Bone Strength as a Trait For Assesing Mineralization in Swine: A Critical Review of Techniques Involved

T. D. Crenshaw
University of Wisconsin

E. R. Peo, Jr.
University of Nebraska-Lincoln

A. J. Lewis
University of Nebraska-Lincoln, alewis2@unl.edu

B. D. Moser
University of Nebraska-Lincoln

Journal of Animal Science 53 (1981), pp. 827-835.

BONE STRENGTH AS A TRAIT FOR ASSESSING MINERALIZATION IN SWINE: A CRITICAL REVIEW OF TECHNIQUES INVOLVED[1,2]

T. D. Crenshaw[3], E. R. Peo, Jr., A. J. Lewis and B. D. Moser

University of Nebraska, Lincoln 68583

Summary

Lack of standardized test procedures has resulted in considerable variation in reported values for bone strength. Such variation can be attributed in part to the type of instruments used to determine physical properties of bone, procedures used to prepare the bones for testing and equations used to calculate strength. If bone strength is to be used as a major criterion of response in mineral nutrition research, standardization of procedures for measuring and reporting bone strength is essential. Traits that describe the mechanical properties of bone as determined in the commonly used flexure test in which force is applied perpendicularly to the longitudinal axis are bending moment, stress, moment of inertia, strain and modulus of elasticity. Bending moment is a measure of the amount of force withstood by the bone, whereas stress is a measure of force per unit area of bone. Stress allows comparisons to be made between bones that differ in size and shape. The moment of inertia is a measure not only of the area over which the force is applied, but also of the shape in which the area is distributed. Strain is a measure of the amount of bending per unit of length that occurs as the bone is tested. The modulus of elasticity is a measure of the rigidity of the bone or, more simply, is the stress to strain ratio. Instruments that allow the researcher to control the rate of deformation as well as to record the force and deformation are important. Since the modulus of elasticity is affected by the rate of deformation, a standard rate of 5 mm/min is suggested. Differences exist in the mechanical properties of wet and dry bones. Wet bones bend to a greater extent but withstand less ultimate force than dry bones. As little as 10 min exposure to air can result in changes in the mechanical properties of wet bones. Simplification of equations used to calculate stress may yield values that are only a reflection of bending moment if the simplifications do not account for differences in shape or size of the bone. Mechanical properties of bones respond differently to nutritional treatments, and different conclusions can be made, depending upon which trait is used. As bone mineralization increases, maximum stress and bending moment of the bone increase. At a point of optimum mineralization, stress reaches a maximum. Bending moment can increase beyond the point of optimum mineralization if the bone continues to deposit more total minerals. Conclusions about the nutrient requirements affecting bone mineralization should be based on several of the mechanical properties rather than just one.
(**Key Words**: Swine, Bone Strength, Mineralization, Techniques.)

Introduction

Bone breaking strength has been used by nutritionists as a response criterion for determining the bioavailability of minerals and establishing requirements for swine (Miller *et al.*, 1962; Libal *et al.*, 1969; Cromwell *et al.*, 1972; Nimmo *et al.*, 1980). The correct physical description of "bone breaking strength" is force per unit of area, but most of the determinations of "bone breaking strength" reported in the literature have involved only a measure of force, with little or no consideration given to the area of bone over which the force is applied. An understanding of engineering principles used for calculating strength of materials is necessary for nutritionists to comprehend fully the meaning and use of "bone breaking strength" as a response criterion.

[1] Published as Paper No. 6110, Journal Ser., Nebraska Agr. Exp. Sta.
[2] Dept. of Anim. Sci.

[3] Current address: Meat and Anim. Sci. Dept., Univ. of Wisconsin, Madison.

This paper is written for nutritionists and includes a discussion of traits used to describe the mechanical properties of bone and techniques used to determine these traits experimentally. The reader is also referred to Evans (1957, 1973), Yamada and Evans (1970), Swanson (1971) and Baker and Haugh (1979) for additional information on theoretical concepts of bone strength.

Traits Used in Mechanical Tests

Numerous kinds of tests are used to determine the strength of materials. That most commonly used to evaluate the mechanical properties of bone is a flexure test (Baker and Haugh, 1979). In a flexure test (bending test), the bone is simply supported at each end and a force is applied at midspan (figure 1). Swanson (1971) and Evans (1973) have described the following traits which are determined in a flexure test.

Bending Moment. A flexure test involves both compressive and tensile forces. A force is a push or pull on an object and is measured in units of mass. A compressive force tends to push an object together, or shorten it, while a tensile force tends to pull an object apart, or lengthen it. As a bone is bent, with force applied from above, compressive forces are exerted on the top fibers, while tensile forces are exerted on the bottom fibers. When two forces act together, as in a flexure test, the moment of force is determined. The moment of force about a point or axis is the product of the force and the distance or length over which the force is applied. Thus, in a flexure test, bending moment is determined. Bending represents the type of force (compressive and tensile), and moment is the product of force and distance. Bending moment is simply the force applied to the bone adjusted for the distance (length) over which it is applied. Bending moment is measured in units of force and distance (kilograms-centimeters). A more common expression of these units would be in foot-pounds (distance-force). Bending moment is calculated by the following equation:

$$\text{Bending moment (kg–cm)} = \frac{\text{force (kg)} \times \text{length (cm)}}{4}.$$

Length is the distance between the two fulcra points that support the bone (figure 1). Calculation of bending moment allows comparisons between bones of different lengths.

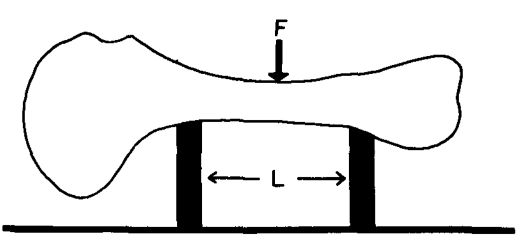

Figure 1. Three-point loading of bone in a flexure test. F = point at which force is applied. L = length between the two fulcra points supporting the bones.

Stress. Bone stress is defined as force per unit of bone area. A more common term for stress is strength, although these terms are used interchangeable. Stress takes into account not only the area over which the force is applied, but also the geometrical shape of this area. For example, if a 200-kg force were applied to a circular or rectangular rod of the same cross-sectional area (8 cm^2), a lower stress would be calculated (figure 2) for the circle (15.67 kg/cm^2) than for the rectangle (18.75 kg/cm^2). Stress cannot be measured directly, and must be calculated. Different formulas are derived for each type of force applied to the bone (compressive, tensile, flexure, *etc.*). In a flexure test, stress is calculated as follows:

$$\text{Stress (kg/cm}^2\text{)} = \frac{\text{force (kg)} \times \text{length (cm)} \times \text{C(cm)}}{4 \times \text{moment of inertia (cm}^4\text{)}},$$

where C equals the distance from the neutral axis to the extreme outer fiber. Equations for determining this distance for different geometrical shapes are given in most engineering handbooks concerned with strength of materials. In a circle or ellipse, C equals ½ the diameter, and, for a quadrant of an ellipse, C equals 4 times the height divided by 3 π.

Equations for calculating the area moment of inertia from simple measurements of an object have been derived for geometrical configurations of known shapes (circles, triangles, rectangles, *etc.*) and are also given in engineering handbooks (Bruch, 1978). Bones are irregular in shape, presenting problems for the determination of the moment of inertia.

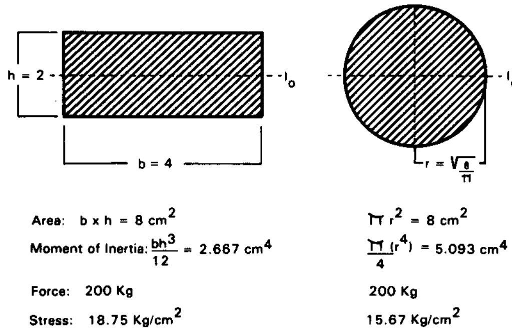

Figure 2. Illustrates the importance of moment of inertia in the calculation of stress for different geometrical shapes to which an equal amount of force has been applied. The moment of inertia is determined at the neutral axis (I_0). See text for equation used to calculate stress.

Engineers and biomechanics have machined small sections of bone with known geometrical configuration to overcome the probelm of irregular shape. Most research by nutritionists has involved the testing of whole bones. Granik and Stein (1973) described a procedure for determining the area moment of inertia for the human rib. Using the same procedure, Crenshaw *et al.* (1981) concluded that the femur and humerus of pigs could be closely approximated by use of the equation for the moment of inertia of an ellipse, while the metacarpal, metatarsal and rib could be approximated by use of the equation for an object shaped as a quadrant of an ellipse. The equations used for calcualting the area moment of inertia[4] from measurements of the diameter of the section are:

$$\text{Moment of inertia} = .0491\ (BD^3 - bd^3)$$
(ellipse)

and

$$\text{Moment of inertia} = .0549\ (BD^3 - bd^3)$$
(ellipitical quadrant)

where B and D are outside diameters (centimeters) of the bone at the point of loading, and b and d are inside diameters (centimeters) at the same points. The diameters B and b are diameters perpendicular to the direction of the applied force, while D and d are diameters parallel to the direction of the applied force.

Strain. Another important physical property of bone is strain. Strain is the ratio between the original length and the change in length of a body as the result of the application of a force. In a flexure test of whole bones, strain is determined by the following equation:

$$\text{Strain} = \frac{12 \times \text{deformation (cm)} \times \text{C (cm)}}{\text{length}^2\ \text{(cm)}}.$$

Deformation is a measure of deflection or bending that occurs as the bone is being tested. Strain is unitless, as it is the change in length per unit length.

Modulus of Elasticity. The modulus of elasticity is a measure of the capacity of the bone to return to its original shape after it has been deformed by a force. Thus, modulus of elasticity is a measure of the degree of rigidity of the bone. An object made of steel would have a higher modulus of elasticity than a similar object made of rubber (Liboff and Shamos, 1973). The ratio of stress to strain is used for determining the modulus of elasticity from the following equation:

$$\text{Modulus of elasticity (kg/cm}^2) = \frac{\text{force (kg)} \times \text{length}^3\ \text{(cm)}}{48 \times \text{moment of inertia (cm}^4) \times \text{deformation (cm)}}$$

The modulus of elasticity is determined from the linear portion of a stress:strain curve.

Bones exhibit both elastic and plastic deformation when tested under the conditions in our laboratory. Whole bones are tested by a flexure test at a deformation rate of 5 mm/min, with an Instron Testing Machine[5] used to record the force-deformation curve. Elastic deformation occurs in the initial phase of the stress:strain curve (figure 3). In this area, the bone will return to its original shape upon removal of the applied force, as no permanent damage is done to the bone. At the inflection point of the stress:strain curve, maximum yield stress is determined. At this point, the amount of force applied to the bone is sufficient

[4] The constant .0491 equals ($\pi/64$) in the calculation of moment of inertia for an ellipse. The constant .0549 equals ($\pi/16 - 16/36\pi$) in the calculation for the moment of inertia of an ellipitical quadrant (Bruch, 1978).

[5] Instron Testing Machine table model 1123, Instron Corp., Canton, MA 02021.

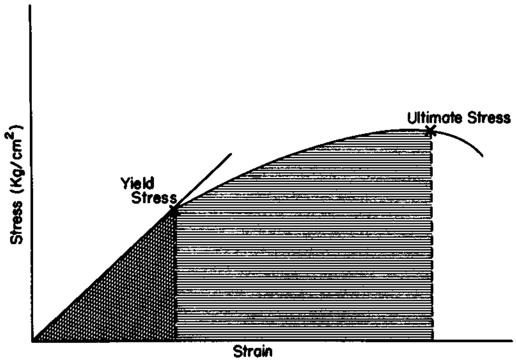

Figure 3. Stress:strain curve of a bone in a flexible test. [hatched] = elastic deformation of bone. [lined] = plastic deformation of bone.

to result in permanent damage to the bone. Ultimate stress is calculated at the point at which the bone fails to withstand any further increase in force. This is the point of bone failure. In the region between yield stress and ultimate stress, the bone exhibits plastic deformation; this is the region where the bone will not return to its original shape if the force is removed. The bone undergoes permanent damage in the region of plastic deformation.

A description of bone measurements taken and equations used for the experimental determination of mechanical properties of bone has been reported for the femur of rats (Weir *et al.*, 1949) and of pigs (Miller *et al.*, 1962). Only recently, Crenshaw *et al.* (1981) reported equations and measurements for the determination of mechanical properties of the femur, humerus, metacarpal, metatarsal and ribs of swine.

Physical Factors Affecting Bone Strength of Swine

Variations exist in "bone breaking strength" data reported from different experiments with pigs of comparable age and nutritional background. This variation may be due to a lack of standarized test conditions or to a failure to use correct equations for calculating mechanical properties. For the most part, nutritionists are not concerned with the absolute strength of bone, but only with the response of bone strength to levels or source of a nutrient. A better understanding of principles involved in the mechanical properties would allow more accurate conclusions to be made concerning the effect of nutrients on mineralization, and would allow more accurate comparisons to be made among various experiments. Two factors that contribute to the lack of uniform testing conditions are (1) variation in the types of instrument used to measure mechanical properties, and (2) variation in the procedures used to prepare the bones for testing.

Variation in the instruments used for mechanical tests can be attributed in part to advances in technology. Weir *et al.* (1949) used an apparatus to measure bone strength in which weights were added to a pan suspended by a hook from the midspan of a rat femur. More recently, instruments similar to a Carver[6] press have been used. With these instruments, a force is applied to the bone by means of a manually operated hydraulic cylinder. Both of the above-cited methods do not produce a uniform rate of deformation in the bone. The modulus of elasticity is dependent upon the rate of deformation and increases with increasing rates of deformation (Sedlin and Hirsch, 1966). With manually operated instruments, it is difficult if not impossible to provide a constant deformation rate, so variation would be expected in data collected with these instruments. Miller *et al.*

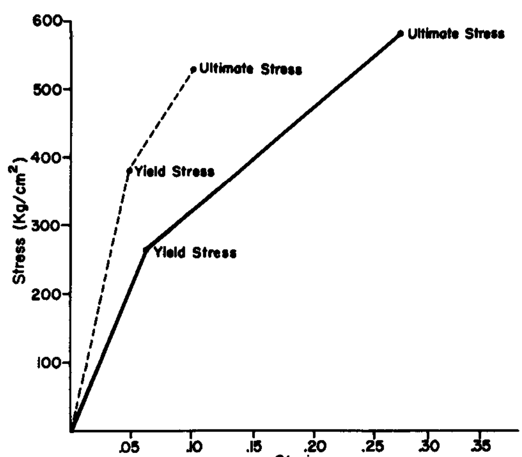

Figure 4. Stress:strain curve for wet and dry (extracted) third metacarpal bones from pigs. - - - dry bones. —— wet bones. (Nebraska swine nutrition Exp. 77301, *unpublished data*).

[6] Fred S. Carver, Inc., One Chatham Road, Summit, NJ.

(1962) used a Tinius-Olsen testing device to record simultaneously the load and deflection as bones were tested. More modern instruments such as the Instron Testing Machnie have the capability to electronically provide a constant rate of deformation. These intruments can also plot a force-deformation curve of the bone as it is being tested. Even when the rate of deformation is known, it is not always reported. However, to date, no standard rate has been defined from which researchers can establish uniform testing procedures. Unreported testing in our laboratory suggests a rate of 5 mm/min is optimal for plotting a force deformation curve with an Instron Testing Machine.

With instruments such as the Carver press, the researcher had to dry and extract the fat from bones so the bone would snap or break completely upon testing. This provided a distinct endpoint to the test. With instruments that record the force-deformation curve, such a break in the bone is not necessary. Questions have arisen concerning the relationship between physical properties of dry, fat-extracted bones and those of wet bones.

Results of a test comparing dry and wet bones are shown in figure 4. Bones were collected from approximately 200 pigs of similar nutritional and management background. One-half of the bones were extracted in anhydrous ether and dried at 100 C for 3 hr before testing. The remaining bones were frozen until testing time, then allowed to thaw to room temperature. Freezing before testing does not affect the mechanical properties of bone, but changes in temperature at the time of testing may result in small changes in strength (Sedlin, 1965). As figure 4 shows, wet bones bend more than dry bones when comparisons are made of the strain to the point of ultimate stress. When strain at the points of yield stress is compared, there appears to be little difference between wet and dry bones, although the yield stress of dry bones is greater. However, the reverse is true at the point of ultimate stress. The modulus of elasticity of the dry bone is greater at both the yield and the ultimate stress point. Values for modulus of elasticity at the yield points were 8,361 and 4,610 kg/cm^2 for dry and wet bones, respectively, while at the points of ultimate stress, modulus of elasticity values were 5,463 and 2,215 kg/cm^2.

These data support other research indicating that dry bones are more nearly elastic (Liboff and Shamos, 1973) and bend less upon testing than wet bones. Miller *et al.* (1965) reported that the wet femurs of 5- to 6-week-old pigs bent nearly twice as much as the dry femurs, but that dry bones were stronger than wet bones. Sedlin and Hirsch (1966) reported that, after only 10 min in air, bone specimens began to show an increase in strength. The effect of drying becomes more pronounced after longer periods.

For nutritionists who are concerned with a response to nutrient quality of the diet, either dry or wet bones can be used. Wet bones would be preferable, as they resemble more closely the bones as they exist in the animal. Extreme care must be taken to avoid any drying of wet bones.

Not only is there a lack of uniformity in testing procedures, resulting in variation in bone test results, but the calculations used to determine bone strength are variable, as well. Examples are given below to point out problems associated with the interpretation of bone strength traits.

Libal *et al.* (1969) and Svajgr *et al.* (1969) reported bone strength in kg/cm^2. No determinations were made of the moment of inertia. The values reported were actually dial readings from a Carver press. Bone strength values are expressed in units of kg/cm^2, but the cm^2 refers to the area of the cylinder supplying the

TABLE 1. EFFECT OF CALCIUM AND PHOSPHORUS LEVELS ON THE GEOMETRICAL MEASUREMENTS OF BONES FROM PIGS[a]

	Dietary levels of Ca, P, %	
Measurement	.4, .4	.8, .8
Avg outside diameter, cm[b]	1.55	1.56
Avg inside diameter, cm[bd]	1.07	1.01
Wall thickness, cm[cd]	.241	.273
Moment of inertia, cm^{4}[d]	.402	.435

[a]From Crenshaw *et al.* (1981).

[b]Average of diameters taken 90° to each other in seven bones (femur, humerus, third and fourth metacarpal, third and fourth metatarsal and rib).

[c]Determined by subtracting inside from outside diameter and dividing by two.

[d]Response to level of Ca, P (P<.01).

force. Multiplication of dial reading by a factor of 17.7862 yields a force in kilograms. If this factor is used, the values reported by Libal *et al.* (1969) and Svajgr *et al.* (1969) for bone strength are within the range of force withstood by bones from pigs of a similar age that were tested with a Carver press (Owens *et al.*, 1973).

Tanksley *et al.* (1976) measured the area of cortical bone using a compensating polar planimeter. Area of bone was used for calculating stress of femur and metacarpal bones. Comparisons between the femur and metacarpal bones are inappropriate here, as differences in the shape of these bones were not considered. However, the authors concluded that femurs were a better indicator of bone development than were the metacarpal bones. On the other hand, in a study with pigs of the same age, Crenshaw *et al.* (1981) concluded that the metacarpal bones were more responsive to Ca and P levels than femurs were. This difference in the conclusions of the two groups might be due to the use of area rather than moment of inertia.

Moser *et al.* (1980) and Nimmo *et al.* (1980) computed the stress of pig femurs and metatarsals from a simplified equation of stress. The area of a circle was calculated from an average of two outside diameter measurements at midshaft. Stress was computed by dividing force by this area. No consideration was given to the inside hollow portion of the bone cross section or to differences in the shape of femur and metatarsal bones.

Data presented in table 1 indicate that the inside diameters of bones in growing pigs respond to variations in levels of Ca and P, while the outside diameters change very little. Cromwell *et al.* (1972) and Tanksley *et al.* (1976) also reported no change in outside diameters of bones due to altered Ca and P levels, but they did observe changes in wall thickness. Data based on calculations that do not consider the inside diameter would not be as sensitive to changes in bone mineralization due to levels of Ca and P. Stress as calculated by Moser *et al.* (1980) and Nimmo *et al.* (1980) would only reflect differences in force, since little change would be expected in outside diameter of bone.

Data from Nimmo *et al.* (1980) are presented in table 2. If one assumes, as discussed above, that the inside diameter decreases with increasing levels of Ca and P, the moment of inertia can be estimated from the reported data and an estimate of stress can be calculated. A difference in the response to Ca and P levels is noted between the stress reported by Nimmo *et al.* (1980) and the estimated stress (table 2). On the bases of the estimates of inside diameter, the estimated stress did not increase with levels of Ca and P but may have actually decreased at the highest level of Ca and P. The findings of Nimmo *et al.* (1980) indicating that bone mineralization was less pronounced in boars fed the diet containing .65% Ca and .50% P than in those fed higher

TABLE 2. RESPONSE OF BONE FORCE AND STRESS TO VARIED LEVELS OF CALCIUM AND PHOSPHORUS

	Dietary Ca and P, %		
Item	.65, .5	.975, .75	1.3, 1.0
Force, kg[a]	227	254	259
Stress, kg/cm^2 [ab]	67	78	78
Cross sectional area, cm^2 [ab]	3.39	3.26	3.32
Avg outside diameter, cm[a]	1.04	1.02	1.03
Avg inside diameter, cm[c]	.90	.85	.84
Wall thickness, cm[d]	.07	.09	.10
Moment of inertia, cm^4 [d]	.0252	.0275	.0308
Stress, kg/cm^2 [d]	1,170	1,177	1,082

[a]Characteristics from Nimmo *et al.* (1980).

[b]Calculated from the equations, stress = peak/cross section, where cross section = πr^2.

[c]Estimated response to Ca, P levels.

[d]Calculated from formulas described in this article with estimated inside diameters.

levels of the two elements is correct when force is the trait. Stress may be a better indicator of mineralization of the bone and, at these levels of Ca and P, mineralization may not differ based on the estimated stress. Pigs fed the two higher levels of Ca and P may simply have laid down more bone, a supposition which would be reflected by the increase in force with increasing Ca and P levels.

Biological Factors Affecting Bone Strength

Biological factors such as dietary nutrients and age affect "bone breaking strength." The responses of the mechanical properties (force and stress) to biological factors are different and can be used to describe changes in the bone matrix. The following examples are offered to illustrate the differential response of force and stress and to explain the implications of the response for changes in bone matrix.

Data from Miller *et al.* (1962), graphically represented in figure 5, indicate that bone stress reaches a maximum before bone force does. Miller *et al.* (1962) fed increasing amounts of Ca to baby pigs. At the lower levels of Ca, bending moment and stress increased with increasing Ca. Bone stress reached a maximum when pigs were fed .8% Ca, while bending moment continued to increase when the pigs were fed 1.2 and 1.6% Ca. The data indicate that .8% Ca is adequate for optimum bone mineralization. Presumably, below .8% Ca, the mineral matrix is less organized, resulting in changes in stress, while above .8% Ca the mineral matrix is not changed — only a greater amount of bone is deposited. The increases in force at 1.2 and 1.6% Ca reflect an increase in the total amount of bone, while increases in force and stress up to .8% Ca reflect a change in both the mineral matrix and the amount of bone.

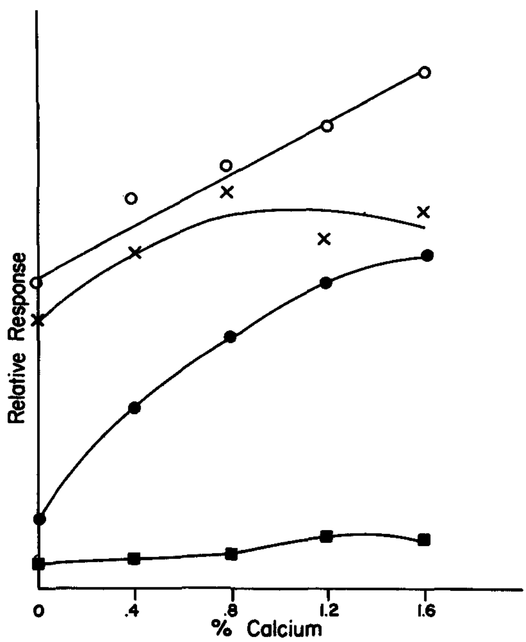

Figure 5. Response of mechanical properties of bone to levels of dietary Ca (Miller *et al.*, 1962). -o-o-o = modulus of elasticity; -x-x-x = stress; -●-●-● = bending moment; -■-■-■ = moment of inertia.

Data from Nimmo (1980) indicate a difference in the responses of force and stress to age (table 3). Bones from gilts slaughtered after one lactation period had a lower stress and modulus of elasticity than bones from gilts slaughtered before reaching breeding age. The bending moment and moment of inertia of the bones were greater after lactation than before breeding. The differential response of stress and force (bending moment) indicates that the bones continued to grow in total mass, but that the organic matrix of bones from older pigs were less calcified than that of bones from younger animals. The decrease in bone stress with age was not as severe in gilts fed 50% more than the NRC (1973) recommended levels of Ca and P as it was in those fed the NRC levels.

Diagrams in figure 6 represent cross sections of bones from pigs fed improved amounts or balances of any nutrients (Ca, P, vitamin D, *etc.*) that might affect the physiological process of bone mineralization. The bone cross sections also represent different degrees of rickets, ranging from severe (A) to none (D, E). Arrows indicate the expected responses in force, stress, moment of inertia and percentage of ash in bone cross sections to the improvements in nutrients or to the decrease in rickets.

The organic matrixes of bones A, B and C are not entirely calcified and are rachitic. As the degree of calcification improves in bone A, B and C, bone stress and force increase. The organic matrixes of bones represented by D and E are completely calcified, and only the total amount of calcified matrix is increased by further increases in nutrients. In E, force is increased beyond that in D because of the increase in the total amount of bone. Stress is constant in D and E because of an absence of

TABLE 3. EFFECT OF CALCIUM AND PHOSPHORUS LEVELS ON MECHANICAL PROPERTIES OF BONE AS INFLUENCED BY REPRODUCTIVE CYCLE[a]

Property	Prebreeding[b] Ca, P level		Postlactation[c] Ca, P level	
	A[d]	A + 50%	A	A + 50%
Bending moment, kg-cm	98	117	119	152
Maximum stress, kg/cm^2	588	628	437	549
Modulus of elasticity, kg/cm^2	1,637	1,763	1,261	1,508
Moment of inertia, cm^4 [e]	.123	.140	.233	.237

[a]From Nimmo (1980). Average of values for third and fourth metatarsal bones.

[b]Slaughtered at approximately 6 months of age.

[c]Slaughtered after a 6-week lactation period.

[d]A = .65, .5% Ca, P for growing-finishing period, or 13 g Ca and 10 g P/day during gestation period.

[e]Response to Ca, P levels (P<.01).

changes in the organic matrix. Stress is not affected by an increase in size but by a change in the calcified matrix.

Bones represented by A, B and C are rachitic and represent a reduction in the proportion of calcified mass to total mass; thus, percentage of ash would be reduced. When expressed as a percentage, ash would not differ between D and E. This explains the absence of a relationship between force and percentage of ash reported by Cromwell *et al.* (1972). On the basis of the above discussion, a relationship should exist between stress and percentage of ash. Vose and Kubala (1959) fitted an exponential curve to show a relationship between stress and ash content. They reported a rapid increase in stress with small increases in ash content. Currey (1969a, b) observed a linear relationship between ash content and modulus of elasticity and proposed that this relationship was due to the fusion of apatite crystals. Crenshaw *et al.* (1981) concluded that stress was a more sensitive indicator of mineralization than percentage of ash on the basis of the responses of stress and percentage of ash across sexes. Bones from boars had significantly lower stress values than bones from gilts or barrows, while percentage of ash showed only a numerical trend rather than statistically significant differences.

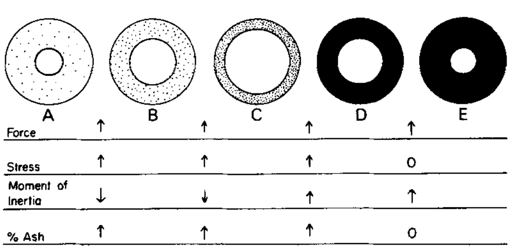

Figure 6. Responses of force and stress to changes in the organic matrix of bone as the nutritional status of the animal increases (from diagrams A to E). The diagrams illustrate bones with the following responses to nutrients: A – severe rickets, uncalcified matrix, remodeled cortical bone; B – moderate rickets, uncalcified matrix, slight remodeling; C – slight rickets, uncalcified matrix, no remodeling; D – no rickets, completely calcified matrix; E – no rickets completely calcified matrix, increase in amount of total bone over D. Arrows represent an increase (↑), a decrease (↓) or (0) no change between diagrams A, B, C, D and E.

With the difference in the responses of stress and force to nutrient level, the question arises as to which trait should be used for the establishment of nutrient requirements. Maximum levels of stress indicate that nutrients are adequate for mineralization of the bone. A further increase in the total amount of bone indicated by force (bending moment) might be desirable for the determination of recommended levels rather than minimum requirements. Although the bone matrix reached the desired level of mineralization at the highest stress, more total bone might be required to maintain structural integrity in the pig, a triat particularly critical for those animals entering the breeding herd.

Literature Cited

Baker, J. L. and C. G. Haugh. 1979. Mechanical properties of bone: A review. Trans. Amer. Soc. Agr. Eng. 22:678.

Bruch, C. D. 1978. Strength of Materials for Technology. John Wiley and Sons, Inc., New York.

Crenshaw, T. D., E. R. Peo, Jr., A. J. Lewis, B. D. Moser and D. G. Olson. 1981. Influence of age, sex and calcium and phosphorus levels on the mechanical properties of various bones in swine. J. Anim. Sci. 52:1319.

Cromwell, G. L., V. W. Hays, C. W. Scherer and J. R. Overfield. 1972. Effects of dietary calcium and phosphorus on performance and carcass, metacarpal and turbinate characteristics of swine. J. Anim. Sci. 34:746.

Currey, J. D. 1969a. The mechanical consequence of variation in the mineral content of bone. J. Biomech. 2:1.

Currey, J. D. 1969b. Technical note: The relationship between the stiffness and the mineral content of bone. J. Biomech. 2:477.

Evans, F. G. 1957. Stress and Strain in Bones: Their Relation to Fracture and Osteogenesis. Charles C. Thomas, Springfield, IL.

Evans, F. G. 1973. Mechanical Properties of Bone Charles C. Thomas, Springfield, IL.

Granik, G. and I. Stein. 1973. Human ribs: Static testing as a promising medical application. J. Biomech. 6:237.

Libal, G. W., E. R. Peo, Jr., R. P. Andrews and P. E. Vipperman, Jr. 1969. Levels of calcium and phosphorus for growing-finishing swine. J. Anim. Sci. 28:331.

Liboff, A. R. and M. H. Shamos. 1973. Solid state physics of bone. P. 335-95. *In* I. Zipkin (Ed.) Biological Mineralization. John Wiley and Sons, New York.

Miller, E. R., D. G. Hendricks and D. E. Ullrey. 1965. Characteristics of fresh and dry femurs of baby pigs. J. Anim. Sci. 24:897. (Abstr.).

Miller, E. R., D. E. Ullrey, C. L. Zutaut, B. V. Baltzer, D. A. Schmidt, J. A. Hoefer and R. W. Luecke. 1962. Calcium requirement of the baby pig. J. Nutr. 77:7.

Moser, R. L., E. R. Peo, Jr., T. D. Crenshaw, B. D. Moser, P. J. Cunningham and G. Kennedy. 1980. Effect of dietary lactose on gain, feed conversion, blood, bone and intestinal parameters in postweaning rats and swine. J. Anim. Sci. 51:89.

Nimmo, R. D. 1980. Effect of varying levels of dietary calcium and phosphorus fed to gilts during growth, gestation and subsequent lactation. Ph.D. Dissertation. Univ. of Nebraska, Lincoln.

Nimmo, R. D., E. R. Peo, Jr., B. D. Moser, P. J. Cunningham, D. G. Olson and T. D. Crenshaw. 1980. Effect of various levels of dietary calcium and phosphorus on performance, blood and bone parameters in growing boars. J. Anim. Sci. 51:100.

NRC. 1973. Nutrient Requirements of Domestic Animals, No. 2. Nutrient Requirements of Swine. Seventh Revised Ed. National Academy of Sciences – National Research Council, Washington, DC.

Owens, A. A., E. R. Peo, Jr., P. J. Cunningham and B. D. Moser. 1973. Chelated trace minerals for G-F swine. J. Anim. Sci. 37:95.

Sedlin, E. D. 1965. A rheologic model for cortical bone. Acta Orthop. Scand. 36(Suppl. 83):1.

Sedlin, E. D. and C. Hirsch. 1966. Factors affecting the determination of the physical properties of femoral cortical bone. Acta Orthop. Scand. 37: 29.

Svajgr, A. J., E. R. Peo, Jr. and P. E. Vipperman, Jr. 1969. Effects of dietary levels of manganese and magnesium on performance of growing-finishing swine raised in confinement and on pasture. J. Anim. Sci. 29:439.

Swanson, S.A.V. 1971. Biomechanical characteristics of bone. *In* R. M. Kennidi (Ed.) Advances in Biomedical Engineering. Academic Press, New York.

Tanksley, T. D., Jr., J. Schroder and R. G. Robinson. 1976. Calcium and phosphorus requirements of large framed developing boars. Proc. Internat'l Pig Vet. Soc., Ames, IA p. A6.

Vose, G. P. and Kubala, A. L. 1959. Bone strength – Its relationship to x-ray determined ash content. Human Biol. 31:262.

Weir, J. B. de V., G. H. Bell and J. W. Chambers. 1949. The strength and elasticity of bone in rats on a rachitogenic diet. J. Bone Joint Surg. 31B:444.

Yamada, H. and F. G. Evans. 1970. Strength of Biological Materials. William and Wilkins Co. Baltimore, MD.