A Correlation Exists Between Subchondral Bone Mineral Density of the Distal Radius and Systemic Bone Mineral Density

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Abstract

Background Intraarticular distal radius fractures are common and risk articular congruity owing to disruption of the subchondral bone. Studies regarding microstructure and mechanical properties of the distal radius, however, focus only on the cortical and trabecular bones in the metaphysis and not on the subchondral bone.

Questions/purposes This study was conducted to (1) quantify the regional bone mineral density of the subchondral plate in the distal radius; (2) analyze the topographic distribution pattern of the subchondral bone mineral density; and (3) evaluate the correlation between the subchondral bone mineral density and the potentially related clinical factors of age, height, weight, BMI, systemic bone

mineral densities, socio-occupational classification, and hand osteoarthritis grading.

Methods Eighty postmenopausal women with a mean age of 68 years (range, 52–88 years) were enrolled in this study. Digital images of the distal radii of the subjects were scanned by conventional CT and processed to provide the regional bone mineral density of the subchondral plate using a CT osteoabsorptiometry technique. The estimated subchondral bone mineral density was analyzed to evaluate the topographic pattern and its correlation with various clinical factors, including age, height, weight, BMI, degree of hand osteoarthritis, socio-occupational class, and systemic bone mineral density measured in the lumbar spine and hip.

Results During topographic analysis of a densitometric map, a bicentric distribution of the subchondral bone mineral density was found. Among the clinical factors, only the systemic bone mineral density measured by dual-energy x-ray absorptiometry in the femur neck and lumbar spine had a significant correlation with the subchondral bone mineral density of the distal radius.

Conclusion Systemic bone mineral density correlates substantially with the subchondral bone mineral density of the distal radius as a constitutional factor, whereas other local factors arising from the gravitational load or joint reaction force are not associated with the subchondral bone mineral density of the distal radius.

Level of Evidence Level II, prognostic study. See Guidelines for Authors for a complete description of levels of evidence.

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Introduction

Distal radius fractures are representative fragility fractures but their relationship with systemic bone mineral density

(BMD) has not attracted much concern compared with vertebral fractures [2, 10, 14, 21]. However, numerous studies reported that systemic osteoporosis affects the incidence, fracture stability, and treatment outcome of distal radius fractures in the elderly [9, 18–20, 38]. Although this correlation between systemic osteoporosis and the nature of distal radius fractures has been reported, another concern regarding whether the systemic BMD could substantially represent the regional BMD of the distal radius or whether other clinical factors except for systemic BMD also can affect the regional BMD. In addition, although several trials examining regional bone density of the distal radius using quantitative CT techniques provided precise and sometimes quantitative information regarding the structure and mechanical properties of the distal radius, they focused fundamentally on just the trabecular bone and its surrounding cortical bone in the metaphysis and not on the subchondral plate of the distal radius [3, 11, 24, 34, 36].

Considering that an intraarticular extension of the distal radius is common (70%–88%) [1, 17, 22] and has been reported to be related to poor treatment outcome including radiocarpal arthrosis, limited motion, and poor functional outcome [13, 22, 23, 31], knowledge of the relationship between systemic BMD and that of the subchondral plate is needed. Because distal radius fractures frequently are caused by falls on an outstretched hand, the major deforming vector of this injury consists of an axial compressive force and dorsal bending force. This load is normally delivered to the subchondral bone and adjacent calcified cartilage and then to the articular cartilage [35]. The subchondral plate is a major shock-absorbing structure in the periarticular region and attenuates most of the impulsive axial load [32, 33]. This mechanism of injury results in an intraarticular fracture if the transarticular load exceeds the ultimate strength of the subchondral bone. In view of this, strength of the subchondral bone is critical and needs to be quantified.

In this study, we (1) quantified regional BMD of the subchondral plate in the distal radius; (2) analyzed the topographic distribution pattern of the subchondral BMD; and (3) evaluated the correlation between the subchondral BMD and potentially related clinical factors such as age, height, weight, BMI, systemic BMDs measured via dual energy x-ray absorptiometry (DXA) at the proximal femur and lumbar spine, socio-occupational class, and radiographic evidence of hand osteoarthritis, to provide insight regarding risk factors for low subchondral BMD in the distal radius.

Patients and Methods

In this study, 80 postmenopausal women aged 52 to 88 years (mean, 68 years) were involved. We excluded

subjects with chronic arthritis, including rheumatoid arthritis or osteoarthritis, in the radiocarpal joint or other preexisting musculoskeletal disorders. The protocol was approved by the Institutional Review Board. Predetermined clinical factors consisting of systemic and local factors were recorded for all patients. For the systemic factors, demographic data including age, height, weight, BMI, and BMD of the axial skeleton measured by DXA at the lumbar area (L2–L4) and proximal femur were checked. The mean T-score in the lumbar area and T-score of the femur neck were selected as representative systemic BMD values. For local factors, we evaluated the accumulated intensity of hand labor using the radiographic grade of osteoarthritis and socio-occupational classification. This evaluation protocol of hand labor intensity arose from the idea that subjects with radiographic evidence of hand osteoarthritis or heavy manual workers in the socio-occupational classification are more likely to be involved in high-level manual labor and long-term joint reaction force around the wrist, which possibly leads to a high subchondral BMD. First, we evaluated radiographic evidence of hand osteoarthritis using the modified Kellgren-Lawrence scale; Grade 2 or higher in this scale measured in the metacarpophalangeal or basal joint is defined as definite hand osteoarthritis (Table 1). This is an extension of the Framingham study, which shows the relationship between grip strength and hand osteoarthritis [7, 8]. This extension appears to be valid because grip strength is related to the action of the muscle-tendon complex around the wrist. All radiographic reviews were performed by one author (SHR) to avoid any potential interobserver bias. Second, for the socio-occupational classification, the scheme described by Erikson et al. [12] was used and subjects with Class IVc, VIIa, or VIIb in the scheme are defined as being heavy manual workers (Table 2).

All digital images of the distal radii were scanned using conventional medical CT (Philips Brilliance 64 multislice CT scanner, Cleveland, OH, USA). The scanning parameters included tube voltage, 120 kVp; tube current, 77 mA; and scan time, 1.0 seconds. The field of view was set to 125 mm and the full area of the articular surface always was captured completely. The slice thickness was determined to be 1.0 mm in all cases. Theoretically, a thinner

Table 1. Modified Kellgren-Lawrence grading system for osteoarthritis

Grade	Description
0	No features of osteoarthritis
1	Equivocal osteophytes
2	Unequivocal osteophytes
3	Joint space narrowing
4	Bone-to-bone appearance

Table 2. Erikson-Goldthorpe-Portocarero scheme for socio-occupational classification

Class	Description
I	Higher-grade professionals, administrators and officials; managers in large industrial establishment; large proprietors
II	Lower-grade professionals, administrators and officials; higher-grade technicians; managers in small business and industrial establishments; supervisors of non-manual employees
III	Routine non-manual employees in administration and commerce; sales personnel; other rank-and-file service workers
IVa	Small proprietor; artisans, etc., with employees
IVb	Small proprietor; artisans, etc., without employees
IVc	Farmers and smallholders; self-employed fisherman
V/IV	Lower-grade technician; supervisors of manual workers; skilled manual workers
VIIa	Semi- and unskilled manual workers (not in agriculture)
VIIb	Agricultural workers

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section might produce more enhanced spatial resolution, but it was reported that enhanced spatial resolution acquired even by microCT did not produce a significantly different density pattern [28]. The wrists were scanned with the rotation of the forearm set to the full pronated position and with the axis of the forearm being as perpendicular to the axial cut plane as possible. The digital images acquired by conventional CT were saved as DICOM files.

The images saved as DICOM files were imported into image analyzing software (Analyze; Mayo Clinic, Rochester, MN, USA). First, acquired images should be converted to true orthogonal images to use the true sagittal images in the next step. The area of the subchondral plate was cropped from each image in the series. In this step of cropping, some portion of the trabecular bone under the subchondral plate will remain in the cropped image because complete deletion of the trabecular portion in the image is technically impossible. However, the signal intensity of the trabecular bone is much lower than that of the subchondral plate, and the signal from the residual trabecular bone does not affect the result during image processing of the maximum intensity projection. In the next step, cropped images from serial images were stacked into a three-dimensional (3-D) object, which then was digitally rotated 90° to reconstruct the subchondral plate to face forward. To present the densitometric value of

the subchondral plate, a maximum intensity projection (MIP) map was developed by extracting the highest signal intensity of each point in the subchondral plate on the projection line. This is the process of converting and compressing a series of voxels on the projection line in a 3-D object to a representative pixel in the two-dimensional densitometric map. The reconstructed image is shown as a gray-scale image, but actually the saved image has information regarding signal intensity with the Hounsfield unit (HU), which is the attenuation coefficient used in CT. For better observation, false-color mapping was applied to the densitometric map by conversion of each range of the HU into eight colors. The highest (> 1400 HU) and lowest (< 200 HU) ranges of density values were set to black and white, respectively, and six more colors were set to be distributed evenly between them (Fig. 1).

The densitometric map that finally was acquired through false-color mapping was used for data analysis. We assessed the gross topographic pattern using a series of densitometric maps. To quantize this topographic densitometric analysis, the subchondral plate of the distal radius was divided into four subareas (radial half of the scaphoid fossa, ulnar half of the scaphoid fossa, interfossa ridge, and lunate fossa) by analyzing the coronal and axial images of the radiocarpal joint of each subject and the average subchondral BMD of each area expressed by HU was determined. In addition, we calculated the mean subchondral BMD of the entire subchondral plate, and its correlation with the clinical factors consisting of systemic and local factors, described above, was assessed.

All statistical procedures were performed with SPSS 12.0 (Chicago, IL, USA). For the statistical evaluation, the mean BMDs of the four subareas in the subchondral plate were compared using Student's paired t-test. The correlation of the mean BMD of the entire subchondral plate with a range of clinical factors including age, height, weight, BMI, and BMD of the femoral neck and lumbar spine was evaluated using the Pearson's correlation model. In addition, we evaluated the correlation between the mean subchondral BMD and the degree of hand osteoarthritis and socio-occupational class using a Mann-Whitney U test and Student's independent t-test, respectively. Probability values less than 0.05 were considered significant.

Results

In the quantification, the mean subchondral BMD of the subjects was 518 HU (range, 360–720 HU), and the range of the highest proportion was 400 to 600 HU (36%), followed by 200 to 400 (25%), 600 to 800 (22%), 800 to 1000 (8%), less than 200 (6%), 1000 to 1200 (2%), and greater than 1200 HU (1%) (Fig. 2).

Fig. 1 The flow diagram illustrates digital image processing with CT osteoabsorptometry (CT-OAM).

Fig. 2 The graph shows the distribution of subchondral BMD of the distal radius. HU = Hounsfield units.

Fig. 3 The box-and-whiskers plot shows the average BMDs of four subareas in the subchondral plate. BMD = bone mineral density.

In the topographic analysis, the gross subchondral BMDs of the scaphoid and lunate fossae were greater than those of the interfossa ridge and outer rim of the subchondral plate (Fig. 1). The result acquired by quantization using division of the subchondral plate by four subareas also showed this bicentric pattern of subchondral BMD. The mean subchondral BMD of the ulnar half of the scaphoid fossa (718 HU) was significantly higher than that of the lunate fossa (556 HU) and interfossa ridge (483 HU) ($p = 0.002$ and $p < 0.001$, respectively). In addition, the mean subchondral BMD of the lunate fossa was significantly higher ($p < 0.001$) than that of the interfossa ridge. Also, a comparison of the radial half and ulnar half of the scaphoid fossa revealed the ulnar half of the scaphoid fossa to have a significantly higher ($p = 0.021$) BMD than the radial half of the scaphoid fossa (640 HU) (Fig. 3).

The mean age, height, weight, BMI, and DXA T-scores assessed in the femoral neck and lumbar spine were 68 years (range, 52–88 years), 154.0 cm (range, 138–164 cm), 57.8 kg (range, 42–70 kg), 24.3 (range, 19.9–30.3 kg/m²), -1.8 (range, -3.8 – 0.8) and -2.7 (range, -4.8 to -0.6), respectively. When correlation of the mean subchondral BMD with these clinical factors was assessed, only BMDs of the femoral neck and lumbar spine were significant factors correlated with the mean subchondral BMD ($r = 0.61$, $p < 0.001$; $r = 0.64$, $p < 0.001$, respectively) (Fig. 4). The subchondral BMD was similar regardless of the socio-occupational classification and radiographic evidence of hand osteoarthritis ($p = 0.11$; $p = 0.53$) (Table 3).

Discussion

Several studies on BMD or strength in trabecular or cortical bone of the metaphysis of the distal radius have been

Fig. 4A–B The scatter diagram shows the correlation between the subchondral BMD of the distal radius with systemic BMDs measured at the (A) femoral neck and (B) lumbar spine. BMD = bone mineral density.

published [11, 24, 34, 36]. However, to our knowledge no reports have focused on the subchondral plate of the distal radius. We examined the topographic pattern of the subchondral plate of the distal radius and the correlation between various clinical factors and subchondral BMD of the distal radius. We assumed that the subchondral BMD of the distal radius can be affected by (1) systemic or constitutional factors, which include age, height, weight, BMI, and T-score measured by DXA at the axial skeleton; and (2) by local factors that are long-term joint reaction forces represented indirectly by radiographic evidence of osteoarthritis and socio-occupational class.

Our study has several limitations. First, we used CT osteoabsorptiometry, which resulted in densitometric

Table 3. Correlation of the subchondral bone density with various clinical factors*

Category	Average	Correlation coefficient	p value
Age (years)	68	−0.26	0.11
Height (cm)	154.0	−0.12	0.45
Weight (kg)	57.8	−0.10	0.53
BMI (kg/m ²)	24.3	−0.19	0.25
T-score (femur neck)	−1.8	0.61	< 0.001
T-score (lumbar spine)	−2.7	0.64	< 0.001

Category	Average	Cases	p value
Socio-occupational class [†]	Nonmanual worker	31	0.11
	Hard manual worker	49	
Hand osteoarthritis [‡]	Nonosteoarthritis	61	0.53
	Osteoarthritis	19	

*Age, height, weight, BMI, and T-scores measured by dual-energy x-ray absorptiometry at the lumbar spine and femoral neck were evaluated statistically using Pearson's correlation model. Comparison of the subchondral bone density between the groups determined by the socio-occupational classification and radiographic evidence of hand osteoarthritis using a Student's independent t-test and Mann-Whitney U test, respectively; [†]hard manual worker group was defined as class IVc, VIIa, or VIIb in the Erikson-Goldthorpe-Portocarero scheme [12]; [‡]osteoarthritis was defined as above Grade II in metacarpophalangeal and basal joint by Kellgren and Lawrence classification; BMI = body mass index.

values in HU. Because the HU is the attenuation coefficient that is calibrated with reference to water and not an absolute value, the results produced in HU may present different values depending on CT scanners or examination conditions, leading to a lack of reproducibility in measurement. However, all subjects were evaluated using an identical CT scanner under the same conditions. Therefore, the topographic and correlational analysis in this study would not have substantial problems. Second, the authors used radiographic evidence of osteoarthritis and socio-occupational class as indirect indicators of the accumulated intensity of hand labor and long-term joint reaction force exerted on the distal radius. Although the criteria of osteoarthritis and hard manual worker were based on previous studies [6, 25, 39], this type of dichotomous way of division is somewhat arbitrary. Third, the estimated densitometric measurement is the maximum value among a series of voxels that are located on the trajectory line because we used the MIP technique. The MIP appears more reasonable, but such a technique is currently unavailable. Nevertheless, selecting the maximum value using MIP will not allow substantial error because the subchondral plate of the distal radius in the elderly is normally very thin.

In the quantification, the mean subchondral BMD of the subjects was 518 HU (range, 360–720 HU). In a previous study, bone quality was categorized into five classes based

on the Hounsfield unit obtained from a CT scan [26]. In this classification, the BMD range of 360 to 720 HU, as in our study, corresponds to the D3 class, which consists of the porous cortical bone and the fine trabecular bone. Considering this, the quantified results of our study showed that the subchondral BMD of the distal radius in postmenopausal women usually corresponds to the interim value between the BMDs of the cortical and trabecular bones, and is relatively widely distributed through the range (eg, 360–720 HU), depending on the subjects.

In the topographic analysis, the gross pattern of the densitometric distribution was assessed and a quantified comparative analysis was performed by dividing the subchondral plate into four subareas (radial half of the scaphoid fossa, ulnar half of the scaphoid fossa, interfossa ridge, and lunate fossa). The subarea division like this was based on the load-bearing situation of each location, ie, the ulnar half of the scaphoid fossa and lunate fossa bear the transarticular (radioscaphoid and radiolunate) load directly but the interfossa ridge does not bear any direct load and the radial half of the scaphoid fossa bears a range of loads depending on the posture of the wrist. Statistically, the areas of the ulnar half of the scaphoid fossa and lunate fossa have a significantly higher BMD than the interfossa ridge, as shown in the gross assessment of each densitometric image (Fig. 1). This bicentric pattern of the subchondral BMD can be explained by the hypothesis that the transarticular load of the wrist is transmitted mainly by the radioscaphoid and radiolunate joints and the subchondral plate of the distal radius adapted to this long-standing mechanical strain. This type of densitometric distribution corresponds well with studies by Carlson and Patel [4, 28]. However, the subchondral BMD of the ulnar half of the scaphoid fossa is significantly higher than the radial half of the scaphoid fossa and lunate fossa, and there was no statistical difference in subchondral BMD between the radial half of the scaphoid fossa and the lunate fossa. This suggests the contact area between the proximal pole of the scaphoid and the ulnar half of the scaphoid fossa is the primary load-transmitting location, and the radiolunate joint and radial half of the radioscaphoid joint are the secondary load-transmitting locations. In addition, this topographic distribution of BMD has several clinical implications. First, when intraarticular extension of the distal radius fracture or lunate die-punch fracture occurs, the interfossa ridge, with a relatively low BMD, is normally involved in fractures. Second, when performing volar plating to a distal radius fracture, locking screws produced better support on a relatively dense subchondral portion of the lunate fossa and the ulnar half of the scaphoid fossa rather than that of the interfossa ridge.

For correlational analysis, several systemic and local factors were assumed to be the clinical factors with a

potential correlation with subchondral BMD. Among the systemic factors, only the systemic BMD measured in the T-score by DXA at the lumbar spine and femoral neck was related to the subchondral BMD. In general, several anthropometric variables including age, height, weight, and BMI are believed to be related to systemic osteoporosis in postmenopausal women despite some debate [27, 30, 37]. However, our study showed such anthropometric variables do not correlate with the subchondral BMD of the distal radius.

The local factors represented by the radiographic evidence of osteoarthritis and socio-occupational class also were found not to correlate with the subchondral BMD of the distal radius. A mechanical load applied to a joint includes the weightbearing force and joint reaction force [29]. Because humans are bipedal animals, the weightbearing force applied to the wrist can be negligible and there remains only a joint reaction force that is made from the muscle-tendon structure. We assessed the accumulated intensity of hand labor experienced in the past using the socio-occupational classification and radiographic evidence of osteoarthritis to objectively determine the long-term joint reaction force exerted on the distal radius. We used the scheme described by Erikson et al. [12] as a socio-occupational classification and the Kellgren-Lawrence scale as an osteoarthritis grading system to objectify and minimize the arbitrariness. The scheme by Erikson et al. [12] has been used to evaluate the socioeconomic factors in a range of disease situations [5, 6, 25], and the Kellgren-Lawrence scale has been used to evaluate hand osteoarthritis and its impact on the functional status in the study by Zhang et al. [39]. As a result, the intensity of accumulated hand labor showed no significant relationship with the subchondral BMD of the distal radius.

These negative correlations can be explained by Frost's mechanostat hypothesis [15, 16]. There is a range of strain that maintains constant bone turnover. The lowest value of that range is called the minimum effective strain (MES) for the remodeling threshold. Bone loss progresses when the strain applied to the bone is less than the MES, whereas bone gain progresses when the strain is beyond that range. Because the wrist is not a weightbearing joint in humans, gravitational factors such as weight or BMI have little effect on the wrist. In addition, the joint reaction force caused by accumulated intense hand labor might not reach the level of the remodeling threshold. Only the systemic BMD measured in the axial skeleton was found to correlate with the subchondral BMD of the distal radius, possibly as a constitutional factor.

We believe our results provide anatomic and clinical insights regarding the microstructure and mechanical properties of the subchondral plate in the distal radius, which have been relatively undisclosed. Also, the topographic findings

in this study may be helpful when performing surgery and for implant development.

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