Total body and regional measurements of bone mineral content and bone mineral density in pigs by dual energy X-ray absorptiometry[1]

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ABSTRACT: Dual energy X-ray absorptiometry (DXA) was used to make total body and regional measurements of bone mineral content, bone mineral density, and bone area during the growth of pigs from 3 to 138 kg. In all, 1,053 total body scans were performed on 587 live pigs. Regional measurements consisted of the front legs, trunk, and back legs. In addition, bone mineral density readings were recorded for the head, pelvis, spine, and ribs. From about 5 to 75 kg, a greater percentage of the total body bone mineral content (BMC) was located in the trunk region. However, the percentage of BMC in the front and back legs continued to increase linearly whereas the percentage of BMC in the trunk region peaked at about 25 kg and then decreased logarithmically. Allometric analysis revealed that up to about 30 kg the BMC increased more rapidly in the trunk region compared to the front or back leg regions ($P > 0.05$), but after 30 kg the increase in BMC was more rapid in the leg regions ($P < 0.05$). Overall, the rate of increase in BMC in the back legs was slightly more than in the front legs ($P > 0.05$). Positive allometric growth of BMC was observed when compared with the increase in bone area for the same region. By far, the highest measured level of bone mineral density (BMD) was in the head region ($P < 0.05$), followed in order by the front legs, spine, back legs, pelvis, and ribs. Over the entire range of growth from 3 to 138 kg, the highest relative growth coefficient for the increase in BMD occurred in the pelvic and back leg regions and the lowest was in the ribs ($P < 0.05$). For pigs < 30 kg, the highest growth coefficient for BMD relative to BW was in the spine ($P > 0.05$). The growth coefficients for BMD in the back legs and total body increased in pigs ≥ 30 kg and those of the front legs and trunk regions decreased.

Key Words: Bone Density, Bone Mineralization, Pigs, X-Ray

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Introduction

Bone growth in pigs varies with age (Cuthbertson and Pomeroy, 1962; Liu et al., 1999), sex (Walstra, 1980; Knudson et al., 1985), breed (Davies, 1975), nutritional status (McMeekan, 1940a,b,c), and the individual bone or body region (Richmond and Berg, 1972). Traditional methods of assessing bone growth in pigs involve slaughter followed by dissection and measurements of length, circumference, volume, and ash or mineral content. Using these methods, studies have described the pattern of bone growth in pigs from birth to maturity (Doornenbal, 1975; Walstra, 1980; Davies, 1984). However, a major disadvantage to this approach is that it only permits measurement of the bone status in dead pigs. By the use of dual energy X-ray absorptiometry (**DXA**) it is now possible to evaluate bone growth in live pigs. It has been shown that DXA measurement of total body bone mineral content (**BMC**) is highly correlated with total body ash content of the pig (Mitchell et al., 1996). In addition to quantifying BMC, DXA also provides a measure of bone mineral density (**BMD**). Yang et al. (1998) used DXA to measure the BMC, BMD, and bone area of swine vertebra relative to the vertebral breaking strength.

The purpose of this study was to evaluate the use of DXA for measuring bone growth in pigs. Thus, DXA was used to quantify the changes in total body and regional BMC and BMD in pigs between 3 and 138 kg BW.

Materials and Methods

A total of 1,053 DXA scans were performed on anesthetized pigs, using a Lunar DPXL densitometer (GE Medical Systems, Waukesha, WI). The study involved

[1]Mention of a trade name does not constitute a guarantee or warranty by the USDA and does not imply its approval to the exclusion of other products that may be suitable.

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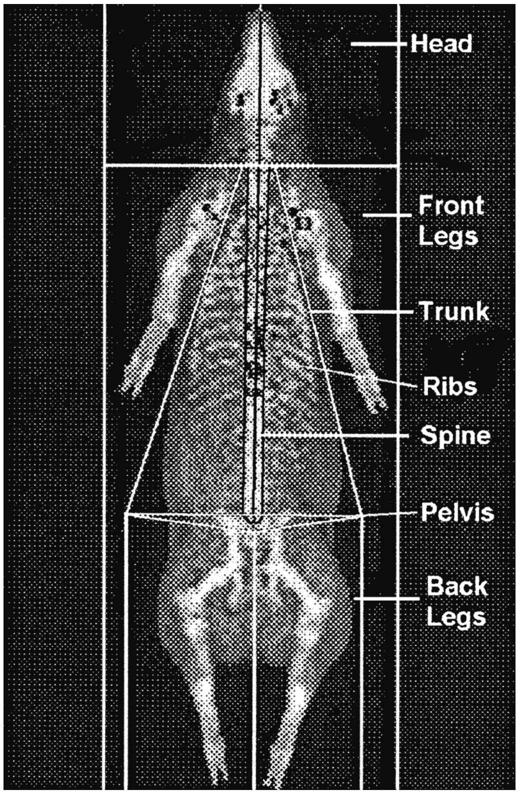

Figure 1. Total body dual energy X-ray absorptiometry scan of a 130-kg pig, showing the major (front legs, trunk, and back legs) and ancillary body regions (head, spine, ribs, and pelvis) that were analyzed in this study.

a total of 587 pigs: 263 pigs were scanned one time only, 216 were scanned twice, 98 were scanned three times, and 10 were scanned (at 2-wk intervals) five or more times. In general, multiple scans involved intervals of approximately 30 kg BW (i.e., 30, 60, 90, or 120 kg). The pigs consisted of a variety of breeds (including crossbreds), sex (males, females, and barrows), and weights (ranging from 3.7 to 137.7 kg). All pigs were fed a common diet that met or exceeded NRC (NRC, 1988) requirements. The pigs were unfed for 18 h then anesthetized (Mitchell et al., 1996) and placed prone on the scan table with their front and back legs extended caudally. The scanning mode varied according to body size: pediatric, 3 to 29 kg; adult (version 1.3z)-medium, 30 to 69 kg; adult-slow, 70 to 138 kg. Scans were analyzed for BMC (g) of the total body and three major body regions (front legs, back legs, and trunk) and for BMD (g/cm^2) of the total body and seven skeletal regions (head, front legs, back legs, trunk, ribs, pelvis, and spine) (Figure 1). By convention, the DXA algorithm divides the bone mineral content in grams by the projectional scan area of bone tissue (based on a threshold attenuation value) within the total body or region to calculate the reported bone mineral density in grams per projectional unit area (g/cm^2) (Antonacci et al., 1996). Experimental protocols used in this study were approved by the Beltsville Area Institutional Animal Care and Use Committee.

The mean values for BMC and BMD for various body regions within BW groups (Table 1) were compared using analysis of variance followed by a multiple range test using Statgraphics Plus 2.0 (Manguistics, Rockville, MD). The increase in BMC and BMD were evaluated using the allometric growth equation $Y = aX^b$ (Huxley, 1932). This equation was fitted by using a nonlinear method. For the allometric equation, a represents the initial growth coefficient or the proportionality between Y and X, and b is the relative growth coefficient that describes the ratio of the relative growth of Y to the relative growth rate of X. The initial growth coefficient was calculated as log·A based on the log (base 10) transformation, where $\log{\cdot}Y = (\log{\cdot}a) + (b{\cdot}\log{\cdot}X)$. Nonlinear regression analysis and graphical presentation were performed using Sigma Plot 6.0 (SPSS, Chicago, IL) procedures. Statistical analysis included the calculations of SE, standard error or estimates of the uncertainties in the estimates of the regression coefficients; R^2, the coefficient of determination or how well the regression model describes the data; SEE, standard error of the estimate as a measure of the actual variability about the regression plane; and DW, the Durbin-Watson statistic as a measure of the correlation between the residuals (the more this value differs from 2, the greater the likelihood that the residuals are correlated). In order to compare the differences among the relative growth coefficients shown in Tables 2 through 5, a t-test for the comparison of regression coefficients described by Weber (1980) following the Bonferoni-Holm test procedure for a multiple a level (with a = 0.05) described by Eßl (1987) was performed. For Tables 6 and 7, a pair-wise t-test for the comparison of the relative growth coefficients of the < 30-kg and ≥ 30-kg body weight groups was used (Weber, 1980). The increase in BMC was evaluated relative to the increase in body weight, BMC, and bone area (**BA**) within the regions, and regional BMC was evaluated relative to the increase in total body BMC. The increase in BMD was evaluated relative to the increase in body weight, BMC, and BA within the regions, and regional BMD was also evaluated relative to the increase in total body BMD. The increase in BA was evaluated relative to the increase in body weight.

Results

A typical DXA total body scan of a 130-kg pig is shown in Figure 1. This figure illustrates the various regions analyzed in this study. Some of the regions were defined primarily for soft tissue analysis and did not correspond specifically to a group of bones. For example, most of the pelvic bones are included with the back legs, whereas only a portion of the pelvic region is included in the area defined as "pelvis." Also,

Table 1. Mean values for total body and regional measurements of bone mineral content (BMC) and bone mineral density (BMD) of pigs grouped according to body weight

Measurement or body region	Weight group[a]				
	12 kg[b]	33 kg[b]	62 kg[b]	92 kg[b]	120 kg[b]
Weight range, kg	3.7–24.8	25.8–44.5	45.0–79.6	80.0–104.3	105.0–137.7
Number of observations	180	127	324	239	183
BMC, g					
Total body	295	807	1,555	2,015	2,392
Front legs	57^{y}	173^{y}	364^{x}	520^{y}	629^{y}
Back legs	65^{y}	185^{y}	395^{y}	563^{z}	702^{z}
Trunk	90^{z}	256^{z}	456^{z}	477^{x}	529^{x}
SEM	3.1	3.4	3.5	4.6	6.5
BMD, g/cm^2					
Total body	0.639	0.850	1.010	1.153	1.232
Head	1.003^{z}	1.416^{z}	1.740^{z}	1.943^{z}	2.012^{z}
Front legs	0.604^{y}	0.858^{y}	0.999^{x}	1.136^{y}	1.214^{y}
Back legs	0.552^{x}	0.775^{x}	0.930^{w}	1.053^{w}	1.163^{x}
Trunk	0.524^{w}	0.685^{w}	0.822^{u}	0.915^{v}	0.955^{w}
Ribs	0.458^{v}	0.557^{v}	0.627^{t}	0.647^{u}	0.669^{v}
Pelvis	0.477^{v}	0.672^{w}	0.847^{v}	0.923^{v}	1.062^{w}
Spine	0.595^{y}	0.840^{y}	1.057^{y}	1.107^{x}	1.165^{x}
SEM	0.0076	0.0063	0.0048	0.0051	0.0066

[a]Mean weights for groups.
[b]Means for BMC or BMD within each weight group followed by a common superscript are not different ($P > 0.05$) based on analysis of variance and multiple range test.

Table 2. Growth coefficients for bone mineral content (BMC), projectional bone area (BA), and bone mineral density (BMD) of pigs as a function of kilograms body weight (BW), based on the allometric equation $Y = aX^b$, where Y is BMC or BMD and X is BW

Measurement and Region	Relative growth coefficient (b)[a]	SE(b)	Intercept (a)	SE(a)	Initial growth coefficient (log·a)	R^2	SEE[b]	DW[c]
BMC, g								
Total	0.786^{y}	0.008	57.249	1.978	1.758	0.954	156	1.174
Front legs	0.925^{z}	0.012	7.739	0.423	0.889	0.925	56	1.534
Back legs	0.947^{z}	0.010	7.660	0.351	0.884	0.948	51	1.106
Trunk	0.556^{x}	0.014	39.549	2.432	1.597	0.753	85	0.992
BA, cm^2								
Total	0.550^{y}	0.006	146.083	4.146	2.164	0.928	142	0.871
Front legs	0.684^{z}	0.009	20.429	0.859	1.310	0.909	46	1.376
Back legs	0.668^{z}	0.008	25.531	0.876	1.407	0.933	45	0.814
Trunk	0.398^{x}	0.012	91.106	4.619	1.960	0.662	97	0.866
BMD, g/cm^2								
Total	0.284^{x}	0.003	0.316	0.003	–0.500	0.943	0.050	1.189
Head	0.295^{xy}	0.004	0.505	0.008	–0.296	0.902	0.117	1.054
Front legs	0.292^{x}	0.003	0.302	0.004	–0.521	0.913	0.064	1.209
Back legs	0.315^{yz}	0.003	0.256	0.003	–0.592	0.934	0.054	1.271
Trunk	0.259^{w}	0.003	0.282	0.004	–0.550	0.889	0.053	1.292
Ribs	0.159^{v}	0.003	0.317	0.005	–0.499	0.715	0.046	1.329
Pelvis	0.333^{z}	0.006	0.211	0.006	–0.675	0.786	0.099	1.559
Spine	0.275^{x}	0.005	0.323	0.007	–0.491	0.808	0.097	1.134

[a]Relative growth coefficients for BMC, BA, or BMD followed by different superscripts are different ($P < 0.05$).
[b]Standard error of the estimate.
[c]Durbin-Watson statistic.

Table 3. Growth coefficients for regional bone mineral content (BMC) of pigs as a function of total body BMC and regional bone mineral density (BMD) as a function of total body BMD based on the allometric equation Y = aX^b, where Y is regional BMC or BMD and X is total body BMC or BMD

Measurement and region	Relative growth coefficient (b)[a]	SE(b)	Intercept (a)	SE(a)	Initial growth coefficient (log·a)	R^2	SEE[b]	DW[c]
BMC, g								
Front legs	1.202[z]	0.013	0.054	0.005	−1.264	0.954	44	1.612
Back legs	1.216[z]	0.011	0.053	0.005	−1.272	0.965	42	1.043
Trunk	0.709[y]	0.014	2.256	0.235	0.353	0.856	65	1.013
BMD, g/cm²								
Head	1.033[x]	0.009	1.671	0.003	0.223	0.947	0.086	1.100
Front legs	1.023[wx]	0.008	0.986	0.001	−0.006	0.958	0.044	1.471
Back legs	1.093[y]	0.006	0.915	0.001	−0.039	0.974	0.034	1.226
Trunk	0.922[v]	0.008	0.801	0.001	−0.096	0.943	0.038	1.216
Ribs	0.572[u]	0.012	0.606	0.001	−0.217	0.731	0.046	1.384
Pelvis	1.164[z]	0.020	0.816	0.003	−0.089	0.817	0.092	1.571
Spine	0.968[vw]	0.015	0.985	0.003	−0.007	0.849	0.086	0.989

[a]Relative growth coefficients for BMC or BMD followed by different superscripts are different ($P < 0.05$).
[b]Standard error of the estimate.
[c]Durbin-Watson statistic.

most of the cervical vertebrae are included in the head region.

Bone Mineral Content. A breakdown of the results of the BMC and BMD measurements into body weight groups at various intervals is shown in Table 1. These groupings at 12, 33, 62, 92, and 120 kg represent the mean BW of pigs from generalized groupings for DXA scanning (i.e., most pigs were scanned at approximately 15, 30, 60, 90, or 120 kg BW). The standard errors of estimation (SEM) associated with the mean values in this table are the result of both the range of body weights within each group and the variation of BMC and BMD and number of observations within each group. Figure 2 shows the distribution of BMC within the major body regions: front legs, back legs, and trunk (ribs and spine). In the smaller pigs a greater percentage of the total body BMC was located in the trunk region; however, the percentage of BMC in the front and back legs continued to increase (linear), whereas the percentage of BMC in the trunk region peaked at about 30 kg and then decreased following a logarithmic pattern (see top inset to Figure 2).

The pattern of increase in total body BMC of pigs over the BW range of 3.7 to 137.7 kg is shown in Figure 3. Also shown in Figure 3 is a comparison of the increase in BMC within the major body regions. The relationship between BMC and BW within this range was described using the allometric equation Y = aX^b shown in Table 2. Up to about 30 kg, the BMC increased more rapidly in the trunk region than in the

Table 4. Growth coefficients for bone mineral density (BMD) of pigs as a function of bone mineral content (BMC) based on the allometric equation Y = aX^b, where Y is BMD and X is BMC

BMC region	BMD region	Relative growth coefficient (b)[a]	SE(b)	Intercept (a)	SE(a)	Initial growth coefficient (log·a)	R^2	SEE[b]	DW[c]
Front legs	Front legs	0.275[v]	0.003	0.203	0.003	−0.691	0.928	0.058	1.091
Back legs	Back legs	0.297[w]	0.003	0.162	0.003	−0.792	0.947	0.048	0.941
Trunk	Trunk	0.297[vw]	0.005	0.141	0.004	−0.851	0.854	0.061	0.885
Total	Total	0.306[w]	0.003	0.111	0.002	−0.956	0.944	0.049	0.812
Total	Head	0.326[xy]	0.003	0.160	0.004	−0.795	0.931	0.098	1.163
Total	Front legs	0.317[wx]	0.004	0.101	0.003	−0.996	0.917	0.062	1.003
Total	Back legs	0.341[y]	0.003	0.079	0.002	−1.102	0.934	0.054	0.910
Total	Trunk	0.284[vw]	0.003	0.104	0.002	−0.983	0.915	0.047	1.288
Total	Ribs	0.175[u]	0.003	0.172	0.004	−0.764	0.769	0.042	1.445
Total	Pelvis	0.373[z]	0.007	0.056	0.003	−1.253	0.809	0.094	1.570
Total	Spine	0.314[wx]	0.004	0.103	0.003	−0.986	0.882	0.076	1.232

[a]Relative growth coefficients followed by different superscripts are significantly different ($P < 0.05$).
[b]Standard error of the estimate.
[c]Durbin-Watson statistic.

Table 5. Growth coefficients for bone mineral content (BMC) and bone mineral density (BMD) of pigs as a function of the projectional bone area (BA) for the same region, based on the allometric equation $Y = aX^b$, where Y is regional BMC or BMD and X is BA

Measurement and region	Relative growth coefficient (b)[a]	SE(b)	Intercept (a)	SE(a)	Initial growth coefficient (log·a)	R^2	SEE[b]	DW[c]
BMC, g								
Total body	1.480[z]	0.012	0.031	0.003	−1.504	0.976	113	1.018
Front legs	1.314[x]	0.009	0.164	0.009	−0.786	0.976	32	1.078
Back legs	1.424[y]	0.010	0.074	0.005	−1.133	0.979	33	1.045
Trunk	1.232[w]	0.015	0.201	0.019	−0.697	0.934	44	0.827
BMD (g/cm^2)								
Total body	0.418[z]	0.006	0.050	0.002	−1.304	0.881	0.072	0.823
Front legs	0.356[y]	0.005	0.127	0.004	−0.898	0.862	0.080	1.067
Back legs	0.404[z]	0.005	0.084	0.003	−1.077	0.891	0.069	0.958
Trunk	0.359[y]	0.009	0.090	0.005	−1.044	0.716	0.085	0.854

[a]Relative growth coefficients for BMC or BMD followed by different superscripts are different ($P < 0.05$).
[b]Standard error of the estimate.
[c]Durbin-Watson statistic.

front or back leg regions, but after 30 kg the increase in BMC was more rapid in the leg regions. Overall, the rate of increase in BMC in the back legs was only slightly higher than in the front legs (larger relative growth coefficient, b) and the increase in both was greater ($P < 0.05$) than in the trunk region. A similar relationship among growth coefficients was observed when the increase in regional BMC was analyzed relative to total body BMC (Table 3). Positive allometric growth (relative growth coefficients > 1.0) of BMC was observed when compared with the increase in BA for the same region (Tables 5 and 7). The changing pattern in the relative growth in BMC as a function of increasing BW was confirmed by splitting the data at 30 kg

Table 6. Comparison by weight group of the relative growth coefficients for bone mineral content (BMC), projectional bone area (BA), and bone mineral density (BMD) of pigs, based on the allometric equation $Y = aX^b$, where Y is BMC, BA, or BMD and X is BW

	< 30 kg BW[a]			≥ 30 kg BW[b]		
Measurement and region	Relative growth coefficient (b)	SE(b)	R^2	Relative growth coefficient (b)	SE(b)	R^2
BMC, g						
Total body	1.103	0.0252	0.924	0.725	0.0095	0.897
Front legs	1.141	0.0228	0.941	0.877	0.0151	0.841
Back legs	1.107	0.0271	0.914	0.915	0.0127	0.891
Trunk	1.238	0.0426	0.856	0.381	0.0181	0.385
BA, cm^2						
Total body	0.839	0.0177	0.928	0.453	0.0082	0.809
Front legs	0.809	0.0157	0.937	0.618	0.0128	0.774
Back legs	0.803	0.0188	0.912	0.615	0.0106	0.832
Trunk	0.988	0.0266	0.897	0.171	0.0157	0.138
BMD, g/cm^2						
Total body	0.255	0.0102	0.747	0.296	0.0043	0.856
Head	0.309	0.0143	0.692	0.258	0.0060	0.706
Front legs	0.312	0.0121	0.761	0.275	0.0058	0.744
Back legs	0.300*	0.0141	0.684	0.317*	0.0050	0.837
Trunk	0.292	0.0112	0.767	0.252	0.0063	0.677
Ribs	0.222	0.0126	0.597	0.131	0.0073	0.285
Pelvis	0.357*	0.0152	0.727	0.339*	0.0118	0.517
Spine	0.383	0.0152	0.759	0.209	0.0085	0.438

[a]Mean body weight (± SD) = 14.8 ± 7.4 (n = 214).
[b]Mean body weight (± SD) = 80.3 ± 27.9 (n = 839).
*Relative growth coefficients followed by an asterisk are not significantly different for the pairwise comparison of < 30 kg and ≥ 30 kg; all others are significant at $P < 0.05$.

BW. Table 6 shows the decrease in the relative growth coefficients of BMC for pigs ≥ 30 kg; the most dramatic decrease (over threefold) occurred in the trunk region.

Bone Mineral Density. By far, the highest measured level of bone mineral density was in the head region, ranging from 1.003 g/cm^2 at 12 kg BW to 2.012 g/cm^2 at 120 kg (Table 1). This was followed, in order, by the front legs, spine, back legs, pelvis, and ribs. The only exception to this order was for the 62-kg group, in which BMD in the spine was slightly higher than in the front legs. The patterns for the increase in BMD in the total body and seven separate regions relative to body weight are shown in Figure 4. The allometric growth coefficients are presented in Table 2. Over the entire range of growth from 3.7 to 137.7 kg, the highest ($P < 0.05$) relative growth coefficient for the increase in BMD occurred in the pelvic region, followed by the back leg region, and the lowest ($P < 0.05$) appeared in the ribs. When the increase in regional BMD was analyzed relative to total body BMD (average BMD for the whole body) the ranking of relative growth coefficients among regions (Table 3) was the same as when it was analyzed relative to body weight.

The patterns for the increase in BMD as a function of the increase in BMC (total body and within region) are shown in Figure 5 and the allometric growth coefficients are presented in Table 4. The ranking of the relative growth coefficients as a function of total body BMC was the same as noted in Tables 2 and 3 when analyzed as a function of body weight or total body BMD. However, when based on the BMC within the same region, the pattern for the relative growth coefficients for the major body regions changed, and the coefficient for the trunk region equaled that of the back legs. Relative to BA, the total body measurement had the highest growth coefficient for BMD, followed by back legs and similar values for the trunk and front leg regions (Table 5).

For pigs < 30 kg, the highest growth coefficient for BMD relative to BW was in the spine region, followed by the pelvis region (Table 6). The growth coefficients for BMD in the total body increased ($P < 0.05$) in pigs ≥ 30 kg whereas those of the front legs and trunk regions significantly decreased, with no significant change in the back legs or the pelvis. Consequently, the highest growth coefficient for BMD in pigs ≥ 30 kg was in the pelvis region followed by the back leg region. A comparison of the growth coefficients of BMD relative to BMC and BA for pigs < 30 kg and ≥ 30 kg is shown in shown in Table 7. In the larger pigs, the growth coefficient for BMD relative to BMC increased ($P < 0.05$) in all but the front leg region. However, the growth coefficient for BMD relative to BA increased ($P < 0.05$) in the back legs and total body, but not in the front legs and trunk regions.

Bone Area. Measurements of the projectional bone area were recorded for the total body and three major regions. The relative growth coefficients for BA as a function of BW were intermediate with respect to BMC and BMD (Table 2). Therefore, when the growth of

Table 7. Comparison by weight group of the relative growth coefficients for bone mineral content (BMC) and bone mineral density (BMD) of pigs, based on the allometric equation $Y = aX^b$, where Y is BMC or BMD and X is BMC or BA (projectional bone area) for the same region

Measurement and region	< 30 kg BW[a]			≥ 30 kg BW[b]		
	Relative growth coefficient (b)	SE(b)	R^2	Relative growth coefficient (b)	SE(b)	R^2
X = BMC						
Y = BMD, g/cm^2						
Total body	0.238	0.0065	0.865	0.367	0.0052	0.866
Front legs	0.285*	0.0081	0.857	0.280*	0.0056	0.767
Back legs	0.280	0.0091	0.822	0.314	0.0047	0.853
Trunk	0.222	0.0045	0.924	0.344	0.0109	0.567
X = BA						
Y = BMC, g						
Total body	1.329	0.0144	0.983	1.499	0.0156	0.937
Front legs	1.371*	0.0191	0.970	1.301*	1.0115	0.947
Back legs	1.314	0.0233	0.952	1.425	0.0128	0.954
Trunk	1.320	0.0131	0.987	1.138	0.0196	0.809
Y = BMD, g/cm^2						
Total body	0.298	0.0110	0.782	0.493	0.0123	0.682
Front legs	0.363*	0.0153	0.732	0.324*	0.0102	0.569
Back legs	0.343	0.0170	0.665	0.402	0.0096	0.698
Trunk	0.276*	0.0073	0.877	0.257*	0.0201	0.175

[a]Mean body weight (± SD) = 14.8 ± 7.4 (n = 214).
[b]Mean body weight (± SD) = 80.3 ± 27.9 (n = 839).
*Relative growth coefficients followed by an asterisk are not significantly different for the pairwise comparison of < 30 kg and ≥ 30 kg; all others are significant at $P < 0.05$.

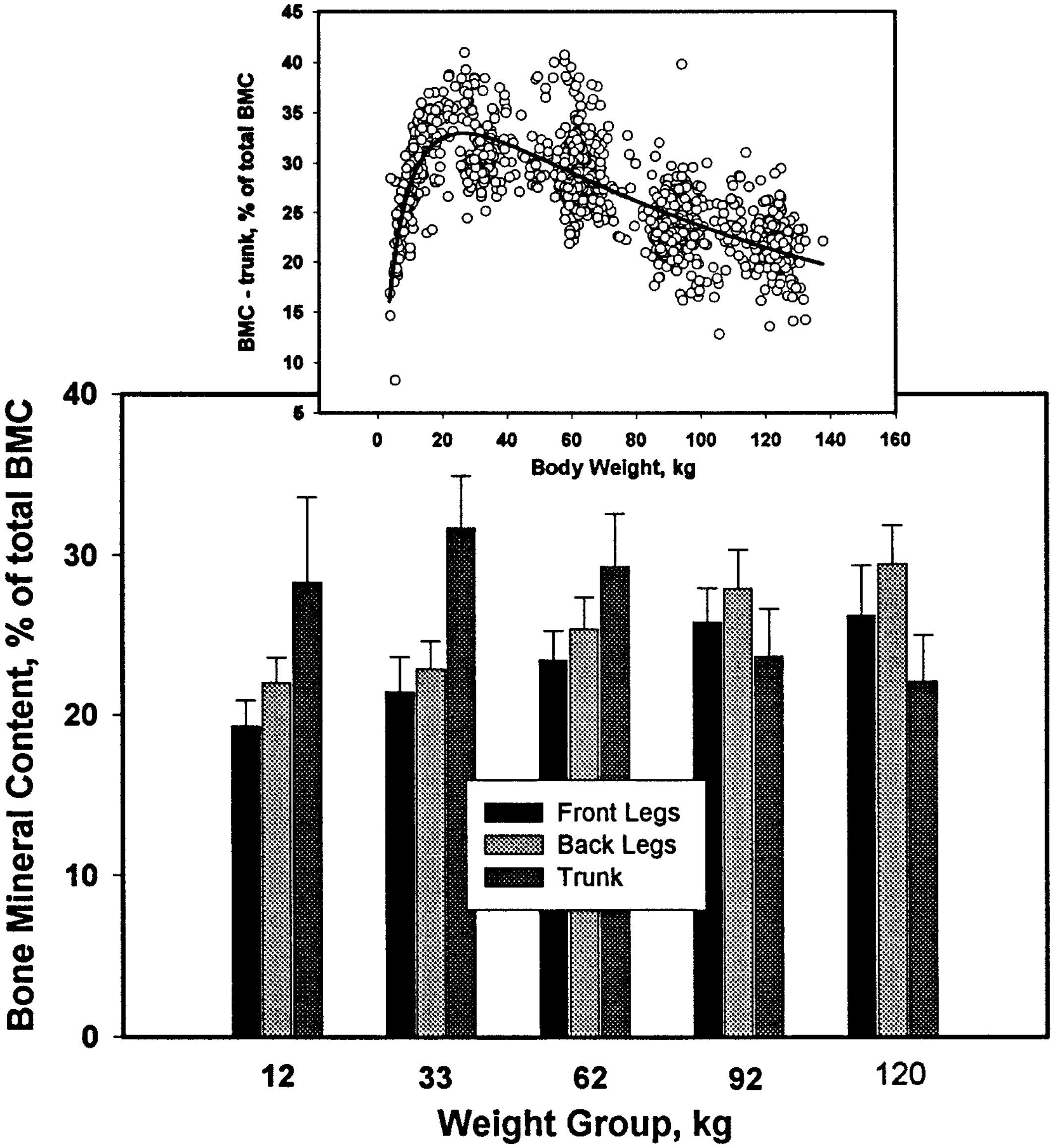

Figure 2. Changes in regional bone mineral content (BMC) in pigs as a percentage of total body BMC at selected weight groupings (bottom panel) and data points and peak plot of the relationship between percentage of BMC in the trunk region and body weight (top panel) using the logarithmic peak equation:

$$Y = ae\left[-0.5\left[\frac{\ln(X/X_o)}{b}\right]^2\right].$$

BMC and BMD were measured as a function of BA there was positive allometric growth for BMC and negative allometric growth for BMD (Table 5). All relative growth coefficients for BA as a function of BW were significantly lower for pigs ≥ 30 kg compared with those < 30 kg (Table 6). In the trunk region, this amounted to a nearly sixfold difference.

Discussion

Numerous studies have described bone growth in pigs. All previous studies, however, have been based on measurements of bones dissected from the carcasses of dead pigs. The measurements of these previous studies involved primarily either bone weight or length, in some cases bone circumference, and in a few, the density of selected bones. Only a few of these studies involved total dissection (McMeekan, 1940a; Cuthbertson and Pomeroy, 1962; Walstra, 1980), and most other studies relied on measurements of the limb bones. The present study reports the in vivo measurement of bone growth using the DXA values of BMC, BMD, and BA. The pattern for the increase in total body BMC as a function of increasing body weight (Figure 2) is similar to that of total body bone growth described by McMeekan (1940a) and total carcass ash (Doornenbal, 1975).

The growth coefficient for total body BMC relative to body weight was 0.786 (Table 2) as compared 0.692 for total body skeletal weight relative to empty live weight (calculated from McMeekan, 1940a), 0.858 (average for German Landrace and Göttingen Miniature Pig) for total side bone weight relative to fat-free (muscle + bone) half-carcass weight (Davies, 1984), 0.894 for total body ash relative to live weight (calculated from Doornenbal, 1975), or 0.842 (Pietrain) and 0.924 (Large White) for total side bone relative to half-carcass weight (Davies, 1974a).

Based on the partitioning of BMC into three major body regions, excluding the head (as shown in Figure 1), the growth of BMC was slightly faster in the back legs than in the front legs (Tables 1 and 2). When the data were analyzed separately for pigs < 30 kg and pigs ≥ 30 kg (Table 6), the growth coefficient for BMC in the front legs was slightly greater ($P > 0.05$) than that of the back legs for pigs < 30 kg; however, the opposite was true for pigs ≥ 30 kg. This pattern is consistent with other studies that have suggested an anterior-posterior gradient for bone growth in the pig (McMeekan 1940a; Richmond and Berg, 1972; Liu et al., 1999). Liu et al. (1999) suggested that greater relative growth rates for hindlimb bones might be related to a functional requirement for the hindlimb to carry more BW than the forelimbs. Actually, based on a random sampling of 50-kg pigs (n = 4), the distribution of weight is approximately 57% front to 43% back (our unpublished observations). Morphometric changes that occur between birth and maturity result in a redistribution in body proportions. Results by McMeekan (1940a) showed that between birth and 100 kg, head weight as a percentage of total BW decreased from 16.8 to 6.4% and shoulder weight decreased from 16.9 to 13.2%. Although there is a shift in the percentage distribution of weight carried by the front and back legs, even at 100 kg more weight is borne by the front legs than by the back legs.

The results of the present study also indicate that the growth of BMC in the trunk region (composed primarily of the ribs and spinal column) was considerably slower than that in either the front or back leg regions. However, the pattern of regional BMC growth shown in Figure 3 suggests that more rapid growth of BMC in the trunk region may have occurred earlier in development (i.e., pigs weighing less than 30 kg), but that the growth of BMC in the trunk region diminished rapidly in heavier pigs. The relationship between BMC in the trunk region and total body BMC is illustrated

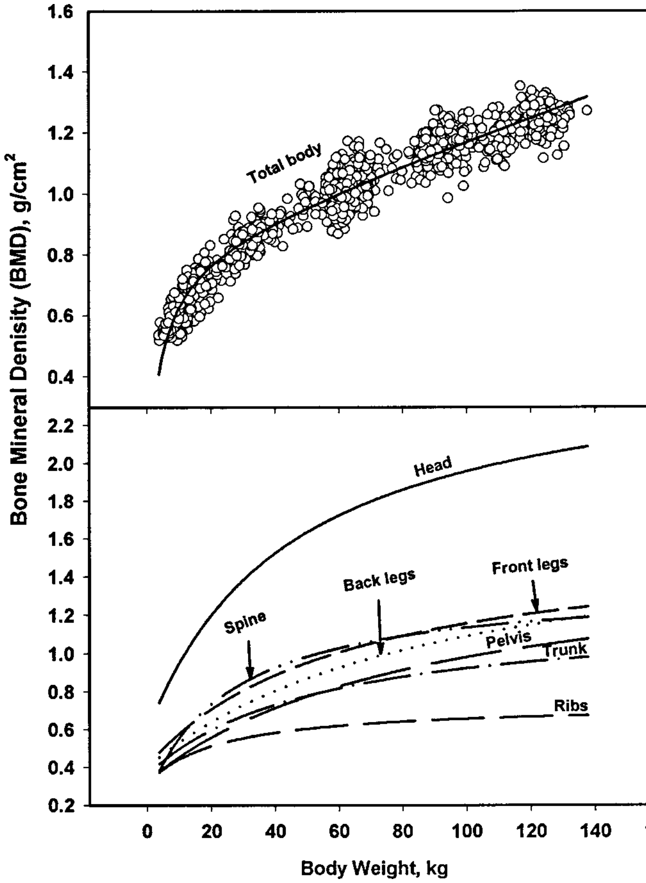

Figure 4. Changes in total body (top panel) and regional (bottom panel) bone mineral density of pigs relative to body weight.

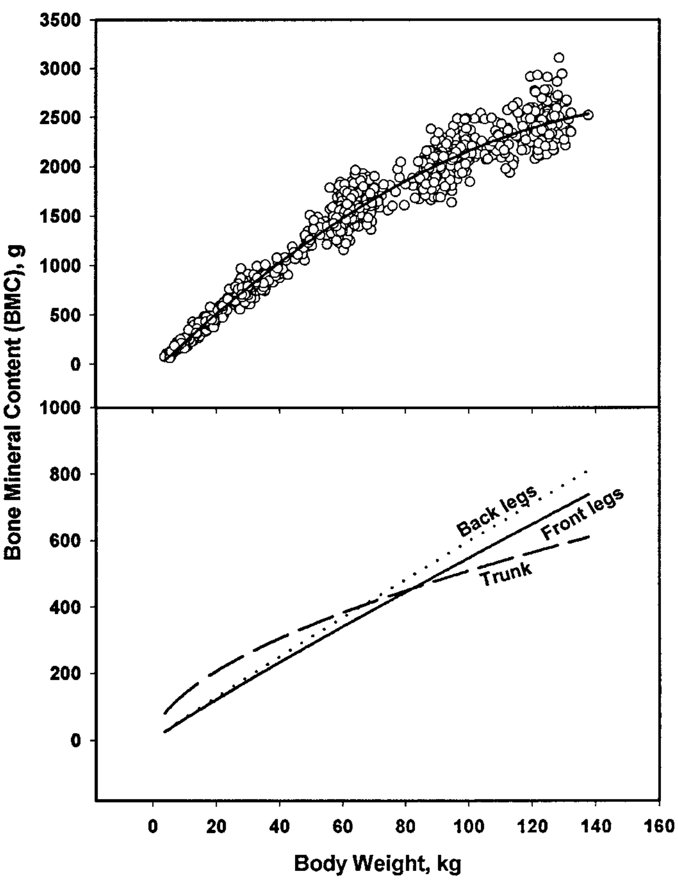

Figure 3. Changes in total body (top panel) and regional (bottom panel) bone mineral content of pigs relative to body weight.

in Figure 2, which shows that trunk BMC expressed as a percentage of total body BMC declines dramatically during growth from about 30 kg to 137 kg. Furthermore, the growth coefficient for BMC in the trunk region of pigs < 30 kg BW was over three times greater than that for pigs ≥ 30 kg (Table 6). For pigs < 30 kg, the highest growth coefficients relative to BW for both BMC and BA were in the trunk region, whereas in pigs ≥ 30 kg they were the lowest.

Growth and maturation of bone is normally accompanied by an increase in bone density (Field et al., 1974). A comparison of weight-to-length ratios has suggested an early growth in bone length followed by a later growth in circumference (McMeekan, 1940a). The study by Cuthbertson and Pomeroy (1962) reported that in the limb bones of pigs with carcasses weighing between 50 and 68 kg, growth in length predominates over growth in thickness and density, whereas during the period between 68 and 92 kg bone growth is characterized by thickening and ossification. Likewise, Knudson et al. (1985) observed that as pigs grew from 105 to 145 kg (live weight), the ratio of weight to length in the tibia and radius increased. Richmond and Berg (1972) observed that for pigs between 23 and 68 kg live weight there was a slightly greater growth rate for bone circumference than for length; between 68 and 114 kg growth rates for length and circumference were similar and bone weight increased at a greater rate than either length or circumference.

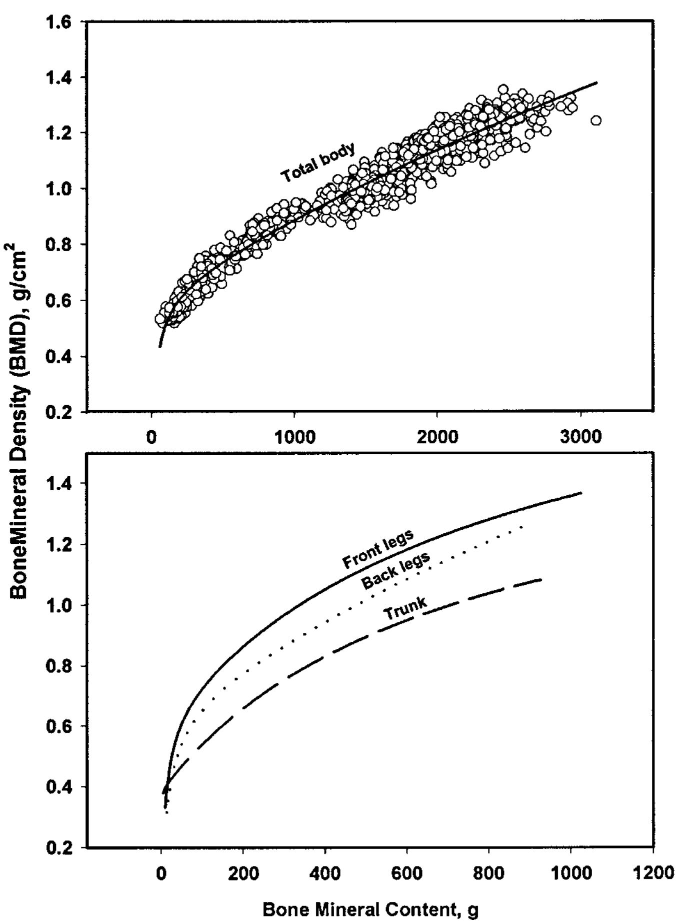

Figure 5. Changes in total body (top panel) and regional (bottom panel) bone mineral density of pigs relative to the bone mineral content of the same area.

In the present study, based on DXA measurement of total body bone mineral density, the pattern (Figure 4) of increase in BMD relative to body weight suggests that bone density might increase more rapidly in younger (i.e., smaller) pigs, but the growth coefficient for total body BMD relative to BW was significantly higher in pigs weighing ≥ 30 kg than in those < 30 kg (Table 6). However, there were significantly higher growth coefficients for BMD in all regions except the back legs and pelvis for pigs weighing < 30 kg. A similar pattern appears when the increase in BMD is relative to the increase in BMC (Figure 5). The growth coefficient for total body BMD relative to BMC was significantly higher in pigs weighing ≥ 30 kg than in those weighing < 30 kg (Table 7). Also, the growth coefficients for both total body BMD and BMC relative to BA were higher ($P < 0.05$) for pigs weighing ≥ 30 kg than for those weighing < 30 kg (Table 7).

When the increase in BMD was compared with that of either BW or BMC, the relative growth coefficients for BMD were considerably less than 1 (ranging from 0.159 for ribs in Table 2 to 0.373 for pelvis in Table 4), indicating that the rate of increase in BMD was less than the rate of increase in either BW or BMC. For BMD to be increasing it is implicit that bone mineral deposition is occurring at a rate faster than a dimensional increase in the bone. Because the DXA measurement of BMD is based on the amount of bone mineral within the projectional scan area of bone (g/cm2), it can only be assumed that the area is proportional to a unit of volume. Liu et al. (1999) noted that the growth coefficients of volumes of limb bones were in general greater than those for bone weights (in pigs between 1.4 and 31.4 kg) and suggested that the difference was due to the late development in bone density. In this study, which covered the growth of pigs from 3 to 138 kg, a comparison of BMC relative to the DXA projectional bone area in the total body and all three major regions indicated positive allometric growth (growth coefficients > 1), meaning that bone mineral was being deposited faster than the bone area was increasing. This was true for growth from both 3 to 30 kg and 30 to 138 kg. During the later stages of growth (> 30 kg) the growth coefficients for BMC relative to BA increased in the total body and back legs but decreased slightly in the front legs and trunk regions. The growth coefficient for total body BMC relative to BA during growth from 30 to 138 kg was 1.499 (Table 7), which is nearly identical to the theoretical growth coefficient (1.5) for the growth of volume relative to area for a spherical object. Relative to BW, the growth coefficients for both BMC and BA in all regions decreased in pigs ≥ 30 kg compared with pigs < 30 kg. This was most dramatic in the trunk region, where the growth coefficients for BMC and BA in ≥ 30-kg pigs decreased to 30 and 17%, respectively, of those for < 30-kg pigs.

The increase in bone density with age is the result of a gradual dehydration and an increase in fat and mineral content (Field et al., 1974). It is important to distinguish between "bone mineral" density as measured by DXA and gravimetric density. The increase in BMD as determined by DXA is only a measure of the increase in BMC per unit of BA and does not necessarily reflect other chemical changes that may occur in the bone. As would be expected (because BMD is calculated as BMC/BA) relative to BA, the growth coefficients for BMC and BMD followed similar patterns for both the total growth (3 to 138 kg) and for < 30 kg and ≥ 30 kg.

Whether compared to BW (Table 2), total body BMD (Table 3), or total body BMC (Table 4), the order for the relative growth coefficient for BMD in the various body regions was the same: pelvis > back legs > head > front legs > spine > trunk > ribs. When the BMD for the major regions (front legs, back legs, and trunk) were compared to the BMC within the same region, the relative growth coefficients for all three regions were similar, and the coefficient for the trunk equaled that for the back legs. Thus, within these regions, the increase in BMD seems to be proportional to the BMC. However, comparing ≥ 30-kg pigs to < 30-kg pigs, there was an increase in the growth coefficient of BMD relative to BMC in all but the front legs (Table 7). When the BMD of the various regions were compared to total body BMD, the growth coefficients for all regions except the spine and ribs (and consequently the trunk) were greater than 1.0 (Table 3). The lower growth coefficient for BMD in the trunk region compared to the front and back leg regions may be due to the fact that the trunk is essentially non-load-bearing. The low growth coefficient for rib BMD (0.572) relative to total body BMD seems to be contrary to the reported (Walstra, 1980) growth coefficient of rib weight (1.05) relative to total carcass side bone weight. The implication is that the BMD maturation of the ribs occurs much sooner than that of the other bones. Although this is possible, it warrants further investigation.

Despite the higher growth coefficient for BMD in the back legs compared to the front legs, the actual measurement of BMD in the front legs remained higher than in the back legs throughout growth from 3 kg to 138 kg BW. In contrast, humans, which rely entirely on bipedal locomotion, have higher bone density in the legs than in the arms but respond to upper body exercise (kayaking) by increasing BMD in the arms, ribs, and spine (Flodgren et al., 1999). The higher growth coefficients for both BMC and BMD in the back legs during the later stages of growth of pigs may reflect the functional need to accommodate greater muscle development in this region (higher growth coefficients for ham muscles than for shoulder muscles; Davies, 1974b), perhaps as a result of selection for larger hams but also due to the greater requirement of the back legs for locomotion.

Implications

Dual energy X-ray absorptiometry provides a method for assessing bone mineral deposition and bone mineral status of the live pig. One thousand fifty-three total body scans from pigs weighing between 3 and 138 kg revealed that during growth from 3 to 30 kg there is a more rapid deposition of bone mineral in the trunk region of the body. However, during growth from 30 to 138 kg, bone mineral was deposited more rapidly in the leg regions. During the latter period, the rate of bone mineral deposition in the back legs predominated over deposition in the front legs, consistent with an anterior-posterior growth gradient of limb bones. These procedures could be quite useful for the development of optimal nutritional and genetic strategies to ensure adequate bone growth in pigs, using standards based on dual X-ray absorptiometry for normal bone mineral content and density within age, weight, sex, and breed classifications.

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