Quantification of Bone Mineral in the Vertebral Body and Whole Body Skeleton with a Newly Developed Dual Energy X-ray Absorptiometric System Using a Multi-detector Array

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ABSTRACT. The usefulness and safety of a newly developed bone mineral quantifyig DEXA system using a multi-detector array, the QDR-2000, were examined. The accuracy of measurements with this system is excellent, and it can quantify BMDs on lumbar AP images, lumbar lateral images and whole body images with high reliability and safety in metabolic bone diseases such as osteoporosis.

Key words: bone mineral — vertebral body — whole body skeleton — dual energy X-ray absorptiometry — multi-detector array

Although various methods of noninvasive bone mineral measurement are now being used clinically, dual energy X-ray absorptiometry (DEXA) has become extremely popular due to the excellent results that have been achieved.[1] Most DEXA systems are used for regional measurement of the lumbar spine or the proximal femur, but some of systems have been employed to measure whole body bone mineral. As 80% of the whole body skeleton is composed of cortical bone, a change in the bone mineral of the whole body reflects a similar change in that of cortical bone. Trabecular bone, on the other hand, has a large bone surface area and a high turnover of bone, which is considered to be the reason why postmenopausal bone loss occurs earlier in trabecular bone than in cortical bone.[2]

The vertebral body of the lumbar spine consists mainly of trabecular bone. However, when data are collected in the anteroposterior (AP) direction, bone mineral in the posterior portion of the spine, which is composed mainly of cortical bone, is also measured.[3] In addition, in aged subjects the calcified abdominal aorta may overlie the lumbar spine and lead to overestimation of bone mineral if data are collected in the AP direction. Therefore, we made an attempt to measure the bone mineral in the vertebral body alone, which consists mainly of trabecular bone, by data acquisition in the lateral direction. However, with conventional DEXA methods, the reproducibility of lateral

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bone mineral density (BMD) measurements is poor because the subjects are measured while lying on their side. In the decubitus position, it is difficult to obtain the same projection through the spine and soft tissue in repeated measurements with re-positioning of the subject.

Recently, a DEXA method which incorporates a multi-detector array into a C-arm and uses an X-ray tube as a photon source has been developed. This new DEXA system (QDR-2000, Hologic Inc.) is expected to shorten the time for data acquisition of bone mineral in the whole body and to improve assay precision because it can measure the vertebral body in the lateral direction with the patient lying in the supine position. In the present study, the fundamental performance and clinical usefulness of this system as well as its safety during the measurement of bone mineral density were evaluated.

OUTLINE OF QDR-2000

The QDR-2000 consists of a patient bed, an X-ray generator, a detector array, a scanner, a control unit and a power unit. Like the QDR-1000, the X-ray generator has a voltage switching function between 70 and 140 KVP. It is also equipped with both pencil-type and fan-type X-ray beams. There are 32 PMT tubes coupled to CdWO4 scintillators in the detector array. Each of these measures the transmitted X-ray intensity. A laser beam unit is attached to the detection unit for positioning of the subject. The scanner unit simultaneously scans with the X-ray generator and the detector, which are placed on the opposite ends of the C-shaped arm. The C-shaped arm can be manually turned from a position anteroposterior to the bed to one lateral to the bed. With this system, therefore, bone mineral density can be measured from the side of the lumbar spine, with the subject lying in the supine position. The data processing unit is composed of a computer, a display unit, and an image printer. Its functions include the selection of regions and modes for scanning, calculation, and the storage of data. Four regions can be scanned with this system ; i.e., the lumbar spine in AP and lateral positions, the whole body, and the proximal femur. The bone mineral content (BMC), bone area, and BMD are calculated by the data processing unit.

With this system, the method of data acquisition depends upon the region that is to be scanned. There are five different modes (Array, Fast Array, High-resolution Array, Turbo Array, and Single Beam) for the lumbar AP image, two modes (Fast Lateral and High-resolution Lateral) for the lumbar lateral image, three modes (Array, Fast Array, and Single Beam) for the proximal femur image, and one mode (Single Beam) for the whole body. Data acquisition of the lumbar AP image always precedes that of the lateral image. In other words, data from the AP image are collected and analyzed first, and then the C-shaped arm is moved 90 degrees manually for data acquisition of the lateral image. The position for initiating the lateral image is automatically set on the lower edge of the fourth lumbar vertebra. The data on whole body image are collected from 10 regions ; i.e., the head, left arm, right arm, left rib, right rib, thoracic spine, lumbar spine, pelvis, left leg and right leg, and BMC, bone area and BMD are calculated for each region as well as for the whole body.

MATERIALS AND METHODS

The 57 subjects of this study included 7 normal subjects, 11 with osteoporosis, 6 with suspected osteoporosis with lumbago or back pain, 11 with hyperparathyroidism (1 primary and 10 secondary: 10 are postoperative), 7 with Basedow's disease, 9 with thyroid cancer (8 are postoperative), 3 with other thyroid diseases, and 3 with other diseases. Written or oral consent for participation in this test was obtained from all the subjects according to the rules of the Consignment Research Committee of Kawasaki Medical School Hospital.

The modes of data acquisition selected for the measurement of bone mineral with the QDR-2000 were Array for the lumbar AP image, Fast Lateral for the lumbar lateral image, and Single Beam for the whole body image. The measurement time was 2.5 min for the lumbar AP image, 3 min for the lumbar lateral image, and 12-13 min for the whole body image.

With the QDR-2000, BMDs were measured in the second to fourth lumbar vertebrae (L_{2-4}) on the AP image in 57 cases, in the vertebral body and its center in the third lumbar vertebra (L_3) on the lateral image, and in the whole body and individual regions (head, left arm, right arm, left rib, right rib, thoracic spine, lumbar spine, pelvis, left leg, and right leg). To compare these BMDs with those obtained by commercially available DEXA systems, BMDs

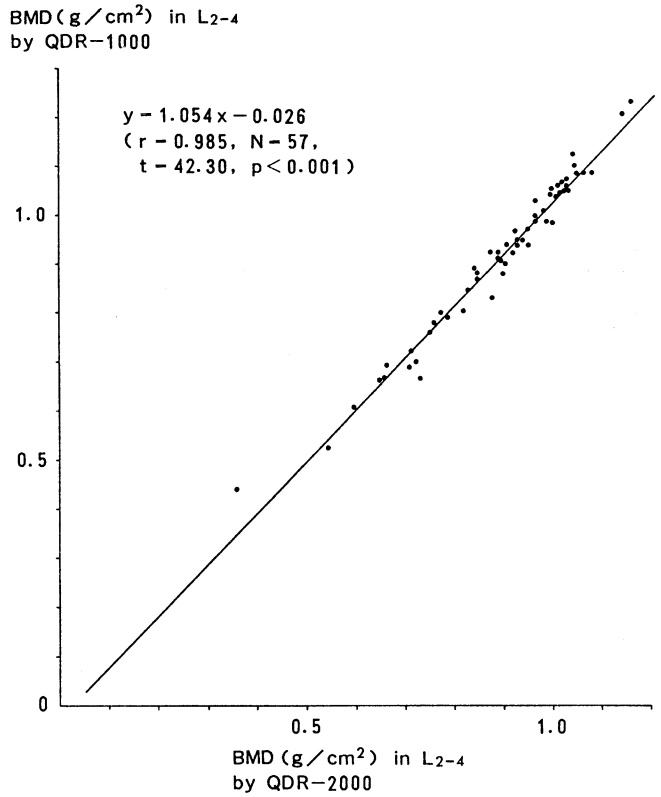

Fig. 1. Correlation between BMDs in L_{2-4} on the lumbar AP image measured by the QDR-2000 and those measured by the QDR-1000

were measured simultaneously in L_{2-4} on the AP image by the QDR-1000 (Hologic Inc.) and in the 1/3 distal radius by the DCS-600 (Aloka Co.) in 57 and 25 cases, respectively. Then correlations between the BMDs obtained by the QDR-2000 and those obtained by the QDR-1000 or DCS-600 were studied. The BMDs in the whole body or in the lumbar spine on the whole body image were also compared with those measured in L_{2-4} by the QDR-1000. Measurements by the QDR-1000 or DCS-600 were done within one month before or after the determinations made by the QDR-2000 in all the cases except one (Case 9).

Regarding each disease group, the BMDs in L_{2-4} on the AP image, in the vertebral body and its center in L_3 on the lateral image, and in whole body and individual regions on the whole body image were measured by the QDR-2000.

Evaluation of the safety of the QDR-2000 was based on reports by both the operator and the subjects.

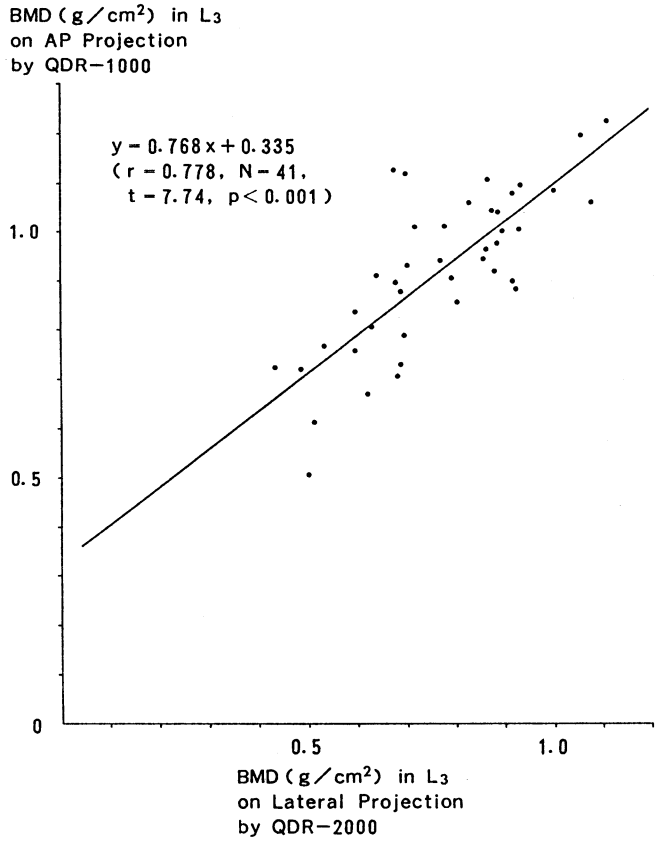

Fig. 2. Correlation between BMDs in the vertebral body of L_3 on the lumbar lateral image measured by the QDR-2000 and those in whole L_3 on the lumber AP image measured by the QDR-1000

RESULTS

1. Correlation between BMDs measured by the QDR-2000 and by other DEXA systems

The correlation between BMDs in L_{2-4} on the lumbar AP image measured by the QDR-2000 and those obtained by the QDR-1000 is shown in Fig. 1. A significant highly positive correlation ($r=0.985$, $p<0.001$, $y=1.054X-0.026$) was found between these two systems.

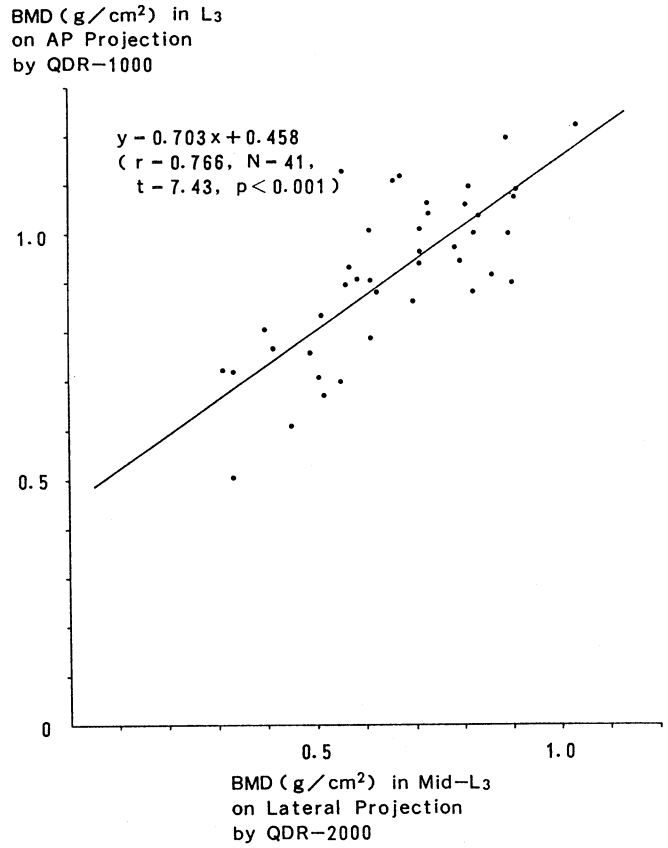

Fig. 3. Correlation between BMDs in the mid-vertebral body of L_3 on the lumbar lateral image measured by the QDR-2000 and those in the whole L_3 on the lumbar AP image measured by the QDR-1000

Figs. 2, 3 show the correlations between the BMDs in the vertebral body or its center in L_3 on the lateral image by the QDR-2000 and those in the whole L_3 on the AP projection by the QDR-1000. These were $r=0.778$ ($p<0.001$, $y=0.768X+0.335$) for the former and $r=0.766$ ($p<0.001$, $y=0.703X+0.458$) for the latter.

The correlations between the BMDs in the whole body skeleton or lumbar spine on the whole body image measured by the QDR-2000 and those in L_{2-4} on the AP projection obtained by the QDR-1000 were $r=0.622$ ($p<0.001$, $y=0.969X-0.032$) and $r=0.938$ ($p<0.001$, $y=0.961X+0.074$), respectively (Figs. 4, 5).

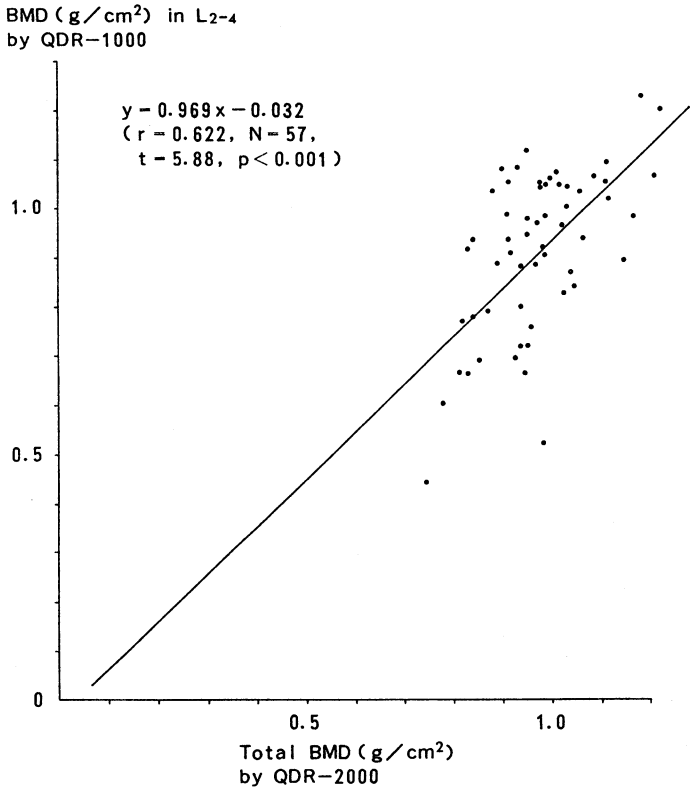

Fig. 4. Correlation between BMDs in the whole body skeleton on the whole body image measured by the QDR-2000 and those in L_{2-4} on the lumbar AP image measured by the QDR-1000

The BMDs in the whole body skeleton on the whole body image measured by the QDR-2000 had a correlation of $r=0.789$ ($p<0.001$, $y=1.017X-0.413$) with those in the radius measured by the DCS-600 (Fig. 6). In the 25 cases in which BMDs were measured simultaneously in the radius by the DCS-600, in L_{2-4} by the QDR-1000, and in the whole body skeleton by the QDR-2000, there was a correlation of $r=0.561$ ($p<0.01$, $y=0.838x+0.108$) between the BMDs in the whole body skeleton obtained by the QDR-2000 and those in L_{2-4} measured by the QDR-1000.

2. BMD values measured by the QDR-2000 in various diseases

Tables 1 and 2 show the BMDs measured in L_{2-4} on the AP image, and in the whole vertebral body and its center in L_3 on the lareral image by the QDR-2000. A significant decrease ($p<0.001$-0.05) in L_{2-4} was found in the cases of osteoporosis, hyperparathyroidism and thyroid cancer, while a significant decrease ($p<0.001$ and 0.01) in both the whole vertebral body and its center in L_3 was seen in patients with osteoporosis and thyroid cancer.

The BMDs in the whole body skeleton and individual parts on the whole body image measured by the QDR-2000 in various diseases are shown in Fig. 7. The osteoporotic group showed a sigificant decrease in BMDs in all

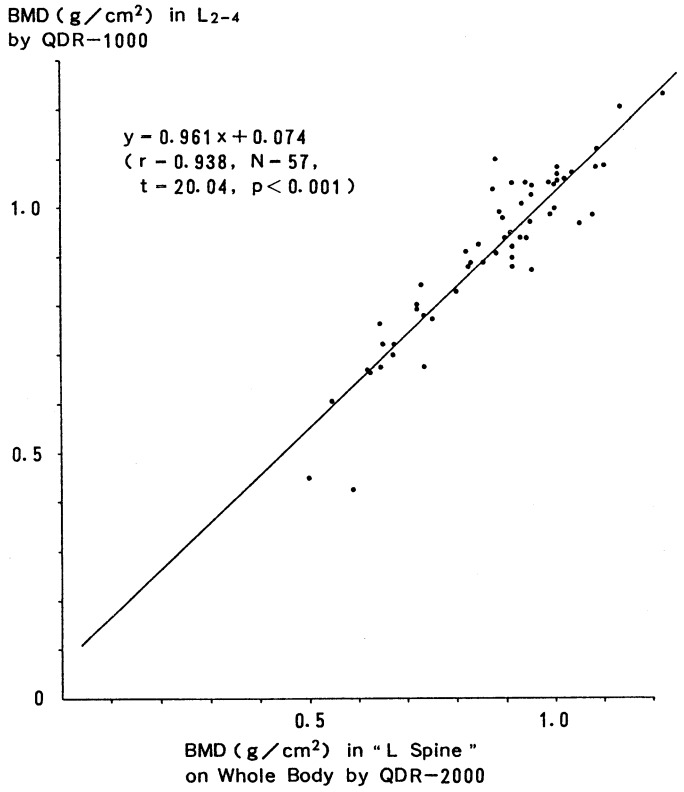

Fig. 5. Correlation between BMDs in the lumbar spine on the whole body image measured by the QDR-2000 and those in L_{2-4} on the lumbar AP image measured by the QDR-1000

TABLE 1. BMDs in L_{2-4} on the AP image measured by the QDR-2000

	N	sex F/M	Age (yrs.)	BMD by QDR-2000 L_{2-4} (AP)
Normal	7	3/4	34.4 ± 7.0	1.020g/cm² ±0.065
Osteoporosis	11	9/2	61.9 ± 9.5	0.682* ±0.136
Osteoporosis(S/O)	6	5/1	61.0 ± 7.1	0.974 ±0.072
Hyperparathyroid	11	7/4	51.5 ±13.7	0.920*** ±0.111
Basedow's Dis.	7	4/3	32.0 ± 8.8	0.975 ±0.106
Thyroid Cancer	9	9/0	49.9 ± 6.6	0.873 ±0.122**
Other Thyroid Dis.	3	1/2	49.7 ±15.2	0.981 ±0.065
Others	3	3/0	53.0 ± 5.6	0.912 ±0.179

vs. Normal : p<*0.001, **0.02, ***0.05

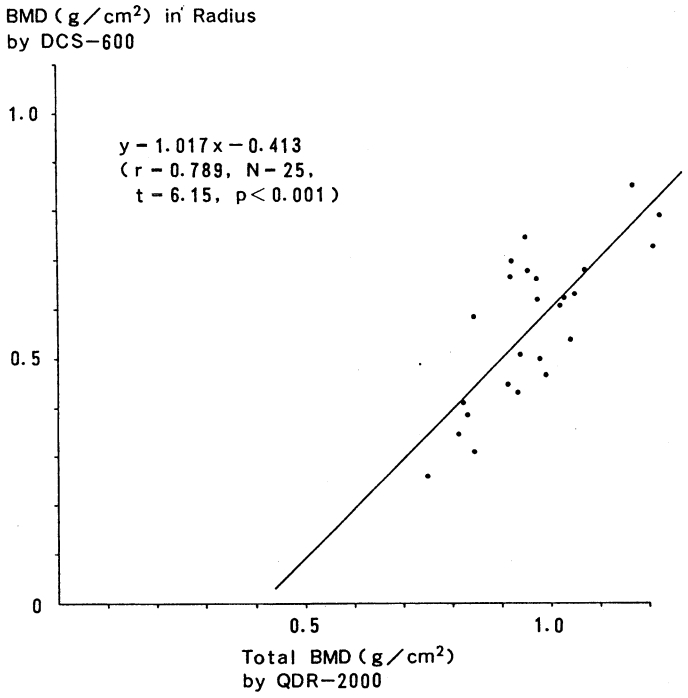

Fig. 6. Correlation between BMDs in the whole body skeleton on the whole body image measured by the QDR-2000 and those in the radius measured by the DCS-600

TABLE 2. BMDs in L_3 and mid-L_3 on the lateral image measured by the QDR-2000

	N	Lateral BMD by QDR-2000	
		L_3	Mid-L_3
Normal	5	0.889g/cm² ±0.103	0.782g/cm² ±0.097
Osteoporosis	7	0.555* ±0.122	0.441* ±0.134
Osteoporosis(S/O)	6	0.781 ±0.177	0.671 ±0.106
Hyperparathyroid	10	0.803 ±0.129	0.699 ±0.185
Basedow's Dis.	4	0.942 ±0.111	0.887 ±0.108
Thyroid Cancer	5	0.716** ±0.041	0.606** ±0.021
Other Thyroid Dis.	2	0.927 −0.931	0.813 −0.838
Others	2	0.596 −0.675	0.489 −0.556

vs. Normal : $p <$ *0.001, **0.01

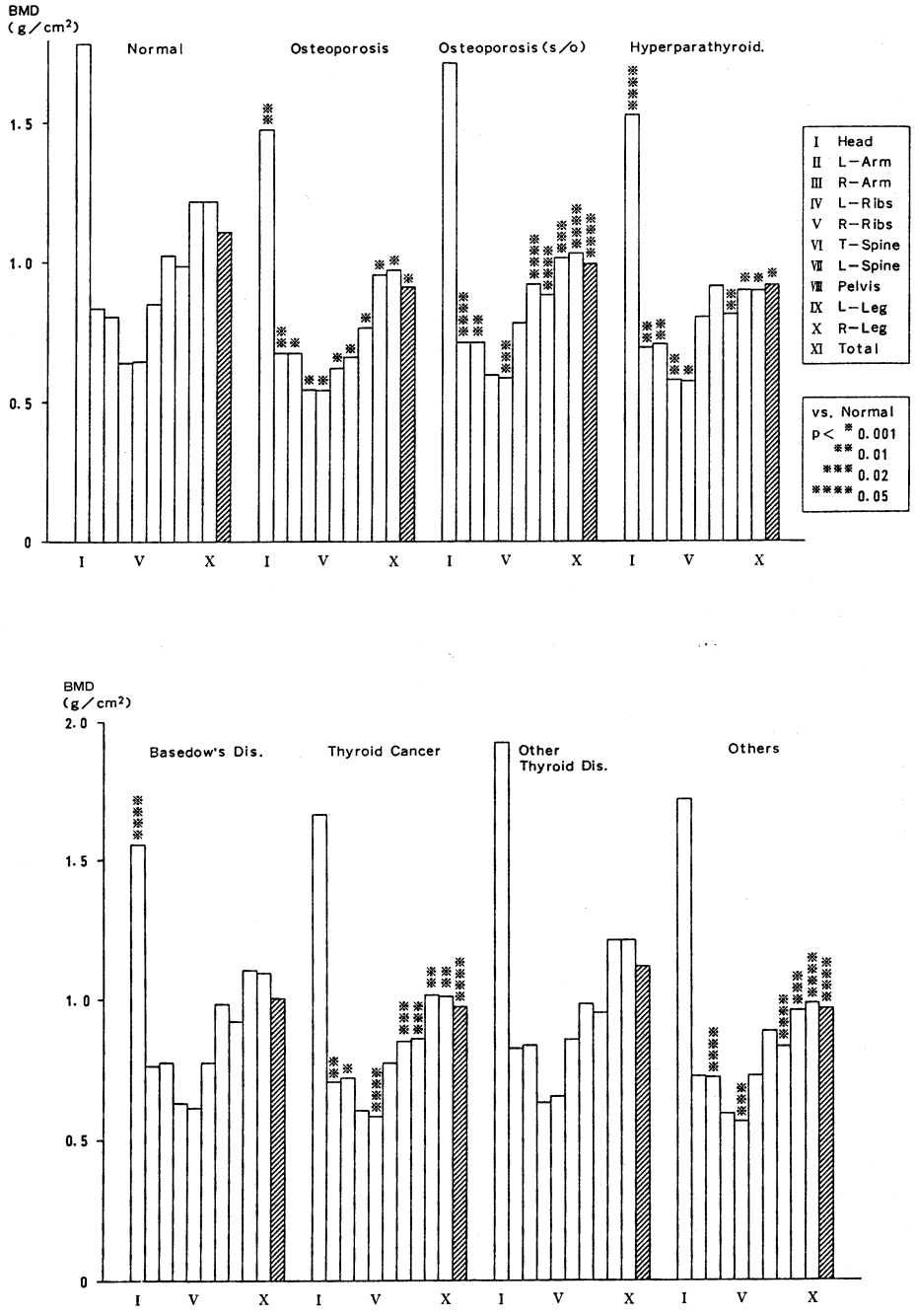

Fig. 7. BMDs in the whole body skeleton and its individual regions on the whole body image measured by the QDR-2000 in various diseases

the regions including the whole body skeleton. In the group with suspected osteoporosis, the BMDs were significantly lower in all the regions except the head, left rib and thoracic vertebrae. In the hyperparathyroid group, a significant decrease was seen in BMDs in the whole body skeleton and all the regions except the thoracic and lumbar vertebrae. The patients with Basedow's disease showed a significant decrease in BMDs in the head, whereas patients with thyroid cancer showed a significant decrease in the whole body skeleton and all the regions except the head and left rib. In the other diseases group, a significant decrease in BMDs in all regions except the head, left rib, and thoracic and lumbar vertebrae was recognized.

3. Safety of measurement of BMD by QDR-2000

The measurement of BMD by the QDR-2000 was performed safely in all 57 cases.

DISCUSSION

DEXA systems are widely available for clinical use because of their excellent performance. However, there are some problems to be solved ; 1) The precision of BMD measurement of the vertebral body of L_3 on the lateral image is slightly inferior to that of the whole L_{2-4} on the AP image, and 2) it is time-consuming to collect whole body skeleton data. It has been reported that the precision of BMD measurement in the vertebral body of L_3 on the lateral image by the QDR-2000 is much better than that obtained by the QDR-1000.[4] This implies that reproducibility of the measurement position is important to achieve high precision on the lateral image. With conventional DEXA systems, lateral data are collected in the vertical direction from an examinee on his/her side, whereas with the QDR-2000 the patient lies in the supine position, and data are collected from the lateral direction. The improvement in precision may be attributed to the use of the spine position because it reduces errors caused by distortion or curvature of the spine. With the QDR-2000, which has a multi-detector array, the time required for measurement of the BMDs in L_{2-4} on the AP image, not including the time for a patient's set-up, analysis and printout, is greatly shortened to 2-3 min. This should be helpful when pediatric patients and the elderly, who often have difficulty in self-control during measurement, are measured.

An excellent positive correlation ($r=0.985$) was noted between BMDs on lumbar AP images obtained by the QDR-2000 and QDR-1000. This result indicates that BMD measurements of the QDR-2000 are as accurate as those of the QDR-1000. Although the lumbar spine consists mainly of trabecular bone, an AP image includes not only the vertebral body, consisting of trabecular bone, but also the posterior component, which is composed of cortical bone. A lateral image, on the other hand, measures the BMD in the vertebral body alone, eliminating the posterior component. The correlations between the BMDs in the vertebral body of L_3 or its center on the lateral image by the QDR-2000 and those in the whole L_3 on the AP image by the QDR-1000 were moderate ($r=0.778$ and 0.766). These coefficients indicate that in some cases decreases in BMD in cortical bone and trabecular bone do not always occur at the same time and to the same degree. In fact, in the case of postmenopausal osteoporosis, it has been reported that the BMD remarkably decreases in the

lumbar spine, which consists mainly of trabecular bone.[5] Therefore, reliable measurement of BMD in the vertebral body of L_3 on the lateral image would be helpful for detecting decreases in BMD at an early stage after menopause.

Since 80% of the whole body skeleton is composed of cortical bone, it was expected that the BMDs measured in the whole body skeleton by the QDR-2000 would show a closer correlation with those in the radius, which mainly consists of cortical bone, than with those in lumbar spine, which is composed mainly of trabecular bone. This was verified by results, indicating that the whole body BMD had a closer correlation with radial BMD ($r=0.789$) than with lumbar BMD ($r=0.561$). In addition, the lumbar BMD on the whole body image measured by the QDR-2000 showed an excellent positive correlation ($r=0.938$) with L_{2-4} BMDs obtained by the QDR-1000, indicating it may be possible to evaluate lumbar BMD using the whole body image mode.

The diagnostic criterion for involutional osteoporosis has been proposed by a research group of the Silver Science Project sponsored by the Ministry of Health and Welfare and chaired by Prof. H. Orimo. According to that group, osteopenia is an important finding in the criterion.[6] In the present study, osteoporotic patients showed a decrease in all BMDs in L_{2-4} on the AP image, in the vertebral body of L_3 and its center on the lateral image, and in the whole body skeleton and individual regions on the whole body image with the QDR-2000. This indicates that BMD decreases in both trabecular bone and cortical bone in osteoporosis. In the cases of suspected osteoporosis, some parts of the bones on the whole body image showed a decrease in BMD. It is worth considering whether or not these results are indicative of an early change in osteoporosis, and further studies should be done.

The present study under abnormal conditions of bone metabolism was preliminary and limited because of the small number of subjects in the control group and the heterogenous nature of the patient populations. Some data should, however, contribute to a better understanding of the state of bone metabolism. Hyperparathyroid patients showed a remarkable decrease in BMD in peripheral bone other than axial bone. This finding agrees with those in a previous report,[7] indicating that hypersecretion of parathyroid hormone causes a more remarkable decrease in BMD in cortical bone than in trabecular bone. In the cases of Basedow's disease, BMD in the head had decreased. Hyperthyroidism is known as one of the causes of secondary osteoporosis, and this result indicates that a decrease in BMD might occur in the head at an early stage of this disease. In the cases of thyroid cancer, a decrease in BMD was shown in the whole body skeleton and individual regions on the whole body image, including L_{2-4} on the AP image, and in the vertebral body and its center on the lateral image by the QDR-2000. Eight out of nine patients in this group had had a total or subtotal thyroidectomy. The thyroidectomy might have caused the osteopenia because of decreased secretion of calcitonin, which exists in the C-cells of the thyroid gland and has an inhibitory effect on bone resorption.

In conclusion, it was shown that the QDR-2000 could be reliably used for bone mineral quantification of BMDs in the whole lumbar spine, vertebral body, whole body skeleton and its individual regions, and that it could be safely used under abnormal conditions of bone metabolism such as osteoporosis.

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