FROM THE UNIVERSITY CENTRAL HOSPITAL, SF-70210 KUOPIO, FINLAND.

BONE MINERAL CONTENT OF THE FOREARM IN A HEALTHY POPULATION

P. KARJALAINEN and E. M. ALHAVA

The mineral content of bone may be affected by age, disease or drugs, which can be demonstrated by various radiologic procedures; the narrow beam gamma attenuation (CAMERON & SORENSON 1963) is the most accurate and perhaps the most used procedure (CAMERON et coll. 1968). The recognition of abnormal bone mineral content presupposes an adequate knowledge of the normal conditions, including the normal range (GOLDSMITH 1973, GOLDSMITH et coll. 1973, MAZESS & CAMERON 1973, BOYD et coll. 1974, VON ROTH et coll. 1974).

The bone mineral content of a healthy Finnish population is now reported and the relative usefulness of different units of the bone mineral 'density' for assessing the quantity of the bone mineral is discussed.

Material. The test subjects were selected from ambulant patients in this hospital and included both urban and rural dwellers and blue and white collar employees. The series included 83 men from 11 to 87 years old, and 89 women from 11 to 81. The subjects and their height and weight distribution by age appear in Table 1. The criteria for exclusion from the material were (VAUGHAN 1970): patients under hormone treatment and those who had or had had an endocrinologic disease, rheumatoid arthritis, malignant tumor, sarcoidosis, chronic nephropathy or renal calculi, malabsorption, osteomalacia, hemiparesis or other paresis, asthma or epilepsy, or had undergone intestinal surgery apart from appendectomy. Pregnant and lactating women and long-term users of psychopharmaceutic drugs and diuretics were also excluded. No clinical laboratory investigations were performed for the selection procedure.

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Table 1

The material

Age group	N	Age (mean)	Height (cm)		Weight (kg)	
			Mean	SD	Mean	SD
Males						
11–14	4	12.5	159	10	45.5	9.7
15–19	7	17.3	176	11	60.7	7.4
20–29	18	25.3	177	6	74.5	6.9
30–39	11	34.5	175	6	80.1	10.1
40–49	10	44.5	173	6	78.1	9.2
50–59	10	54.4	171	8	73.7	14.9
60–69	10	64.5	169	5	66.3	11.3
70–79	9	74.1	170	7	74.7	10.9
80–87	4	82.5	169	6	74.3	6.8
Females						
11–14	5	12.0	151	12	38.5	6.4
15–19	7	16.7	169	6	54.6	5.3
20–29	24	24.7	163	6	56.4	9.2
30–39	10	34.5	163	7	65.0	9.6
40–49	10	44.5	162	4	72.4	8.9
50–59	11	54.4	161	6	70.3	13.4
60–69	10	63.9	156	6	67.7	9.6
70–79	10	74.9	158	3	67.0	9.8
80–81	2	80.5	156	6	66.0	19.8

Methods

The bone mineral measurements were made by a modification (KARJALAINEN 1973) of the gamma ray attenuation method described by SPRING (1967). The source of the radiation was 45 mCi ^{241}Am with a gamma energy of 60 keV. The bone mineral linear density, λ(g/cm), was calculated from the equation

$$\lambda = K \frac{\Delta x \varrho_m}{\mu_m \varrho_m - \mu_s \varrho_s} \sum_{1}^{n} \ln \frac{I_o}{I_1}$$

(on the distal radius λ_1, on the shaft of the radius λ_2, and on the shaft of the ulna λ_3). Irradiation may penetrate fat-containing trabecular bone better than an equivalent thickness of water, in other words, the recording line rises above the basic level (Fig. 1). Therefore, in this equation, an empirical correction factor, K, for the intra-osseus constituents lighter than water was inserted. In the region of compact bone it was assumed that $K = 1.00$.

The mineral density of the distal radius was calculated from $\varrho_1 = \lambda_1/A$, where A

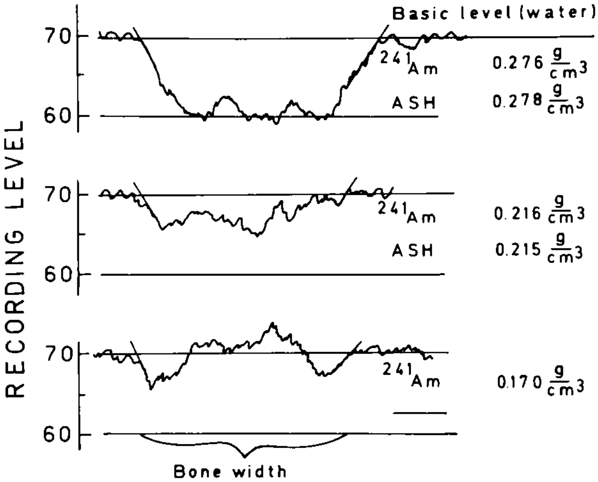

Fig. 1. Attenuation curves from normal bone (upper), osteoporotic bone (middle) and very osteoporotic bone (lower), recorded from the distal radius and corresponding quantities of bone mineral densities. The two upper curves are from in vitro and the lower from in vivo experiments.

($=0.47d^2+0.47$) is the cross-sectional area of bone at the measuring site, d is the bone width at the scanning site measured from the attenuation curves.

On the assumption that the shape of the cross-section of compact bones in the forearm is circular, mineral density indices were calculated from $\varrho_2=\lambda_2/A$ and $\varrho_3=\lambda_3/A$; $A=\pi(d_2^2-d_1^2)/4$, where d_2 and d_1 are the outer and inner diameters of the bones measured from roentgenograms. The quantities λ_2/d and λ_3/d were also calculated.

The methods used and the constants required are presented in detail elsewhere (Karjalainen 1973, Alhava & Karjalainen 1973).

Results

The bone mineral linear density (g/cm), bone mineral density or mineral density index (g/cm^3) and mineral linear density/bone width (g/cm^2) values for both dominant and nondominant forearm are given in Tables 2 and 3. The mean values of the variation coefficients calculated from these Tables show that presented from the narrower to the broader distributions the results fall in the following order: in the distal radius, $\varrho_1<\lambda_1$; in the midshaft radius, $\lambda_2/d<\varrho_2<\lambda_2$; and in the midshaft ulna, $\lambda_3/d<\lambda_3<\varrho_3$.

Table 4 presents some statistical results of differences between the mineral quantities of dominant and nondominant forearms and between the mineral density of males and females (t-test, paired comparison).

The mineral linear density (g/cm), bone mineral density or mineral density index (g/cm^3) and mineral linear density/bone width (g/cm^2) depend differently on the height of the subject measured. When this correlation was determined for both dominant and nondominant forearms of both sexes aged 20 to 45 years, in other words four correlations for each unit of the bone mineral content, the correlation

Table 2

Bone mineral content of the dominant forearms

Age group	λ_1 (g/cm)		λ_2/d (g/cm^2)		λ_3/d (g/cm^2)	
	Mean	SD	Mean	SD	Mean	SD
Males						
11–14	1.198	0.293	0.738	0.078	0.698	0.191
15–19	1.597	0.176	0.899	0.092	0.864	0.099
20–29	1.802	0.237	1.007	0.099	1.029	0.107
30–39	1.688	0.280	1.024	0.095	1.066	0.127
40–49	1.699	0.198	1.007	0.059	1.046	0.073
50–59	1.677	0.409	0.984	0.104	1.056	0.097
60–69	1.563	0.380	0.912	0.109	0.945	0.117
70–79	1.376	0.171	0.836	0.131	0.920	0.102
80–87	1.530	0.267	0.855	0.042	1.000	0.149
Females						
11–14	0.826	0.201	0.708	0.080	0.678	0.126
15–19	0.961	0.202	0.824	0.060	0.826	0.083
20–29	1.151	0.171	0.839	0.082	0.862	0.084
30–39	1.194	0.208	0.823	0.038	0.899	0.104
40–49	1.163	0.180	0.861	0.106	0.943	0.107
50–59	1.022	0.136	0.802	0.100	0.867	0.132
60–69	1.010	0.172	0.714	0.117	0.835	0.138
70–79	0.955	0.092	0.674	0.107	0.700	0.115
80–81	0.845	0.092	0.610	0.042	0.720	0.042
	ϱ_1 (g/cm^3)		ϱ_2 (g/cm^3)		ϱ_3 (g/cm^3)	
	Mean	SD	Mean	SD	Mean	SD
Males						
11–14	0.312	0.005	0.783	0.067	0.990	0.343
15–19	0.323	0.040	0.853	0.061	1.146	0.116
20–29	0.348	0.041	0.858	0.116	1.220	0.183
30–39	0.324	0.039	0.880	0.108	1.288	0.131
40–49	0.306	0.039	0.918	0.092	1.318	0.181
50–59	0.285	0.036	0.857	0.098	1.244	0.196
60–69	0.276	0.034	0.907	0.134	1.179	0.236
70–79	0.245	0.019	0.724	0.100	1.210	0.120
80–87	0.277	0.055	0.868	0.187	1.125	0.147
Females						
11–14	0.274	0.043	0.962	0.122	1.096	0.319
15–19	0.272	0.021	0.961	0.098	1.237	0.248
20–29	0.290	0.032	0.917	0.104	1.187	0.172
30–39	0.289	0.032	0.925	0.150	1.347	0.280
40–49	0.269	0.034	0.893	0.134	1.324	0.257
50–59	0.258	0.022	0.876	0.110	1.079	0.213
60–69	0.249	0.018	0.784	0.097	1.111	0.174
70–79	0.235	0.014	0.734	0.147	1.096	0.327
80–81	0.226	0.016	0.760	0.057	0.865	0.304

Table 3

Bone mineral content of the nondominant forearms

Age group	λ_1 (g/cm)		λ_2/d (g/cm^2)		λ_3/d (g/cm^2)	
	Mean	SD	Mean	SD	Mean	SD
Males						
11–14	1.155	0.364	0.748	0.022	0.708	0.097
15–19	1.469	0.194	0.906	0.125	0.833	0.116
20–29	1.818	0.259	0.988	0.091	1.028	0.115
30–39	1.697	0.346	1.011	0.120	1.071	0.139
40–49	1.683	0.134	0.965	0.064	1.016	0.091
50–59	1.650	0.237	0.955	0.128	1.090	0.155
60–69	1.381	0.253	0.922	0.102	0.976	0.119
70–79	1.297	0.211	0.819	0.079	0.901	0.103
80–87	1.400	0.195	0.858	0.101	0.925	0.085
Females						
11–14	0.836	0.306	0.690	0.085	0.654	0.120
15–19	1.049	0.256	0.783	0.053	0.809	0.087
20–29	1.094	0.148	0.835	0.084	0.875	0.094
30–39	1.148	0.208	0.849	0.074	0.885	0.107
40–49	1.139	0.169	0.839	0.056	0.939	0.085
50–59	0.970	0.148	0.785	0.149	0.815	0.107
60–69	0.931	0.173	0.709	0.102	0.779	0.137
70–79	0.896	0.117	0.631	0.117	0.693	0.066
80–81	0.790	0.084	0.620	0.028	0.700	0.071
	ϱ_1 (g/cm^3)		ϱ_2 (g/cm^3)		ϱ_3 (g/cm^3)	
	Mean	SD	Mean	SD	Mean	SD
Males						
11–14	0.311	0.023	0.828	0.063	0.935	0.124
15–19	0.309	0.035	0.877	0.133	1.207	0.195
20–29	0.343	0.056	0.866	0.081	1.277	0.183
30–39	0.316	0.055	0.933	0.081	1.324	0.149
40–49	0.304	0.043	0.899	0.096	1.232	0.138
50–59	0.309	0.042	0.909	0.155	1.240	0.243
60–69	0.295	0.039	0.905	0.125	1.186	0.250
70–79	0.256	0.017	0.783	0.097	1.122	0.134
80–87	0.267	0.027	0.820	0.110	1.050	0.047
Females						
11–14	0.275	0.041	0.920	0.204	1.028	0.326
15–19	0.288	0.037	0.943	0.085	1.151	0.231
20–29	0.293	0.033	0.919	0.108	1.219	0.171
30–39	0.302	0.053	0.954	0.079	1.215	0.233
40–49	0.273	0.041	0.899	0.125	1.190	0.204
50–59	0.277	0.045	0.839	0.169	1.077	0.262
60–69	0.248	0.020	0.810	0.091	1.184	0.333
70–79	0.238	0.019	0.677	0.087	1.056	0.211
80–81	0.230	0.008	0.850	0.014	0.965	0.361

Table 4

Some statistical results of bone mineral measurements (t-test, paired comparison, NS = not significant)

Sex	Mineral content	Comparison	Age	Pairs	t	Significance
M	λ_1	Dominant–nondominant forearm	11–87	83	2.21	$p < 0.05$
F	λ_1	Dominant–nondominant forearm	11–82	89	2.88	< 0.005
M	λ_2	Dominant–nondominant forearm	11–87	83	3.11	< 0.005
F	λ_2	Dominant–nondominant forearm	11–82	89	5.22	< 0.001
M	λ_3	Dominant–nondominant forearm	11–87	83	0.47	NS
F	λ_3	Dominant–nondominant forearm	11–82	89	3.95	< 0.001
M	ϱ_1	Dominant–nondominant forearm	11–87	83	−0.41	NS
F	ϱ_1	Dominant–nondominant forearm	11–82	89	−2.28	< 0.05
M	ϱ_2	Dominant–nondominant forearm	11–87	83	−2.36	< 0.05
F	ϱ_2	Dominant–nondominant forearm	11–82	89	0.45	NS
M	ϱ_3	Dominant–nondominant forearm	11–87	83	0.15	NS
F	ϱ_3	Dominant–nondominant forearm	11–82	89	1.12	NS
M	λ_2/d	Dominant–nondominant forearm	11–87	83	1.26	NS
F	λ_2/d	Dominant–nondominant forearm	11–82	89	1.75	NS
M	λ_3/d	Dominant–nondominant forearm	11–87	83	0.30	NS
F	λ_3/d	Dominant–nondominant forearm	11–82	89	1.86	NS
	ϱ_1	Male–female forearm	11–81	68	4.08	< 0.001
	ϱ_2	Male–female forearm	11–81	68	−0.03	NS
	ϱ_3	Male–female forearm	11–81	68	1.66	NS

decreased in the following order: mineral linear density (g/cm)—mineral linear density/bone width—mineral density or mineral density index (g/cm^3). Statistically significant ($p < 0.05$) correlations were established for both mineral linear density and mineral linear density/bone width. They were not observed in mineral density and mineral density index.

Discussion

The test subjects were selected to ensure that they had no disease affecting bone metabolism and were not being treated with drugs that might influence the mineral balance in the bones. Patients with senile osteoporosis are included because the material represents a 'normal' series, but patients with a history of osteoporotic fractures were excluded as cases of osteoporosis.

Cancellous bone changes faster than compact bone (Johnston 1968). On the other hand, when bone mineral disappears, substances lighter than water (fat) fill the place of the mineral at least in part (Meunier et coll. 1970). The consequence is that the formulas for bone mineral content deduced for two intermediary substances were not valid when a distal region of an osteoporotic radius was measured. The error caused by this effect was corrected by means of a correction factor. The correction factor for

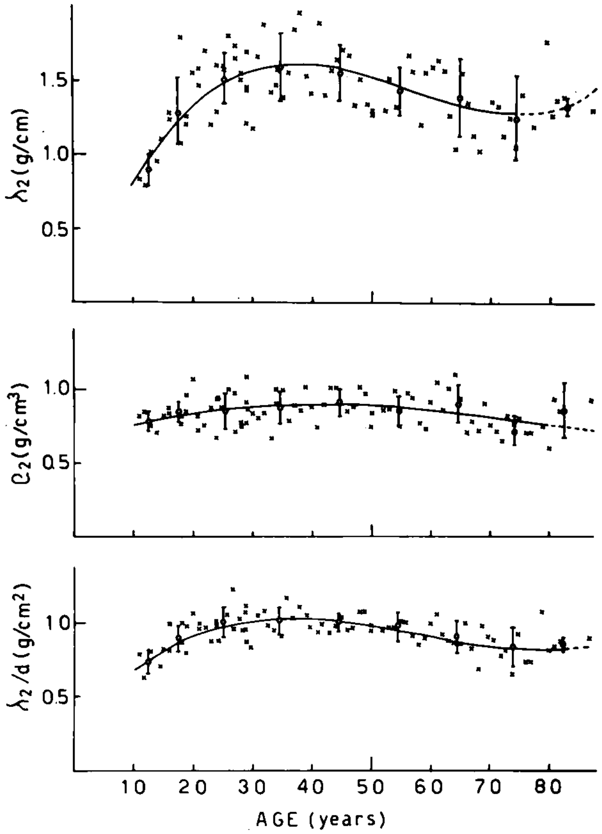

Fig. 2. The age distribution of bone mineral content measured at the dominant midshaft radius of males. In addition, the mean values at five- (between 10 and 19 years of age) and ten-year intervals (between 20 and 90 years), and the third degree regression curves measured from the mean values at five-year intervals are presented.

young persons is usually only a little over 1, for older subjects commonly 1.1 to 1.4, and for aged females and subjects with osteoporosis well over 2.

In the method used, extraosseous 'disturbance tissues' were corrected for by taking into consideration the effect of tissues lighter than water (subcutaneous fat) and tissues denser than water (membranes, tendons) (KARJALAINEN 1974). It follows from the presence of a disturbance of this kind that results obtained by different automatic or manual measuring methods are not necessarily comparable (LINDERGÅRD et coll. 1974). The results for in vivo measurements depend on whether the basic level is determined from water or from the soft tissues of the forearm. Hence, two normal series cannot be compared without comparing measuring apparatuses by means of measurements in vivo.

Several normal series in which the bone mineral content was measured by a method similar to the present one have been described in recent years (GOLDSMITH et coll., GOLDSMITH, MAZESS & CAMERON, BOYD et coll., MAZESS & MATHER 1974, VON ROTH et coll.). Differences in mineral content have been found between different nationalities and races. The results presented in Tables 2 and 3 are distinctly greater, especially for males, than those reported previously. This is probably not due, at least not entirely, to geographic or racial factors, but to differences in the measuring methods used in vivo. The coefficients of variation calculated from Tables 2 and 3, in contrast, were of the same magnitude as those reported by, for example, MAZESS & CAMERON. The mineral density of the distal radius in the present material was clearly less scattered than the mineral linear density or the mineral linear density/bone width at the corresponding measuring site.

The results of the mineral measurements showed that increasing and decreasing of bone mineral is an event of steadily changing magnitude but of slow progress. It was therefore decided to use third degree regression curves, rather than linear functions limited to certain age groups, to describe the changes in bone mineral content with age (Fig. 2).

The bone mineral content reaches its maximum value between the 3rd and 4th decades. However, it seems obvious that the mineral content of the distal radius and, in women also that of the radial diaphysis, achieves its maximum a little earlier. Since the mineral linear density continues to grow for almost ten years, it may be concluded that the surface area of the cross-section of the distal radius must increase at least up to about the age of forty. After it has reached the maximum the bone mineral content decreases; between the ages of 40 and 80, 4.4 per cent per decade for men and 5.4 per cent for women. The figures were determined from the third degree regression curves.

The mineral linear density (g/cm) is greater in the dominant than in the nondominant limb, although the difference is not significant at every measuring site. In contrast, if a difference in the mineral density exists, it is significantly greater in the nondominant limb (Table 4). These results are explained by the difference in bone width. The mineral linear density/bone width for the radial and ulnar diaphysis showed no statistically significant difference, although it was always greater in the dominant than in the nondominant limb. Comparison of the mineral content of the male and female forearm bones showed statistically significant differences for the radial metaphysis but no significant difference for the diaphysis of radius or ulna.

According to the present results, the conventional units of bone mineral content, mineral linear density (g/cm) and mineral linear density/bone width (g/cm^2) do correlate with the size of the subject measured, as in other reports (BOYD et coll.). This correlation was not established for bone mineral density, and the mineral density index (g/cm^3). For the mineral density index this was possibly due, at least in part, to the wide scatter of the measurement values.

The presented measurements of the mineral content in a healthy Finnish population seem to provide adequate normal data allowing evaluation of disturbances of bone mineral metabolism. The use of the mineral density (g/cm^3) of the distal radius seems to be preferred because changes in the bone mineral content are most easily detected in cancellous bone, and because this unit is least dependent on the size of the subject.

SUMMARY

The bone mineral content in the distal radius, in the midshaft radius and ulna was measured in 83 healthy males and 89 females from 11 to 87 years old using the ^{241}Am gamma ray attenuation method. The age distributions of different 'density' quantities characterizing bone mineral are presented and the usefulness of these quantities is discussed.

ZUSAMMENFASSUNG

Der Knochenmineralgehalt des distalen Radius, im mittleren Teil des Radius und der Ulna bei 83 gesunden männlichen und 89 weiblichen Personen in Alter von 11 bis 87 Jahren wurde unter Verwendung der ^{241}Am Gamma-Strahlen Abschwächungs-Methode untersucht. Die Altesverteilung der verschiedenen 'Dichte'-Mengen, die den Mineralgehalt des Knochens charakterisieren, werden gegeben und die Brauchbarkeit dieser Mengenverhältnisse diskutiert.

RÉSUMÉ

Le contenu minéral de l'os a été mesuré au niveau de la partie distale du radius et au milieu de la diaphyse du radius et du cubitus chez 83 hommes et 89 femmes en bonne santé, âgés de 11 à 87 ans au moyen de la méthode d'atténuation du rayonnement gamma de ^{241}Am. Les auteurs présentent les distributions en fonction de l'âge des différentes quantités de 'densité' qui caractérisent le contenu minéral de l'os et ils examinent l'utilité de ces mesures.

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