The cortical thickness of the proximal humeral diaphysis predicts bone mineral density of the proximal humerus

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The operative treatment of fractures of the proximal humerus can be complicated by poor bone quality. Our aim was to evaluate a new method which allows prediction of the bone quality of the proximal humerus from radiographs.

Anteroposterior radiographs were taken of 19 human cadaver humeri. The cortical thickness was measured at two levels of the proximal humeral diaphysis. The bone mineral density (BMD) was determined for the humeral head (HH), the surgical neck (SN), the greater tuberosity (GT) and lesser tuberosity (LT) using dual-energy x-ray absorptiometry.

The mean cortical thickness was 4.4 ± 1.0 mm. Specimens aged 70 years or less had a significantly higher cortical thickness than those aged over 70 years. A significant positive correlation was found between cortical thickness and the BMD for each region of interest.

The cortical thickness of the proximal diaphysis is a reliable predictor of the bone quality of the proximal humerus.
fort associated with the trauma and the rare availability of these techniques in emergency units. Additionally, regular CT scans of the shoulder, which are obtained in patients with certain types of fracture of the proximal humerus, do not provide the required resolution for determination of the BMD of the humerus.

Our aim therefore was to determine the BMD of the proximal humerus using DXA and to evaluate its correlation with the cortical thickness of the proximal humeral diaphysis measured on anteroposterior (AP) radiographs. This information may provide a simple way of determining the bone quality of the proximal humerus and of facilitating decision-making in the surgical treatment of patients with fractures of the humerus.

Materials and Methods

Preparation of specimens. We harvested 21 unpaired human humeri and stored them at –20˚C. They were thawed at room temperature for 24 hours before testing. After thawing, the specimens were dissected free from all soft tissue. All showed a macroscopically intact rotator cuff. Two which showed surgical treatment of previous fractures of the proximal humerus were excluded from the study, giving a total of 19 specimens (12 male, 7 female) with a mean age of 72 ± 11 years (59 to 98).

Determination of the cortical thickness of the proximal humeral diaphysis from radiographs. Each proximal humerus was fixed horizontally in a custom-made jig so that the greater tuberosity had the maximum projection on a two-dimensional AP view. A radiopaque ruler was positioned horizontally in the middle of the humeral diaphysis to determine the magnification factor and AP radiographs were taken of each proximal humerus in a Cabinet X-ray System (Faxitron Series; Hewlett-Packard, McMinnville, Oregon) (tube voltage, 80 kV; time, 25 s).

The lateral and medial cortical thickness of the proximal humeral diaphysis was measured at two different levels (Fig. 1). Level 1 was the most proximal level of the humeral diaphysis where the endosteal borders of the lateral and medial cortices were parallel to each other. Level 2 was 20 mm distal to level 1. The radiographic cortical thickness was measured by a digital calliper (Mitutoyo Co, Tokyo, Japan) with a precision of ± 0.02 mm. The combined cortical thickness based on radiographic measurements and that determined directly from the humerus were compared, and the coefficient of variation (CV %) was calculated.

Anatomical measurements of the cortical thickness of the proximal humeral diaphysis. Five specimens were cut at levels 1 and 2 using a band saw. The lateral and medial cortical thickness was measured directly at each level using the same digital calliper. The combined cortical thickness based on radiographic measurements and that determined directly from the humerus were compared, and the coefficient of variation (CV %) was calculated.
Determination of BMD of the proximal humerus. The total BMD of the humeral head, surgical neck, greater tuberosity and lesser tuberosity was measured using DXA (QDR-2000 plus; Hologic Inc, Waltham, Massachusetts). The height of each head (HH in Figure 3) was measured before scanning and a scan area of twice this height was used for DXA.

All DXA scans were performed by the same investigator (MT). The humeri were fixed horizontally in a custom-made jig and the bicipital groove orientated at 12 o’clock so that the greater and lesser tuberosities could be easily separated on the scans (Fig. 2). Each humerus was placed in a waterbath with at least 50 mm of water surrounding the humerus to simulate soft tissue. DXA scans were performed using the single-beam spine algorithm (1 mm line spacing, 0.95 mm point resolution).

A horizontal line through the lowest point of the articular surface separated the region of interest (ROI) of the humeral head from that of the surgical neck (Fig. 3). The height of the head was measured and that of the surgical neck which was defined as 50% of that of the humeral head. The ROIs for the greater and lesser tuberosities were separated by a 2 mm wide bicipital groove (Fig. 3). The choice of these ROIs was based on their clinical importance for internal fixation of displaced fractures of the proximal humerus. The BMD (g/cm²) of each ROI was calculated using software from Hologic.

Statistical analysis. This was performed using Statistica 5.0 software (Statsoft Inc, Tulsa, Oklahoma). A power analysis indicated that a sample size of 19 specimens would provide statistical power of 90% to detect differences in the BMD between ROIs of the humeral head and surgical neck ($\beta = 0.1, \alpha = 0.05$). Shapiro-Wilk’s W test was performed to confirm that continuous data followed a normal (Gaussian) distribution. The Pearson product-moment correlation coefficient ($r$) was used to measure the correlation between the combined mean cortical thickness of the proximal humeral diaphysis, obtained by two observers (MT, DS), and the BMD of each ROI. Fisher’s $z$-transformation was used to determine the 95% confidence intervals (CI) for the Pearson correlations. Paired $t$-tests were used to assess differences in BMD between ROIs. Student’s $t$-tests was used to evaluate whether cortical thickness and BMD varied according to age and gender. Intra- and interobserver variation was measured by the Pearson correlation and the paired $t$-test. In addition, 95% CIs for intra- and interobserver variation were calculated using the standard formula based on the $t$-distribution for a paired difference. Furthermore, the intra- and interobserver variabilities were calculated as a coefficient of variation. Linear regression analysis based on least-squares was used to derive equations for predicting the BMD from cortical thickness.

Results

Cortical thickness of the proximal humeral diaphysis. The combined mean cortical thickness of the proximal humeral diaphysis of all specimens was 4.4 mm (2.3 to 6.1) (Table I).

Specimens 70 years of age or younger showed a significantly higher combined mean cortical thickness (4.8 ± 0.96 mm) than those older than 70 years (3.8 ± 0.86 mm) ($p < 0.05$).

No significant differences in combined cortical thickness were found between female and male specimens (3.9 ± 0.44 mm vs 4.6 ± 1.02 mm, $p = 0.08$).
The mean BMD of the humeral head was 0.44 g/cm². The BMD of the surgical neck (0.52 g/cm²) was 18% higher than that of the humeral head (paired t-test, p < 0.01). The BMD of the greater tuberosity (0.36 g/cm²) was 30% lower than that of the lesser tuberosity (0.51 g/cm²) (paired t-test, p < 0.01).

Specimens 70 years of age or younger showed a significantly higher BMD in the humeral head and the greater and lesser tuberosities than those older than 70 years of age (Student’s t-test, p < 0.05), while no significant differences in the BMD of the surgical neck were seen between these specimens (Student’s t-test, p > 0.05). Examples of specimens with high and low BMD are shown in Figure 1. Male specimens showed a significantly higher BMD in the humeral head and the greater and lesser tuberosities than those older than 70 years of age (Student’s t-test, p < 0.05), while no significant differences in the BMD of the surgical neck were seen between these specimens (Student’s t-test, p > 0.05). Examples of specimens with high and low BMD are shown in Figure 1. Male specimens showed a significantly higher BMD in the humeral head and the greater and lesser tuberosities than those older than 70 years of age (Student’s t-test, p < 0.05), while no significant differences in the BMD of the surgical neck were seen between these specimens (Student’s t-test, p > 0.05).

Correlation between cortical thickness and BMD. A significant positive correlation was found between the BMD of different ROIs of the proximal humerus and the combined cortical thickness of the proximal humeral diaphysis (p < 0.01). For the humeral head a correlation was found between the cortical thickness and the BMD of $r = 0.69$ (95% CI 0.34 to 0.87) (Fig. 4a). For the surgical neck the correlation was $r = 0.84$ (95% CI 0.62 to 0.94) (Fig. 4b), for the greater tuberosity $r = 0.70$ (95% CI 0.36 to 0.88) (Fig. 4c), and for the lesser tuberosity $r = 0.68$ (95% CI 0.33 to 0.87) (Fig. 4d). Specimens with a combined cortical thickness of less than 4 mm had a significantly lower BMD of the humeral head, surgical neck, and greater and lesser tuberosities than those with a cortical thickness of more than 4 mm (p < 0.01). The highest correlation between cortical thickness and BMD demonstrated by both observers was found in the surgical neck. Table II presents the Pearson correlations and 95% CIs as determined using Fisher’s z-transformation.

Based on the mean cortical thickness determined by the two observers (MT, DS), linear regression analysis was used to determine the equations to estimate the BMD for each ROI as follows:

- Humeral head (HH): $0.10 \times$ cortical thickness – 0.00
- Surgical neck (SN): $0.14 \times$ cortical thickness – 0.10
- Greater tuberosity (GT): $0.09 \times$ cortical thickness – 0.05
- Lesser tuberosity (LT): $0.11 \times$ cortical thickness – 0.05

For example, given a cortical thickness of 5 mm, the predicted values of the BMD would be 0.50 g/cm² for the humeral head, 0.60 g/cm² for the surgical neck, 0.40 g/cm² for the greater tuberosity, and 0.50 g/cm² for the lesser tuberosity.

### Table I. Details of the gender, age, combined cortical thickness and BMD (g/cm²) of each specimen for humeral head, surgical neck, greater tuberosity and lesser tuberosity

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Gender</th>
<th>Age (yrs)</th>
<th>Cortical thickness (mm)</th>
<th>Humeral head</th>
<th>Surgical neck</th>
<th>Greater tuberosity</th>
<th>Lesser tuberosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>87</td>
<td>2.3</td>
<td>0.17</td>
<td>0.23</td>
<td>0.12</td>
<td>0.21</td>
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<tr>
<td>2</td>
<td>M</td>
<td>88</td>
<td>5.1</td>
<td>0.68</td>
<td>0.83</td>
<td>0.57</td>
<td>0.77</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>76</td>
<td>4.0</td>
<td>0.42</td>
<td>0.38</td>
<td>0.39</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>87</td>
<td>4.3</td>
<td>0.33</td>
<td>0.49</td>
<td>0.25</td>
<td>0.42</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>98</td>
<td>3.4</td>
<td>0.26</td>
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<td>0.16</td>
<td>0.38</td>
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<tr>
<td>6</td>
<td>M</td>
<td>65</td>
<td>4.3</td>
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<td>0.55</td>
<td>0.39</td>
<td>0.59</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>66</td>
<td>4.7</td>
<td>0.65</td>
<td>0.74</td>
<td>0.52</td>
<td>0.77</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
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<td>2.8</td>
<td>0.32</td>
<td>0.36</td>
<td>0.25</td>
<td>0.38</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>67</td>
<td>3.9</td>
<td>0.46</td>
<td>0.36</td>
<td>0.35</td>
<td>0.53</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>62</td>
<td>4.7</td>
<td>0.43</td>
<td>0.56</td>
<td>0.38</td>
<td>0.49</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td>70</td>
<td>4.8</td>
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<td>0.64</td>
<td>0.55</td>
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<tr>
<td>12</td>
<td>M</td>
<td>62</td>
<td>5.2</td>
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<td>0.56</td>
<td>0.40</td>
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</tr>
<tr>
<td>13</td>
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<td>65</td>
<td>3.8</td>
<td>0.44</td>
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<td>0.47</td>
</tr>
<tr>
<td>14</td>
<td>M</td>
<td>59</td>
<td>5.8</td>
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<td>0.65</td>
<td>0.33</td>
<td>0.50</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>62</td>
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<td>0.60</td>
<td>0.66</td>
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<tr>
<td>16</td>
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<td>64</td>
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<td>0.52</td>
<td>0.65</td>
<td>0.46</td>
<td>0.58</td>
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<tr>
<td>17</td>
<td>F</td>
<td>80</td>
<td>3.5</td>
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<td>0.24</td>
<td>0.08</td>
<td>0.18</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>77</td>
<td>3.6</td>
<td>0.38</td>
<td>0.40</td>
<td>0.33</td>
<td>0.45</td>
</tr>
<tr>
<td>19</td>
<td>M</td>
<td>66</td>
<td>6.1</td>
<td>0.52</td>
<td>0.69</td>
<td>0.45</td>
<td>0.60</td>
</tr>
</tbody>
</table>

### Table II. Pearson correlations between cortical thickness and BMD according to each ROI. Correlations are based on 19 specimens and were all statistically significant (p < 0.01). The 95% CIs for the observed correlations determined using Fisher’s z-transformation are shown in parenthesis.

<table>
<thead>
<tr>
<th>ROIs</th>
<th>Humeral head</th>
<th>Surgical neck</th>
<th>Greater tuberosity</th>
<th>Lesser tuberosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observer 1</td>
<td>0.65 (0.28 to 0.85)</td>
<td>0.83 (0.60 to 0.93)</td>
<td>0.64 (0.26 to 0.84)</td>
<td>0.64 (0.26 to 0.84)</td>
</tr>
<tr>
<td>Observer 2</td>
<td>0.73 (0.41 to 0.89)</td>
<td>0.85 (0.64 to 0.94)</td>
<td>0.73 (0.41 to 0.89)</td>
<td>0.71 (0.38 to 0.88)</td>
</tr>
<tr>
<td>Both observers</td>
<td>0.69 (0.34 to 0.87)</td>
<td>0.84 (0.62 to 0.94)</td>
<td>0.70 (0.36 to 0.88)</td>
<td>0.68 (0.33 to 0.87)</td>
</tr>
</tbody>
</table>
A high correlation was found between the combined cortical thickness based on radiographs and that determined from anatomical measurements of the proximal humeral diaphysis \((r = 0.98, p < 0.01, 95\% \text{ CI} 0.95 \text{ to } 0.99)\). The coefficient of variation between the combined cortical thickness based on a radiograph and that measured directly was ±5.5%.

**Intra- and interobserver reproducibility.** The combined cortical thickness was determined with excellent intra- and interobserver agreement from radiographs. The variation in cortical thickness between the two measurements for observer 1 was 0.05 mm \((95\% \text{ CI}, 0.05 \pm 0.13 \text{ mm})\). The Pearson correlation for both sets of measurements for observer 1 was high \((r = 0.97, p < 0.0001, 95\% \text{ CI}, r = 0.92 \text{ to } 0.99)\).

Similarly, the mean variation in cortical thickness for observer 2 was 0.04 mm \((95\% \text{ CI}, 0.04 \pm 0.16 \text{ mm})\). The Pearson correlation for both sets of measurements for observer 2 was high \((r = 0.95, p < 0.0001, 95\% \text{ CI}, r = 0.87 \text{ to } 0.98)\). For the interobserver variation, the mean difference in cortical thickness for both observers was 0.10 mm \((95\% \text{ CI}, 0.10 \pm 0.12 \text{ mm})\). A paired \(t\)-test indicated no significant difference between the observers regarding measurements of cortical thickness \((p = 0.15)\).

The coefficient of variation for intraobserver reproducibility was ±3.6%, and that for interobserver reproducibility ±2.6%.
Discussion

Reduced bone quality of the proximal humerus may complicate the surgical treatment of fractures of the proximal humerus. There is no simple method which allows for reliable quantitative clinical assessment of bone quality of the proximal humerus.

We found a significant positive correlation between the cortical thickness of the proximal humeral diaphysis measured on conventional radiographs and the BMD of clinically important locations in the proximal humerus. These findings may provide the clinician with a valuable easy method and simple equations to estimate bone quality and the BMD of the proximal humerus.

Previous studies have found the cortical thickness of various bone sites such as the femur, radius, metacarpals and humerus, to be an effective predictor in assessing osteoporotic changes in bone. Virtama and Telkkä defined the cortical index of the humeral shaft as the cortical thickness divided by the bone diameter and found a significant correlation between the cortical index and bone density determined from the dry weight of humeri.

In a clinical study by Meema and Meema the combined cortical thickness of the distal humerus and the proximal radius were measured in 1200 patients. There was a significant decrease in cortical bone after the age of 45 years for both female and male patients. Similar results were reported by Bloom and Laws who determined the combined cortical thickness of the distal humerus on AP radiographs and found a significant lower combined cortical thickness in patients older than 50 years of age.

In our study, we found a significantly higher combined cortical thickness in specimens of 70 years of age and younger than in those older than 70 years of age. No differences in combined cortical thickness were seen, however, between females and males, which may be attributed to the limited number of female specimens in our study.

The intra- and interobserver agreement in determining the combined cortical thickness on radiographs was excellent in our study. This correlates well with the findings of Bloom and Laws who reported a small interobserver error in determining the combined cortical thickness of the distal humeral shaft. Our interobserver reproducibility was slightly higher than that reported in other studies which determined the cortical thickness of the femur or the metacarpals. We also confirmed a high correlation between the combined cortical thickness determined from AP radiographs and that measured directly after cutting the proximal humeral diaphysis.

In our study, the BMD of the proximal humerus was determined using DXA. This is a two-dimensional technique which does not allow assessment of the spatial distribution of bone mass or discrimination between trabecular and cortical BMD. Therefore, measurements of the BMD may have been influenced to some degree by the size of the humeral head. To exclude a relevant association between the size of the humeral head and its BMD measured with DXA, the Pearson correlation was calculated. There was, however, no significant correlation between the size and the BMD of the humeral head (r = 0.38, p > 0.05) or between the size of the humeral head and the cortical thickness of the proximal humeral diaphysis (r = 0.26, p > 0.05).

We conclude that the combined cortical thickness of the proximal humeral diaphysis is a reliable and reproducible predictor for the BMD of the proximal humerus. A cortical thickness of less than 4 mm is highly indicative of a low BMD. In these patients, internal fixation of fractures of the proximal humerus may be complicated by loosening of the implant. Therefore conservative treatment or primary implantation of a shoulder prosthesis may be indicated.

The results of our study provide a rationale for future prospective randomised clinical studies for evaluating the implications of a reduced cortical thickness of the proximal humerus and its relationship to complication rates and failure of fixation.

We wish gratefully to acknowledge the continuous assistance of Mary L. Bouxsein throughout this study. We would like to thank Deutsche Forschungsgemeinschaft and Orthopedic Laboratories Alumni Council for financial support. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References


