CRITERIA TO EVALUATE BONE MINERALIZATION IN CATTLE:
I. EFFECT OF DIETARY PHOSPHORUS ON CHEMICAL,
PHYSICAL, AND MECHANICAL PROPERTIES1,2

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ABSTRACT

Fourteen Angus heifers (210 ± 6 kg initial BW) were allotted randomly to either a low P
(LP: .12% P, DM basis) or an adequate P (AP: .20% P, DM basis) diet fed for 14 to 16 mo
under drylot conditions on concrete floors to determine the influence of dietary P on
chemical, physical, and mechanical properties of bone. Three weeks postpartum, after 14 to
16 mo on their diets, heifers were slaughtered and the right and left third metacarpals
(McIII) were excised; soft tissue was removed and metacarpals were frozen in .9% saline.
Metacarpals were subjected to a three-point flexure test using an Instron Testing Machine
with a crossload speed of 50 mm/min to determine mechanical properties. Broken McIII
were reassembled and a 2-cm section was removed at point of loading for determination of
chemical and physical properties. Breaking load (BL) was greater (P < .05) for McIII from
the AP than for those from LP heifers (1,348 vs 1,179 kg). Breaking strength (BS) was
greater (P < .05) for AP than for LP heifers (202.5 vs 189.2 MPa). Animals receiving AP
diets had greater (P < .01) bone mineral content (12.6 vs 11.2 g/2-cm slice) and percentage
of bone ash (68.0 vs 67.2%) than did LP animals. No differences (P > .10) were observed
between treatment groups in Ca, P, or Mg percentage in bone ash. Circular, elliptical,
radiographic, and planimeter area indices all were greater (P < .05) in AP than in LP
animals (1,048,729, 1,069, and 570 vs 932, 660, 957, and 523 mm2, respectively). These
data indicate that mechanical properties of bovine third metacarpals are sensitive to dietary
P and reflect P status in the bovine. Mineral content of bone was highly correlated with its
mechanical and physical properties.

Key Words: Beef Cattle, Phosphorus, Metacarpus, Breaking Strength


Introduction

Interest in studying chemical, physical, and
structural properties of bone as they relate to
bone development has intensified. Clearly, this

is demonstrated in livestock operations where
the trend for maximal production has created
situations in which optimal bone development
and strength are necessary components of
animal performance. This is true not only for
young animals, but also for extending the
useful life of animals within the breeding herd.

Bone development, along with the chemical
and physical properties of the material, is
affected by a number of factors, including age,
nutrition, hormones, and disease. Dietary P
level has been shown to greatly affect bone
development and associated chemical and
physical properties in different species (Har-
mon et al., 1970; Schryver, 1978; Crenshaw et
al., 1981b; Little, 1984); however, few com-
prehensive studies involving the influence of
The objectives of the present experiment were 1) to evaluate the effects of two levels of dietary P on various chemical, physical, and mechanical properties of third metacarpals (McIII) in growing beef heifers and 2) to assess the use of different bone properties as indicators of P status. A companion paper (Williams et al., 1991a) evaluated noninvasive techniques to assess P status and predict bone mineral content and bone strength.

Materials and Methods

Fourteen weaned Angus heifers, 7 to 8 mo of age, averaging 160 ± 3 kg initially, were housed on concrete floors in a covered barn and allowed ad libitum access to a low P diet (.10%; Table 1) during a 270-d P depletion period. At the end of this period, heifers were allowed a 10-d adaptation period to the basal P supplementation diet (.12%; Table 1). In the P supplementation phase of the experiment, heifers (averaging 210 ± 6 kg) were allotted randomly (seven animals per group) to two dietary P levels: 1) continuation of the low P (LP) basal diet containing .12% P (DM basis) or 2) an adequate P (AP) diet that consisted of the basal diet supplemented to provide .20% P (DM basis; Table 1). Basal diets fed during the course of the experiment were formulated to be low in P yet to provide adequate energy, nitrogen (N), other minerals, and vitamins to promote .5 kg/d gain. Calcium (Ca) to P ratios in the P supplementation phase ranged from 3.1:1 in the AP diet to 5.2:1 in the LP diet (6:1 in P depletion phase).

Animals in this second phase of the experiment were group-fed and had ad libitum access to their respective diets for the initial 210 d of the P supplementation phase. All animals in both treatment groups were bred naturally during 120 d of exposure to a single bull. Two heifers from each treatment were determined via rectal palpation as nonpregnant and subsequently were slaughtered on d 245 of the P supplementation phase. Remaining pregnant heifers (five per group) were maintained until 3 wk postpartum. Calving occurred between d 386 and 471 of the P supplementation phase.

At slaughter, the left and right McIII were collected, wrapped in gauze soaked in .9% saline, and frozen (-15°C) for later analysis.

The McIII were prepared for mechanical testing in a manner similar to that employed by Lawrence (1986). All soft tissue including fibrous periosteum was removed; care was taken not to scratch the surface of the bones. While all surrounding soft tissues were being

![Image](https://via.placeholder.com/150)

**TABLE 1. DRY MATTER COMPOSITION OF BASAL DIETS FED DURING PHOSPHORUS DEPLETION AND SUPPLEMENTATION PHASES**

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<tr>
<th>Ingredient</th>
<th>Depletion phase</th>
<th>Supplementation phase</th>
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<tr>
<td>Citrus pulp, %</td>
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<td>Cottonseed hulls, %</td>
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<td>Soybean hulls, %</td>
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<tr>
<td>Ground, pelleted coastal bermudagrass hay, %</td>
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<td>—</td>
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<td>Ground cardboard paper, %</td>
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<td>Cane molasses, %</td>
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<td>Animal fat, %</td>
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<td>Urea, %</td>
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<td>Mineral premix, %</td>
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<td>Vitamins A and D, %</td>
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<td>+</td>
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<tr>
<td>Total</td>
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</table>

**Chemical composition of basal diets fed during P depletion and supplementation phases**

- **Calcium, %**: 60, .62
- **Phosphorus, %**: 10, .12
- **Magnesium, %**: 32, 34
- **Potassium, %**: 1.17, 1.31
- **Sodium, %**: .28, .24
- **Zinc, mg/kg**: 37.60, 39.40
- **Copper, mg/kg**: 13.80, 14.90
- **Cobalt, mg/kg**: .13, .15
- **Molybdenum, mg/kg**: 4.30, 4.70
- **CP, %**: 10.83, 11.91

**a**Monosol™ (Pittman-Moore Corp., Mundelein, IL) added to the basal diet at the expense of cane molasses to achieve 20% total P in supplemented diet.

**b**Supplied mg per kg diet DM (compound, element): sodium selenite (Na2SeO3) 21, .10; nickel sulfate (NiSO4·6H2O) 8.96; 2; stannous chloride (SnCl2·2H2O) 3.80; 2; chromium chloride (CrCl3·6H2O) .51, .10; ammonium vanadate (NH4VO3) .23, .10; potassium iodate (KIO3) .17, .10; sodium molybdate (Na2MoO4·2H2O) 12.3, 5; cobalt carbonate (CoCO3) .22, .10; cupric sulfate (CuSO4·5H2O) 24, 4; manganese oxide (MnO2) 15.8, 10; zinc oxide (ZnO) 37.5, 30; ferrous sulfate (FeSO4·7H2O) 49.7, 10; sodium chloride (NaCl) 2,700, 2,700; calcium carbonate (CaCO3) 450, 180; potassium chloride (KCl) 6,350, 3,300; Dyna-Mate (18% K, 22% S, 11% Mg; Pitman-Moore Corp., Mundelein, IL) 11,200 (2,000, 2,425, 1,223).

**c**Supplied per kg of diet: 2,200 IU vitamin A palmitate and 440 IU vitamin D3.

**d**By laboratory analysis.

**e**Average phosphorus (P) content of basal diet; P content varied from .11 to .13% (DM basis) during the course of the supplementation phase.
dissected, McIII always were kept submerged in 9% saline. They were prepared in this manner to ensure that mechanical tests would be performed on "wet" bones that closely resembled bones as they exist in the animal. Sedlin and Hirsch (1966) reported that as little as 10 min of exposure to air can greatly alter the biomechanical properties of bone.

Cortical bone index (CBI) and radiographic area index (XRI) were determined from anterioposterior radiographs using radiographic guidelines described by Meakim et al. (1981). Calculation of CBI was performed according to a method described by Suttie et al. (1983) and XRI using a method described by Meema et al. (1964).

Mechanical properties of wet McIII were tested by bending by three-point loading using an Instron Testing Machine. Bones were rested on round pivot supports 13 cm apart. Force was applied to the posterior surface of McIII at a constant rate of 50 mm/min. Testing was completed upon failure (rupture) of McIII. Applied loads were normalized on the midspan geometry of the bone cross-section. A strip chart recorder was used to record the force-deformation curve necessary for calculation of mechanical properties. Breaking load (BL, kg), the force required to cause failure of the McIII, was determined directly from the force-deformation curve.

Broken McIII were placed in a 70% ethanol solution (w/vol) for 72 h to aid in removing bone marrow. Metacarpals then were carefully reassembled using Elmer's Glue-All. Reassembled McIII then were placed in plastic containers slightly larger than all McIII dimensions and liquid urethane was poured around them. After it solidified, the liquid urethane provided a uniform, flat surface that enabled accurate removal of particular diaphysis cross-sections of interest from McIII. A 2-cm cross-section was removed at the point of loading (1 cm on either side of midpoint) on the McIII diaphysis using a table band saw.

Caliper cross-sectional measurements from the 2-cm sections were anterioposterior bone diameter (B) and medullary diameter (b), as well as lateromedial bone diameter (D) and medullary diameter (d). Diameters of cross-sections were used in an equation \[ \pi/64 (Bd^3-bd^3) \] for calculating the area moment of inertia of an ellipse (MIE, cm^4). Caliper measurements also were used to determine the mediolateral wall thickness (MLWT, mm) using the equation \[ (D-d)/2 \].

Equations for calculating breaking strength (BS, MPa) and Young's modulus (E, GPa) were BS = \( (F)(L)(C)/4(MIE) \) and E = \( (F)(L^2)/(48(MIE)(D)) \), where F = force (kg), L = distance between the bone rests upon (cm), C = distance from neutral axis to extreme outer fiber (cm), and D = deformation (cm). Force and deformation values were determined from force-deformation curves. Strain was computed as the change in length per unit length at the point of failure.

Cross-sections of McIII were photographed along with a reference standard and actual area (PAI, mm^2), regardless of geometry determined by planimeter. Equations for calculating cross-section area indices (mm^2) for known geometrical shapes were \( (B^2-b^2) \) for circular cross-section area index from bone (CAI) and radiographic area index from anterioposterior radiographs (XRI) and \( (BD-bd) \) for elliptical area index (EAI) from bone.

The 2-cm cross-sections were dried at 105°C for 8 h and ether-extracted in a soxhlet apparatus for 48 h according to the procedure of Fick et al. (1979). Extracted samples were ashed in a muffle furnace at 600°C for 12 h. Cross-section bone ash was expressed as g/2-cm section and defined as bone mineral content (BMC). Calcium and Mg were analyzed by flame atomic absorption spectrophotometry (Perkin-Elmer Corp., 1982) and P was determined colorimetrically (Harris and Popat, 1954) in ash of McIII cross-sections.

Paired t-tests (Montgomery, 1976) were initially performed to determine whether chemical, physical, and mechanical criteria measured in right and left McIII differed between pairs of bones within heifers. After it was determined that sides (i.e., right and left) were similar for these properties within a heifer, average side response was computed and used in subsequent statistical analyses.

All data were analyzed by ANOVA using the GLM procedure (PROC GLM) of SAS.
Correlation coefficients between various chemical, physical, and mechanical McIII properties for each bone in each side (n = 28) were estimated using the PROC CORR procedure of SAS (1982). Graphical representation of relationships between various McIII properties were generated using the PROC GPLOT procedure of SAS (1981); related linear regression equations were determined using the PROC REG procedure of SAS (1982).

Results and Discussion

Gains were higher (P < .01) for the AP group at 245 d of treatment (257 vs 205 kg; Williams et al., 1991b). No physical signs of lameness or stiffness were observed in LP heifers. However, Call et al. (1982) and Shupe et al. (1988) reported that cows fed low amounts of dietary P (less than 7 g/d) for 14 to 24 mo prior to their eighth gestation showed various signs of osteoporosis and other related bone changes, as well as some pathological and traumatic fractures. One could speculate that, if our animals had been allowed to continue on this present regimen, including subsequent gestations and lactations, in time the marginal P level (P = .12% of DM) probably would cause severe, if not debilitating, lameness, thus affecting the useful productive life of the animal.

Cortical bone index (CBI, %) estimated at the midpoint of McIII diaphysis using AP radiographs was greater (P < .01) in AP than in LP heifers (Table 2). Similarly, MLWT (mm) also was greater (P < .01) in HP than in LP heifers (Table 2). Both these measurements indicate that there was less cortical bone at the midshaft of the McIII diaphysis of LP heifers. Similar findings of decreased quantities of cortical bone measured at the midpoint of bone metatarsals in P-deficient cows have been reported previously. Little (1984) reported that the ratio of medullary width:total width was greatest in P-stressed animals whereas the total widths were very similar between P-stressed and P-supplemented cows.

The results of the mechanical tests performed on McIII, along with various chemical properties and some geometrical measurements, are shown in Table 2. Correlation coefficients between these various properties are shown in Table 3. Currey (1970) reported that bending is a closer approximation to the

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<th>Item</th>
<th>Dietary phosphorus levela</th>
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<td>Breaking load, kg</td>
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<td>Breaking strength, MPa</td>
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<td>Ca, % of ash</td>
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<td>Mg, % of ash</td>
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<td>XRI, mm2</td>
<td>957f</td>
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<td>PAI, mm2</td>
<td>523f</td>
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aLP = low phosphorus (.12% P, DM basis); AP = high phosphorus (.20% P, DM basis).

bCBI = cortical bone index; MLWT = medial-lateral wall thickness; BMC = bone mineral content; CAI = circular area index; EAI = elliptical area indices; XRI = radiographic area index; PAI = planimeter area index.

cBMC, Ash, Ca, P, Mg, CAI, EAI, XRI, and PAI were all measured from the 2-cm third metacarpal cross-section removed at the break point.

f, g, h means differ (P < .10).

j, k, l means differ (P < .05).

m, n, o means differ (P < .01).
kind of loading often causing failure in life than is tensile loading, but only if whole bone is used (as was true in this study).

Frankel and Burstein (1970) stated that the structure of bone responds to and is derived from its mechanical properties. Animal nutritionists long have used the mechanical properties of bone for determining the bioavailability of minerals and establishing nutrient requirements (Miller et al., 1962; Haugh et al., 1971; Schryver, 1978; Crenshaw et al., 1981b). Crenshaw et al. (1981a) concluded that a better understanding of the principles involved in determining mechanical properties of bone would allow more accurate conclusions to be drawn concerning the effects of nutrients on mineralization and more accurate comparisons to be made among various experiments.

This latter point must be addressed due to the anisotropic and viscoelastic nature of bone derived from the composite nature of bone material (i.e., the association between collagen and hydroxyapatite). Because bone is anisotropic, values will vary when tested across the grain, in some instances by a factor of two or more. Viscoelastic properties signify that all results of mechanical testing will vary with the strain or loading rate, requiring that this criterion be specified. Increasing the loading rate reportedly increased the capacity of long bones to absorb energy (McElhaney, 1966). Bones may demonstrate nearly twice the stiffness at high speed loading rates that they demonstrate at slow rates (Frost, 1973); thus, as loading rate increases, so will breaking strength.

The nominal full length of all McIII was approximately 18 cm. Force-deformation curves indicated that metacarpals from both groups showed little plastic behavior during the flexure test while undergoing loading prior to failure (i.e., they were more nearly elastic during testing). The BL (kg) was greater \((P < .05)\) in AP than in LP heifers (Table 2). The BL represents the force at which any further increase in force results in failure of the bone. Breaking load is a structural test of bone and is determined by both the size and quality of the material (Lawrence, 1986). Crenshaw et al. (1981a) reported that total BMC is the most critical factor involved with BL. Table 2 shows that BMC (g) values recorded in the 2-cm McIII diaphysis cross-sections removed at the point of loading were greater \((P < .01)\) in AP than in LP heifers. The correlation coefficient between BL and BMC was .884 \((P < .0001; \) Table 3). This correlation coefficient is similar to that reported by Lawrence (1986) of .961 for BL and BMC in a longitudinal study of McIII from horses 1 d to 33 yr of age. The relationship between BL and BMC is shown graphically in Figure 1 with the fitted linear regression model.

If normal bovine cortical bone is uniformly mineralized, a linear relationship should exist between cortical area of McIII and BMC. The relationships between area indices and BMC are shown in Figures 2, 3, 4, and 5. All area indices seemed to be good predictors of BMC, with the more precise indices (i.e., PAI and EAI) having the highest correlations (Table 3) and the least scatter. All cortical area estimates (i.e., CAI, XRI, and EAI) were greater \((P < .05)\) in AP than in LP heifers (Table 2), indicating that bone mineral was distributed over a greater area in the AP animals; these estimates take into account both outside and
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<th>Ash</th>
<th>P</th>
<th>Ca</th>
<th>Mg</th>
<th>BL</th>
<th>BS</th>
<th>E</th>
<th>Strain</th>
<th>MIE</th>
<th>CAI</th>
<th>EAI</th>
<th>XRI</th>
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*BMC = bone mineral content; P = phosphorus; Ca = calcium; Mg = magnesium; BL = breaking load; BS = breaking strength; E = Young’s modulus; MIE = moment of inertia of an ellipse; CAI = circular area index; EAI = elliptical area index; XRI = radiographic area index; PAI = planimeter area index. N = 28 based on two bones per animal.

†P < .10.
*P < .05.
**P < .01.
***P < .001.
****P < .0001.
inside diameters of the cross-sections. Area indices were highly correlated with BL (Table 3), as would be expected based on the relationships between BL and BMC as well as BMC and the area indices.

There are few reports in the literature that pertain to the mechanical properties of bovine McIII determined by flexure with respect to mineral nutrition, although thorough investigations with the horse (Schryver, 1978; Lawrence, 1986) and the pig (Crenshaw et al., 1981b) have been reported. Becker and Neal (1930) reported data on bone "strength" in cattle fed diets low in Ca and P. Values reported as BS (but which actually represent BL) in McIII ranged from 710 kg in a Florida native cow receiving no supplemental Ca or P to 1,581 kg in a cow receiving a bone meal supplement; however, no information was provided on loading rate. Breaking load values in the present study were in a similar range, that is, 920 to 1,640 kg across both treatments.

Breaking strength (BS, MPa), or force per unit area of material, takes into account not only the cross-sectional area over which the force is applied but also the geometrical shape of this area, thus allowing comparison between bones that differ in both size and shape. This is accomplished by incorporation of moment of inertia (I) into the calculation of BS. When testing a bone in bending, resistance to change is a property of the mass of bone and its cross-sectional area. The effects of mass are measured by the force required to break the bone. The resistance attributed to cross-sectional area and its shape are determined by the area moment of inertia (I). Bone, being irregular in shape, makes calculation of I difficult; however, equations for calculating I from simple measures of known geometrical shapes have been derived. Lawrence (1986) reported that the use of a circle in estimating I in horses may result in a 100% overestimation of measured I, whereas the moment of inertia of

Figure 2. Relationship between bone mineral content (Y) and radiographic area index (XRI)(X) of the third metacarpal break section. Dashed lines represent 95% confidence intervals. SE(B_0) = standard error of intercept estimate; SE(B_1) = standard error of slope estimate. N = 28 based on two bones per animal.

Figure 3. Relationship between bone mineral content (Y) and circular area index (CAI)(X) of the third metacarpal break section. Dashed lines represent 95% confidence intervals. SE(B_0) = standard error of intercept estimate; SE(B_1) = standard error of slope estimate. N = 28 based on two bones per animal.
an ellipse (MIE) closely approximated measured I. In the present study, McIII mid-diaphysis geometry was assumed to most closely approximate two ellipses. This assumption was based on the observations that measured McIII cross-sectional area (PAI, mm²) was most nearly approximated by EAI (mm²) (Table 2) and was most highly correlated with EAI (Table 3); also, cross-section geometry visually resembled an ellipse more than a circle.

The estimated MIE (cm⁴) of McIII from AP heifers was numerically greater than that from LP heifers (Table 2), indicating a larger distribution of material from the neutral axis of the McIII cross-sections. Although MIE tended to be larger in AP McIII, BS was greater (P < .05) in McIII from AP than in that from LP groups. This indicates that AP McIII had a greater area of bone material over which the load was distributed and that this material was of higher quality. Crenshaw et al. (1981b) reported that increased BS is indicative of increased mineralization. This is in agreement with findings in this study, for percentage of bone ash was greater (P < .01) in AP than in LP heifers (Table 2). No differences (P > .10) in Ca, P, or Mg content, expressed as a percentage of ash, were observed between treatment groups (Table 2).

Magomedov (1978) reported BS values of 174 MPa in McIII from Black Pied heifers fed recommended P levels; however, their method of testing and loading rate were not reported. Lawrence (1986), using loading rates similar to those used in the present trial, reported that BS of McIII reached a maximum in horses between 1.5 and 4 yr of age (the approximate age of heifers in this study) of 211 MPa, similar to BS values observed herein. Studies pertaining specifically to mechanical properties of bovine bone as affected by dietary P level could not be found. However, other researchers have reported that bone strength increases due to an increase in the level of Ca and P fed to pigs (Miller et al., 1962; Cromwell et al., 1972; Crenshaw et al., 1981b). Care must be
taken, however, in comparing these results with those of the present study due to such factors as species difference, age at testing, Ca:P ratio, loading rate, length between roller supports, method of preparation and point of load application.

The relationship between BS and percentage of ash has been studied in several species. In a classic study, Vose and Kubala (1959), working with human femurs, reported that BS increased rapidly with small increases in ash; they fitted an exponential curve because they felt a linear curve would not make "biological" sense. Currey (1969) attributed the lack of a linear relationship between BS and percentage of ash to a failure of bone to mineralize completely. Mineralization beyond an optimal value would decrease the resiliency of bone and reduce its ability to resist dynamic loading. This is an important concept; during the daily activities of an animal, the bones of the skeleton, individually and collectively, are subjected repeatedly to a variety of force systems by gravity, muscular activity, and various extrinsic factors. Consequently, the capacity of bone to withstand repetitive loading without breaking is of considerable importance with respect to fractures, especially the fatigue of stress fractures.

The relationship between bone mineral and collagen in bone matrix has been suggested (Currey, 1969) to be responsible for the correlation of BS and percentage of ash. As percentage of ash values reach 63 to 68%, the organization of bone matrix produces optimal strength. Below this point, hydroxyapatite crystals may disrupt collagen molecules when a load is applied; above this range, the apatite needles coalesce and allow cracks in the solid phase, which then are not dissipated by the collagen matrix (Currey, 1969).

El Shorafa et al. (1979) reported a correlation of .58 between BS and percentage of ash in a longitudinal study of equine McIII. In the present study, the correlation was .368 (P < .10; Table 3). Although our correlation was somewhat lower, the narrow constraints of age and gender in our study must be considered in terms of comparing results with more longitudinal studies. This relationship is shown graphically in Figure 6. This relationship between BS and BMC also has been investigated. Lawrence (1986) reported a correlation between these variables of .643; in our study, this correlation was .462 (P < .05; Table 3).

This relationship is shown graphically in Figure 7. Note that this correlation (BS vs BMC) is greater than that between percentage of ash and BS. This suggests that the relationship between the amount of mineral is more important than the percentage of mineral and that percentage of bone ash does not account for the influence of collagen on strength of bone.

As bone develops, the inorganic mineral fraction is deposited within the protein matrix in a highly organized manner with a specific mineral to protein ratio. Optimal mineralization produces the lightest bone contained in the smallest area to give effective adequate support for locomotion (Lawrence, 1986). Optimal bone mineralization occurs when BS is maximized (Currey, 1969); below this level the mineral matrix is less organized. Increases in BS and BL up to the point of optimal bone mineralization reflect increased mineralization within the bone matrix and in the total amount of bone present. Above the point of optimal bone mineralization, the organization of mineral within the matrix is not changed, but a greater amount of total bone is deposited. Miller et al. (1962) and Crenshaw et al.
(1981b), both working with pigs, showed that BS reaches a maximum before BL, which continues to increase as more total bone is deposited. Although optimal mineralization of bone matrix is reached at the highest stress, more total bone may be important to maintaining structural integrity of bone, especially in those animals expected to have long-term productive use. This may be desirable in establishing recommended vs minimum requirements.

The crux of the previous discussion is that mechanical characteristics of bone may yield different responses when influenced by various biological factors, including dietary manipulation, and that results must be interpreted carefully. If the load (force) required to cause failure is less in one bone than in another, no information is gathered about whether the quality of the bone material is different or whether the shape, amount, and arrangement of the bone material is different. Thus, even though the load required to break a bone is greater for one than for another, it may withstand less force per unit area of bone material.

Young's modulus (E) was greater ($P < .10$) in AP than in LP heifers, which is suggestive of a greater ratio of bone mineral to protein in the bone matrix (Table 2). This value is indicative of the stiffness of bone under normal stress. Young's modulus is much more important as a mechanical characteristic of bone than generally is realized. If bone were less stiff, the design of skeletons could be altered appreciably. For example, long bones would need to be stouter to prevent lateral collapse when loaded in compression. A stiffer material (as that seen in AP heifers) will require a greater stress for a certain strain or greater load for a given deformation than will a more flexible material.

Currey (1969) reported a linear relationship between E and percentage of ash; he postulated that the resistance of the bone material to static stresses is related to percentage of ash, but this is not necessarily true for dynamic stresses. Correlations between E and percentage of ash ($r = .445$, $P < .05$) and BMC ($r = .204$; Table 3) in our study tend to agree with the hypothesis of Currey (1969). Strain (change in length per unit length) was not different ($P > .10$) between the treatment groups (Table 2). Results of measurements of BS, Young's modulus, and strain suggest that AP McIII also were more resilient than LP McIII; recoverable and absorbed strain energy prior to rupture would be greater. Resilience of McIII would be an important physiological trait of these bones under field conditions because the chance of fracture would be diminished in the range of normal stress.

Results of this study indicate that the chemical, physical, and mechanical properties of bovine McIII are sensitive to dietary P level. These properties clearly indicated differences in dietary P level. Results indicate that McIII from AP heifers had both a greater quantity and quality of bone material. The lower dietary P level ($P = .12\%$ of DM) utilized herein seems to be inadequate for maximum bone mineralization and strength of McIII based on lower BS values relative to cattle fed the .20% P diet. Also, AP heifers had a greater total mass of bone present in McIII based on BL and BMC values. These criteria are of particular interest in animals of the breeding herd that are expected to maintain a given level of
production for a long time. Results of this study suggest that the use of selected chemical and physical traits of various bones would allow reliable and objective assessment of P status in ruminants.

Implications

Chemical, physical, and mechanical properties of bone (third metacarpals) can be used to evaluate phosphorus status of cattle. Compared to those fed a low phosphorus diet (12%), heifers receiving an adequate phosphorus diet (20%) had greater cortical bone index, medial lateral wall thickness, breaking load, breaking strength, Young's Modulus, ash, circular area index, elliptical area index, and radiographic area index.

Literature Cited


