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SCIENTIFIC ARTICLE

Preoperative assessment of the cancellous bone mineral density of the proximal humerus using CT data

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Abstract
Background Osteoporotic fractures of the proximal humerus show an increasing incidence. Osteoporosis not only influences the fracture risk after low-energy trauma, but also affects the mechanical stability of internal fixation. Preoperative assessment of the local bone quality may be useful in the surgical treatment of patients sustaining these injuries. The aim of the present study was to present a method for the preoperative assessment of the local cancellous bone mineral density (BMD) of the proximal humerus using CT data.
Methods In the first part of the study, CT scans of 30 patients with unilateral fractures of the proximal humerus after low-energy trauma were used. The local BMD was assessed on the contralateral uninjured side. All 30 patients additionally underwent dual-emission X-ray absorptiometry (DXA) of the lumbar spine, proximal femur, and forearm of the side of the uninjured proximal humerus within 6 weeks after trauma. Three independent trauma surgeons performed measurements on the uninjured proximal humerus twice with a time interval of 4 weeks in order to assess the inter- and intraobserver reliability of the method. In the second part of the study, the local BMD of 507 patients with either proximal humerus fractures or chronic shoulder instability was assessed by a single trauma surgeon. In both parts, the average HU values in standardized ROIs of the humeral head were automatically calculated after correcting for HU values below the water equivalent. A linear calibration equation was computed for the calculation from HU to BMD using a calibration device (EFP).
Results The intra- and interobserver reliability was high (ICC$>$0.95). Correlation coefficients between the local BMD of the proximal humerus and other anatomical sites were between 0.35 (lumbar spine) and 0.64 (forearm). We found a high correlation between the local BMD and age. The BMD in the fracture group was significantly lower than in the instability group. These patients were significantly older and more likely to be female.
Conclusion Our method may provide a preoperative tool for the assessment of the local bone quality of the proximal humerus using CT data. Therapeutic adjustments such as augmentation or primary arthroplasty may be considered in patients with very low local BMD.

Keywords Low-energy fracture · Proximal humerus · Local BMD · Implant failure · CT

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Introduction

Low-energy osteoporotic fractures of the proximal humerus have shown a threefold increasing incidence in the last three decades [1, 2]. As a result of an ageing population, an additional threefold increase is expected in the next 30 years [2]. Osteoporosis not only influences the fracture risk after low-energy trauma, but also highly affects the mechanical stability of internal fixation. Biomechanical studies have shown minor screw purchase in osteoporotic bone [3, 4]. Failure after internal fixation of osteoporotic fractures of the proximal humerus in terms of loss of reduction and implant loosening are frequently observed even with the use of locking plates [5–8]. Accordingly, preoperative assessment of the local bone quality may facilitate decision-making in the surgical treatment of patients sustaining these injuries.

Computed tomography (CT) is usually available in emergency units, and CT scans of proximal humerus fractures are frequently performed in order to precisely classify the fracture and to plan surgical procedures. The objective of this study was therefore to present a Hounsfield Unit (HU)-based standardized method for the preoperative assessment of the cancellous bone mineral density (BMD) of the humeral head using CT data.

Materials and methods

The study consisted of two parts. In the first part of the study, CT scans of a consecutive series of 30 patients with unilateral fractures of the proximal humerus after sustaining low-energy trauma, but with no regard for age and gender, were used. No patient suffered from unilateral loss of shoulder function beforehand. CT scans of both shoulders were performed within 24 h after trauma for preoperative fracture evaluation in all patients. Additionally, all 30 patients underwent dual-emission X-ray absorptiometry (DXA) of the lumbar spine, proximal femur and forearm on the side of the uninjured proximal humerus within 6 weeks after trauma. Three independent trauma surgeons performed measurements on the uninjured proximal humerus twice at an interval of 4 weeks in order to assess the inter- and intraobserver reliability of the method. In the second part, CT scans of a consecutive series of 507 patients receiving CT scans of both shoulders with no regard for age, gender, shoulder function, and the presence of fractures were used. Indications were either preoperative fracture evaluation in the presence of a proximal humerus fracture or diagnostic assessment in the presence of chronic shoulder instability. One trauma surgeon, who was not involved in the measurements of the first part, performed all measurements on the uninjured proximal humerus. The purpose of the first part was to evaluate our method in a small, but consistent series of patients with osteoporotic proximal humerus fractures. This represents a patient cohort our method is primarily aimed at. The purpose of the second part was to evaluate the method in a larger, but more heterogeneous series with no regard for age, gender, or the presence of a fracture in order to assess the influence of these factors on the local BMD of the proximal humerus.

CT scans were performed in a supine position with a GE Light Speed VCT (GE, Milwaukee, WI, USA) using a standardized protocol (120 KV, mA Auto, 8.8 s/HE; 1.25 mm slice/39.38 HQ) without radiopaque material. The assessment of the local MD was typically performed within 1 week. The PACS software J-Vision 3.3.16 (Tiani Medgraph, Brunn am Gebirge, Austria) was used. True axial slices of the humeral head were obtained by using a multiplanar reconstruction tool. In this way, two of the three perpendicular planes were adjusted parallel to the shaft axis of the humerus (Fig. 1a and c, green and blue plane) resulting in a true axial plane of the humeral head (Fig. 1b, red plane). The height of the head segment was determined in the frontal plane by measuring the distance between the transition zone at the calcar and the highest point of the humeral head (Fig. 1d). The height of the humeral head was then quartered and three axial planes equidistant to each other and to the calcar were defined (Fig. 1d). Circular regions of interest (ROI) were placed in the humeral head in each of the previously defined axial planes. The diameter of the ROIs was then reduced by 15% in order to definitely exclude cortical bone from the ROI (Fig. 1e–g). HU values were automatically corrected for HU values below the water equivalent of the European Forearm Phantom (EFP) by adjusting the histogram (Fig. 1e–g). The blue part of the histogram shows the HU values above and the yellow part the HU values below the water equivalent of the EFP. The blue values assessing the cancellous BMD corrected for yellow fat marrow were used for the calculation of the mean HU values in the ROI only. The average HU value of the humeral head was defined as the mean HU value of the three ROIs.

The European Forearm Phantom-02-45 (EFP) was placed on the sternum of the patients [9]. Three HU measurements were performed in section I (200 mg/cm^3), section II (100 mg/cm^3), section III (50 mg/cm^3), and section V (water equivalent) of the EFP, respectively (Fig. 2). The mean HU values in the ROIs of the EFP were pasted in the calibration template. A linear calibration equation was automatically computed for the calculation from HU to BMD. BMD values of the humeral head were obtained by pasting the mean HU values of the ROIs of the humeral head in the template. The average BMD value of the humeral head was defined as the mean BMD value of the three ROIs.

Statistical analysis was performed using PASW 18.0 (SPSS, Chicago, IL, USA). Metric scaled data are reported as arithmetic mean ± standard deviation. For paired samples, a paired *t* test or a nonparametric Wilcoxon signed rank test was used. The Kolmogorov-

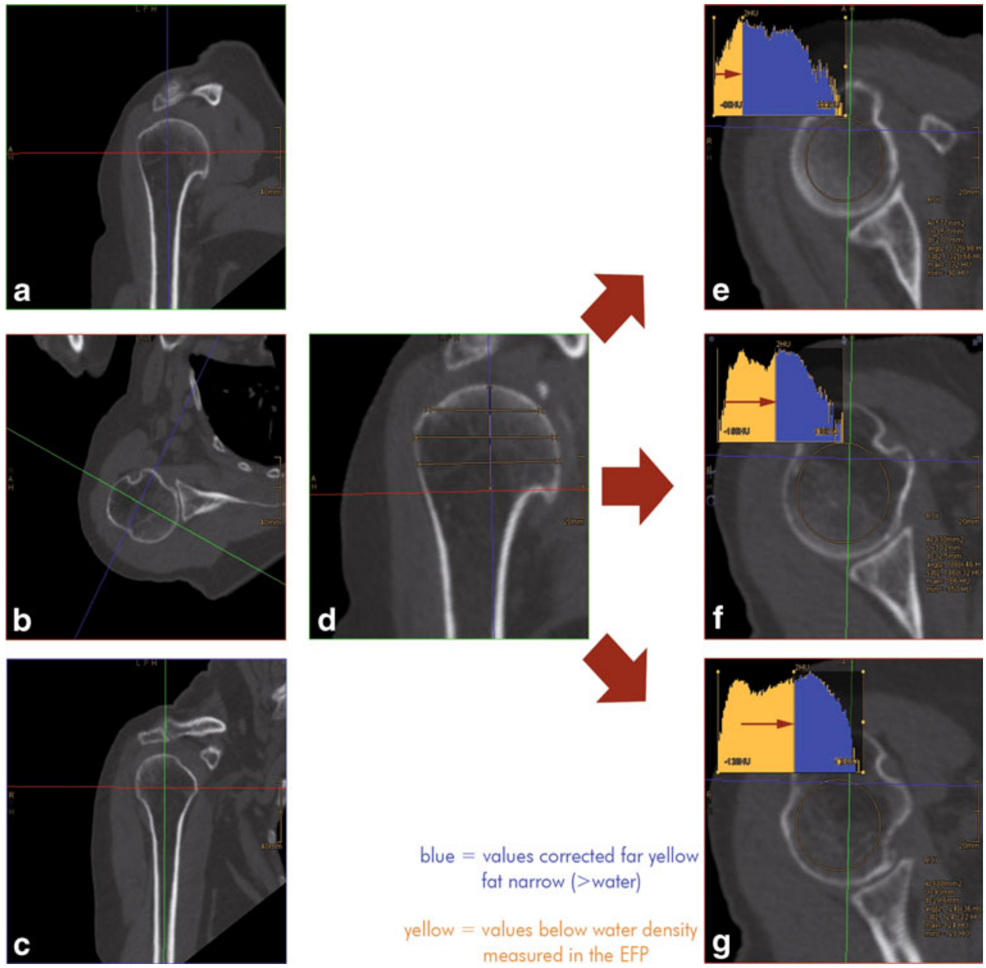

Fig. 1 Using a multiplanar reconstruction tool, true axial slices of the humeral head (**b**) were obtained by adjusting two of the three perpendicular planes to the shaft axis (**a** and **c**). After determining the height of the head segment, three axial planes equidistant to each other and to the calcar were defined (**d**). ROIs were placed in the humeral head in each of the previously defined axial planes (**e**–**g**). The blue values in the histogram assessing the cancellous BMD corrected for yellow fat marrow were used for the calculation of the mean HU values in the ROI only

Smirnov test was used for the determination of the distribution form. Correlations for metric scaled data were quantified using the Pearson coefficient. The probability level was set at $P<0.05$. For the analysis of the reliability in an intra- and interobserver setup, the intraclass correlation coefficients (ICC) and their 95% confidence intervals were calculated. The ICC ranges from 0.00 (no agreement) to 1.00 (perfect agreement). Data from both readings were used for the assessment of the reliability in the interobserver setup.

Results

Thirty patients were included in the first part of the study. There were 27 women and 3 men with a mean age of 81.3 years (72–89). The results of the first part are summarized in Tables 1, 2, and 3. Table 1 shows the average HU and BMD values of the humeral head. There were no significant differences either between the observers or between the two readings ($P>0.05$). Correlations between the average BMD values of the humeral head and BMD values on other anatomical sites determined by using DXA are shown in Table 2. Correlations to the forearm were found to be highest ($r=0.64$) and correlations to the lumbar spine lowest ($r=0.35$). The inter- and intraoberver reliability was very high (Table 3). The ICC values were >0.95 in all cases with minimally higher values for the intraobserver setup.

In the second part of the study, CT scans of 507 patients with a mean age of 49.3±20.2 years were used. There were 317 men and 190 women. Of these, 185 patients sustained a fracture of the proximal humerus, and 322 patients had a chronic shoulder instability. We found a high correlation between BMD and age ($r=0.71$, $P<0.05$). Figure 3 shows a scatter plot of age (x-axis) vs. BMD (y-axis). The formula of the linear regression line was $y=-1.319x+184.338$. Women were significantly older (60.3±19.6 vs. 42.7±17.6 years, $P<0.05$) than men and had a significantly lower BMD (97.3±28.2 vs. 132.5±35.6 mg/cm^3, $P<0.05$). Patients from the fracture group had a significantly lower BMD than patients from the instability group (95.9±28.6 vs. 132.8±34.7 mg/cm^3, $P<0.05$). They were significantly older (63.3±15.9 vs 41.3±17.9 years, $P<0.05$). A total of 57.9% of the women and 23.7% of the men sustained fractures of the proximal humerus ($P<0.05$).

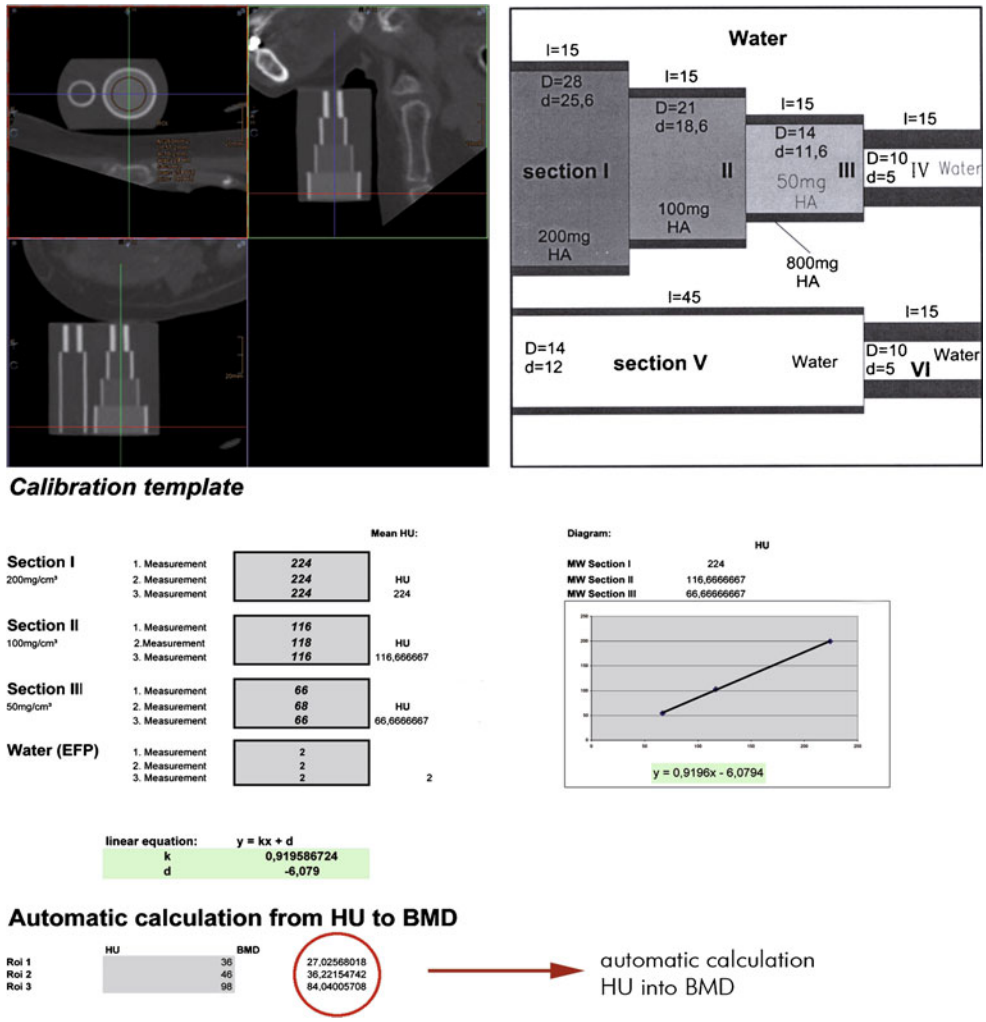

Fig. 2 Three HU measurements were performed in section I (200 mg/cm^3), section II (100 mg/cm^3), section III (50 mg/cm^3), and section V (water equivalent) of the EFP (*top*). The mean values of sections I–III are used for the calibration of the linear equation (*middle*). BMD values of the humeral head are obtained by pasting the mean HU values of the three ROIs of the humeral head in the template (*bottom*)

Discussion

The aim of our study was to present and evaluate a standardized method for the preoperative assessment of the cancellous BMD of the humeral head in patients with unilateral acute fractures using CT data. For the evaluation of a new method both its reliability and validity need to be assessed. In the first part of the study, we found that the intra- and interobserver reliability of our method was very high with ICC values of >0.95 in all cases (Table 3). The evaluation of our method in terms of validity was more challenging, as there is no gold standard for the assessment of the local BMD of the proximal humerus that could serve as a reference. The low correlations that we found between the BMD values of the humeral head assessed with our method and BMD values on other anatomical sites assessed using DXA (Table 2) may express the heterogenity of the BMD between different anatomical sites. We therefore

Table 1 Average HU values (in HU units) and BMD values (in mg/cm^3) of the humeral head

	Occasion	Average HU	Average BMD
Observer 1	1	99.2±23.6	83.4±20.7
	2	100.8±24.3	84.5±21.7
Observer 2	1	102.1±23.4	83.0±20.2
	2	102.7±23.1	82.4±20.4
Observer 3	1	98.7±22.9	82.4±19.7
	2	98.2±21.9	81.7±18.9
All	1	100.0±23.1	82.9±19.4
	2	100.6±22.9	82.9±20.2

Table 2 Correlations between the average BMD values of the humeral head and BMD values on other anatomical sites. Data from all observers were used for the assessment of correlation

Region	Correlation coefficient	*P* values
Lumbar spine	0.35	<0.001
Proximal femur	0.58	<0.001
Radius	0.57	<0.001
Ulna	0.49	<0.001
Forearm	0.64	<0.001

Table 3 Assessment of the intra- and interrater reliability using the ICC

	Observer	ICC HU	ICC HU 95% CI	ICC BMD	ICC BMD 95% CI
Intraobserver	1	0.986	0.972–0.993	0.989	0.978–0.995
	2	0.988	0.975–0.994	0.987	0.972–0.994
	3	0.988	0.974–0.994	0.988	0.975–0.994
	All	0.987	0.980–0.991	0.988	0.982–0.992
Interobserver	1 vs 2	0.978	0.963–0.987	0.964	0.940–0.978
	1 vs 3	0.968	0.947–0.981	0.953	0.923–0.972
	2 vs 3	0.970	0.951–0.982	0.985	0.975–0.991

assessed a larger and more heterogeneous patient series in a second part of the study. We found a high correlation between age and BMD (Fig. 3) and lower local BMD values in patients with fractures of the proximal humerus.

To the best of our knowledge, there is no previous study assessing the local BMD of the proximal humerus using CT data. Preoperative planning of surgical procedures on the proximal humerus, however, frequently necessitates CT scanning. Scanning the contralateral uninjured side and using a calibration device increases neither the radiation dose nor the time for the CT scan. The described method, however, is not intended for serial monitoring of patients with osteoporosis as DXA is. Accordingly, we consider the observed intra- and interobserver reliability to be adequate for our aim.

It was our goal to assess the cancellous BMD of the proximal humerus. Therefore, the diameter of the ROIs was reduced by 15% in order to definitely exclude cortical bone from the ROI (Fig. 1). However, these few millimeters of subchondral bone should not be used for screw purchase in order to prevent screw perforation. Yellow fat marrow is another known source of error in single-energy quantitative CT. Its density in CT scans is about −100 HU and its relative amount in relation to the cancellous bone increases with age. This may lead to an underestimation of the

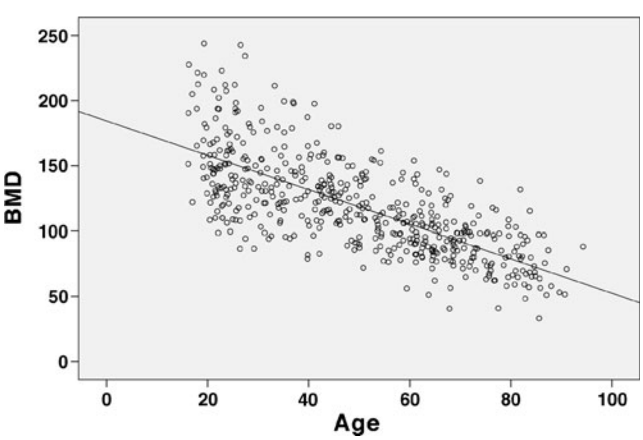

Fig. 3 Scatter plot of of age (x-axis) vs. BMD (y-axis). Formula of the linear regression line: $y=-1.319x+184.338$

cancellous BMD in the elderly [10]. Dual-energy quantitative CT allows for correction for yellow fat marrow by scanning twice with different settings [11]. This, however, increases the exposure to radiation. In our method HU values below the water equivalent of the EFP (HU values< O) were automatically excluded from the calculation of the mean HU in the ROI, thus correcting for yellow fat marrow.

Several studies show a substantial heterogenity of the local BMD values on different anatomical sites [12–14]. We agree, as we found only low to moderate correlations between the average BMD values of the humeral head and BMD values on other anatomical sites (Table 2). Accordingly, Groll stated that BMD measurements should be performed directly at the site of interest [14]. In the acute setting of a fracture, however, the contralateral uninjured proximal humerus has to be assessed. Diederichs et al. showed good agreement between the BMD values of the left and right humeral head [12]. Conditions with unilateral loss of shoulder function such as strokes or severe unilateral rotator cuff tears are known to change the local bone quality [15, 16]. Accordingly, these conditions need to be ruled out by anamnesis. Additionally, they cause muscle atrophy, which is easily detectable by CT [17, 18].

Dual energy X-ray absorptiometry (DXA) is the gold standard for the assessment of bone mineral density (BMD). DXA is a clinically well established method for the lumbar spine, the proximal femur and the distal forearm, but not for the proximal humerus. Doetsch described a method for measuring the local BMD of the proximal humerus using DXA [19]. Besides the limited availability of DXA in emergency units, this method requires the patient to be positioned on the fractured side, which is not feasible in the acute setting. Tingart estimated the local BMD by measuring the cortical thickness of the proximal humeral diaphysis on radiographs in a cadaveric study [20]. The authors found only a moderate correlation between the cortical thickness and the cancellous BMD of the humeral head (r=0.69, 95% CI 0.34–0.87). Additionally, the frequent lack of an ideal projection in the AP view in patients suffering from pain after sustaining a proximal humerus fracture may also alter the estimation of the local BMD. Using CT data, multiplanar reconstruction tools allow for standardized projections independent of the patients' position.

Some limitations of this study have to be noted. First, only 30 patients were included in the first part of the study. Including more patients would have increased the power of the statistical analysis. Second, it is known that conditions with unilateral loss of shoulder function change the local bone quality of the proximal humerus. While these patients were excluded from the first part of the study, all patients with CT scans of both shoulders were included with no regard to shoulder function. Accordingly, patients with high-energy fractures of the proximal humerus were not excluded from the second part of the study neither. Third, the reduction of the diameter of the circular ROIs by 15% was chosen in order to definitely exclude cortical bone from the ROI in the proximal humerus, which is not perfectly circular. The chosen amount of reduction, however, was not validated in previous studies.

Several studies indicate that BMD only partly explains bone strength [21, 22]. The assessment of macro- and microstructural features of the bone may improve the estimation of the local bone quality [23]. Our method is basically a volumetric QCT method. Due to its relatively low resolution, microstructural analysis of the bone is not feasible. Accordingly, it is not an alternative option to μCT or high-resolution CT. Neither is it an alternative option to DXA in the serial monitoring of patients with osteoporosis. It may provide a preoperative tool for the assessment of the local bone quality of the proximal humerus using generally available data and resources. In patients with very low local BMD, therapeutic adjustments such as augmentation or primary arthroplasty may be considered. Further studies are crucial in order to determine the relation between the local bone quality and implant failure on the proximal humerus.

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