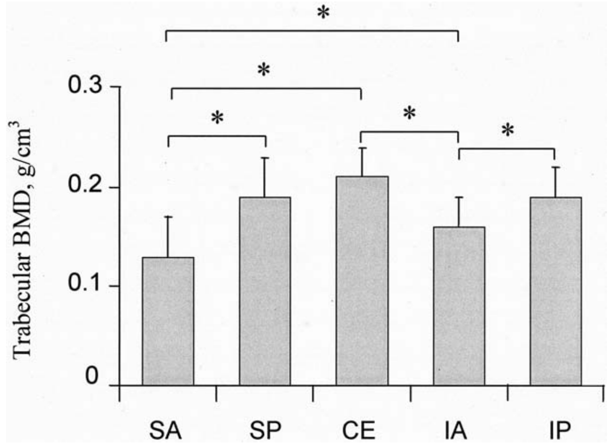

Figure 5 Trabecular BMD of specific ROIs of humeral head (mean ± SD) (*asterisk*, $*P < .01$). Statistical comparisons between ROIs are described in the text.

placement of cancellous screws, one in the center of each quadrant (SA, SP, IA, and IP) and the fifth in the center of the cut surface (CE) (Figure 3).

Each humeral head was fixed in a custom-made jig with the cut surface in a horizontal position (Figure 4). In the center of each ROI, 3.2=mm holes were drilled, 6.5= mm threads were tapped, and fully threaded cancellous screws (6.5 mm, Synthes Co, Monument, CO) were inserted. Before insertion of the screws, the depth of each predrilled hole was measured with a digital caliper (Mitutoyo Co) (error, ±0.02 mm). The screw head was fixed in a custom-made clamp and connected to the cross-head of a material testing machine (Bionix 200, MTS Systems Co, Eden Prairie, MN) (Figure 4). Screws were cyclically loaded with a preload of 5 N and an extension rate of 1 mm/s. A maximum of 80 cycles was performed. Load was increased in 100-N increments after each 10 cycles, starting with a load of 100 N (maximum, 800 N). If screws had not pulled out after 80 cycles, linear load to failure was applied. For each pullout test, the failure load was calculated as the primary outcome parameter. Furthermore, the number of cycles and total load were determined. Total load was defined as the sum of load that each anchor sustained during cyclic testing plus the final failure load. For example, if an anchor pulled out after completing the first 10 cycles ($10 \times 100 = 1000$ N) with a failure load on the 11th cycle of 125 N, the resulting total load would be 1,125 N. Total load for those specimens completing 80 cycles was equal to 36,000 N plus the failure load. Real-time data acquisition was performed by use of Test Works software (version 4.04 B; MTS Systems, Co), and load-elongation data for each screw in each bone location were recorded.

Statistical analyses

Trabecular BMD, failure load, number of cycles completed, and total load were checked for normality by use of the Kolmogorov-Smirnov test and were found to follow a normal Gaussian-shaped distribution.[1] Therefore, data are reported as mean ± SD. Mixed-model analysis of variance (ANOVA) with repeated measures was used to compare ROIs with respect to trabecular BMD, failure load, number of cycles completed, and total load, controlling for depth of screw insertion as a continuous covariate and region of the humeral head as a fixed factor.[11] The Pearson product- moment correlation coefficient (r) was calculated to measure the association between trabecular BMD versus (1) failure load, (2) number of cycles completed, and (3) screw insertion. Statistical analysis was performed with the SPSS statistical package (version 11.0; SPSS Inc, Chicago, IL). A 2-tailed $P < .05$ was considered statistically significant, and a value of $P < .01$ was used to indicate highly significant.

RESULTS

Trabecular BMD of different ROIs of humeral head

Overall, the trabecular BMD at the superior level (0.159 ± 0.042 g/cm^3) was lower than that at the inferior level (0.173 ± 0.035 g/cm^3) ($P < .01$). The posterior half of the humeral head (0.186 ± 0.039 g/cm^3) showed a higher trabecular BMD than the

Table I BMD of humeral head and pullout strength of cancellous screws according to ROI

ROI	Screw insertion (mm)	Trabecular BMD (g/cm³)	Failure load (N)	No. of cycles	Total load (N)
SA	19.3 ± 3.6	0.13 ± 0.04	505 ± 236	41 ± 24	13,330 ± 12,488
SP	19.1 ± 3.4	0.19 ± 0.04	597 ± 225	50 ± 22	17,403 ± 11,960
CE	23.4 ± 3.4	0.20 ± 0.03	738 ± 220	62 ± 18	24,700 ± 12,745
IA	19.4 ± 2.7	0.16 ± 0.03	600 ± 185	50 ± 18	16,394 ± 10,416
IP	20.0 ± 2.9	0.19 ± 0.03	636 ± 190	55 ± 20	20,212 ± 11,500

Statistical comparisons between ROIs are described in the text.

Table II Correlations between trabecular BMD of humeral head and pullout strength of cancellous screws according to ROI

	Pearson correlation (*r*)		
ROI	BMD vs failure load	BMD vs No. of cycles	BMD vs total load
SA	0.83*	0.80*	0.71*
SP	0.66*	0.67*	0.62*
CE	0.61*	0.59*	0.60*
IA	0.28	0.30	0.33
IP	0.35	0.25	0.17

*$P < .01$.

anterior half (0.145 ± 0.039 g/cm³) ($P < .01$). A higher trabecular BMD was found for CE than for SA and IA ($P < .01$), whereas no significant differences were seen between CE, SP, and IP ($P > .01$) (Figure 5 and Table 1). The trabecular BMD of IA and SP was higher than that of SA ($P < .01$). The trabecular BMD of IP was higher than that of IA and SA ($P < .01$), whereas no significant differences were found between IP and SP ($P > .01$).

Pullout strength of cancellous screws in different ROIs of humeral head

Mixed-model ANOVA controlling for depth of screw insertion indicated a significantly lower failure load, number of cycles, and total load in the SA region compared with each of the other 4 regions of the humeral head ($P < .05$) (Table I). No significant differences in pullout strength were seen between the superior and inferior half of the humeral head and between the anterior and posterior half. Furthermore, no other regional differences were observed.

Statistical correlations between trabecular BMD and pullout strength parameters

Trabecular BMD was positively correlated with failure load in the SA ($r = 0.83$, $P < .01$), SP ($r = .66$, $P < .01$), and CE ($r = .61$, $P < .01$) regions of the humeral head but was not significantly correlated in the IP or IA region (Table II). Similarly, trabecular BMD was positively correlated with the number of cycles completed in the SA ($r = 0.80$, $P < .01$), SP ($r = .67$, $P < .01$), and CE ($r = .59$, $P < .01$) regions but was not significantly correlated in the IP or IA region (Table II).

DISCUSSION

Implant loosening as a result of poor bone quality is a serious complication after internal fixation of displaced fractures of the proximal humerus.[4–6,13] In this study, we investigated the relationship between trabecular BMD and the pullout strength of cancellous screws and determined regions in the humeral head that provide stronger fixation for cancellous screws. A significant correlation was found between trabecular BMD and pullout strength of cancellous screws. The highest pullout strengths were seen in the center of the humeral head, whereas the superior-anterior region showed the lowest. These findings correlated well with the results of Liew et al,[6] who performed linear load-to- failure pullout testing of cancellous screws in the humeral head. However, they found mean pullout forces that were up to 7 times lower than those in our study, whereas the screw diameter and screw insertion depth were comparable.[6] The higher failure loads in our study may be attributed to the way the load was applied to the screws. We performed cyclic testing and chose a higher displacement rate, because it represents more physiologic loading.[4,5]

Previous studies investigated the effect of bone quality on the strength of internal fixation for proximal humeral fractures.[5,13] Koval et al[5] evaluated the strength of different internal fixation techniques in fresh-frozen and embalmed proximal humeri, assuming embalmed specimens to be more osteoporotic. They found significantly higher fixation strengths for T plates and screws than for figure-of-8 tension bands. Furthermore, the fixation strength of implants was significantly lower in embalmed specimens than in fresh-frozen specimens. However, using embalmed specimens may not be representative of osteoporotic bone changes, because the embalming process may not alter BMD, even if it affects the mechanical properties of bone.[5,10,12]

Williams et al[13] investigated the influence of BMD on the torsion strength of figure-of-8 fixation and Ender rods. They found significantly higher torsion strengths for figure-of-8 wire combined with Ender rods than for figure-of-8 wire alone, whereas no significant correlation was seen between total BMD and torsion strength. However, total BMD of the humeral head may be less important for the fixation strength of cancellous screws, blade plates, or intramedullary rods than trabecular BMD. Because 2-dimensional DXA does not allow discrimination between trabecular and cortical bone, we investigated trabecular BMD using 3-dimensional pQCT. Our results showed significant differences in trabecular BMD for specific regions of the humeral head and a significant correlation between trabecular BMD and pullout strength of cancellous screws.

We investigated the effect of BMD on the pullout strength of cancellous screws. However, there are other different implants and fixation techniques described in the literature for internal fixation of proximal humeral fractures.[4,5,13] Other fixation techniques may have shown different failure patterns and failure loads, had they been tested in our experiment. Furthermore, the association between the pullout strength of these implants and BMD might have been different when compared with the correlations we found in our study. This might be considered to be a limitation of our study, but with a better knowledge of the trabecular bone distribution within the humeral head, other fixation techniques also might benefit from our results.

By performing mixed-model ANOVA, a relevant effect of the depth of screw insertion on the pullout strengths of cancellous screws was revealed. However, after adjusting for these differences in depth of screw insertion, we still found significant differences in pullout strengths between ROIs and a significant correlation between trabecular BMD and pullout strength.

In conclusion, this study shows that trabecular BMD of the humeral head has a significant effect on the pullout strength of cancellous screws. On the basis of our results, placement of cancellous screws in the superior-anterior region of the humeral head should be avoided, whereas the central region is deemed to be more favorable. These findings may help to improve surgical techniques and prevent implant loosening and fracture redisplacement, thus improving patient outcome after proximal humeral fractures.

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