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MECHANICAL PROPERTIES OF NORMAL AND AVASCULAR CANCELLOUS BONE

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ABSTRACT

Several investigators have attempted to define and assess the material properties of cancellous bone (stiffness, strength) with respect to such tissue variables as apparent density, area fraction, and trabecular orientation. Such studies usually dealt with cadaveric bone from different locations of normal individuals. Of considerable interest in clinical practice is the question of how the material properties are affected in avascular bone and after subsequent revascularization, which is the purpose of the present study.

INTRODUCTION

The ever-increasing use of prostheses has encouraged studies of the behavior and material properties of cancellous bone. This two-phase composite is an anchoring material for total joint replacements as well as a valuable shock absorber in the healthy individual.[8] Several investigators have successfully documented the strength and stiffness of this material with respect to such variables as specimen apparent density, trabecular orientation, and composition.[4-6, 8-10] Cancellous bone, however, is frequently subjected to abnormal circumstances such as high temperatures during acrylic cement polymerization and lack of blood during avascular necrosis.[1,7] Thus a documentation of cancellous bone response after an abnormal in vivo situation might be useful clinical information for diagnosis and treatment of disabling bone diseases. This study attempted to assess the material properties of cancellous bone after isolated avascularization as compared to that of normal healthy cancellous bone.

MATERIALS AND METHODS

Fifteen female adult African goats were used for this study. The anterior one-third section from the left femoral head of ten animals was avascularized and isolated in situ using a sterile, surgical procedure (fig.1). The goats were then returned to pasture before being sacrificed in three equal groups: a normal, unoperated group, a six-week post-operated group, and a twelve-week post-operated group. Prior to sacrifice, all operated goats received a tetracycline injection intravenously (25mg/kg body weight).

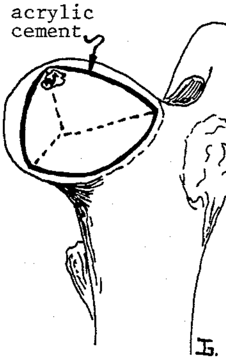


Figure 1

Isolated, avascular segment of the anterior, left femoral head

Both femurs were excised from the sacrificed goats. X-rays were taken to ascertain maturity. Under continuous irrigation with physiological salt, 5mm cylindrical plugs, 4mm thick, were cored from the anterior segments approximately 30^{o} from the vertical in the sagittal plane. After machining the ends parallel, the specimens were stored in physiological salt at -45^{o}C.

Bulk specimen dimensions were determined using a micrometer. Each plug was then subjected to unconfined compression using a Zwick materials testing apparatus. Crosshead speed was 1mm/min and the prescribed total deformation was 75% of the original thickness. A porous platen allowed fluid to escape. Load and deformation were recorded on a Hewlett-Packard x-y recorder. From these graphs yield strength and stiffness (Young's modulus) were assessed.

Following testing, all specimens were re-equilibrated in physiological salt overnight, and the bone marrow was removed with running water and compressed air. The deformed plugs were then degassed in a vacuum oven, first using 100% ethanol and then distilled water. Following centrifuging for fifteen minutes at 6000rpm, each specimen's hydrated weight was determined in order to evaluate its apparent density (ρ_A = hydrated weight/bulk specimen volume).[7]

The differences between normal healthy trabecular bone and the isolated segments of avascular bone were histologically determined using decalcified microscopic sections stained with hemotoxylin-eosin and by applying fluorescent labeling with tetracycline in undecalcified sections and subsequent evaluation by means of ultraviolet light microscopy. These preparations not only determined whether the operated segments were avascular but also provided a means of comparing the osteocytes, osteoblasts, and hemopoietic cells of living, healthy bone with those of the dead, avascular bone.

RESULTS AND DISCUSSION

From a clinical viewpoint, the operated goats recovered successfully prior to sacrifice. The joint capsule healed with a minimum of scar tissue and synovial fluid was present. Joint function outwardly appeared normal, although the range of motion may have been slightly impaired in some animals. In nine of the ten cases the isolated segment remained completely secured to the undisturbed femur; in the tenth case, at twelve weeks post-operatively, the segment was loose but still in place. The segments were generally tinted yellow whereas the remaining parts of the operated heads and the unoperated femoral heads were slightly tinted reddish-blue. No outward evidence of resorption or necrosis was observed in or around the isolated area.

Histologically the isolated segments were clearly distinguishable from the control specimens. In each of the control specimens, i.e., the right femoral heads and the undisturbed sections of the left femoral heads, vital osteocytes, osteoclasts, fat cells, and hemopoietic cells were present. Healthy osteoblastic linings adhered to the trabeculae. However, in all the six-week avascular specimens and four of the twelve-week specimens the bone was observed to be avital. Lacunae were empty, no osteoclasts were seen and osteoblastic linings were were missing (fig.2). No hemopoietic cells were present and only ghosts of fat cells remained. Two of the twelve-week specimens did show ingrowth of dense fibrous tissue, which further inhibited revascularization of the intertrabecular spaces.

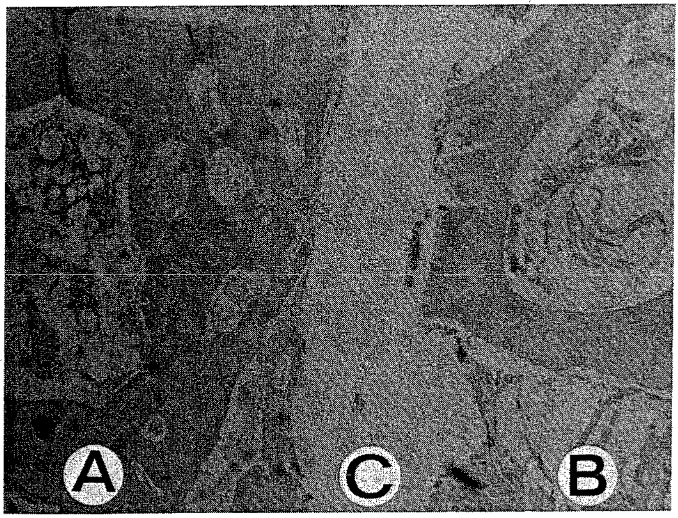


Figure 2

A. vital bone
B. avascular bone
C. acrylic cement

7µm H.E. section, decalcified, 16x

Tetracycline was not observed in any of the avascular six-week specimens (fig.3). In two of the twelve-week specimens, minor amounts of tetracycline were observed in the bone segments at the cement interface only. The remaining twelve-week avascular segments were completely free of tetracycline. Thus from these observations and the previously discussed histology, it was concluded that the cored areas of the segments were completely avascular and avital.

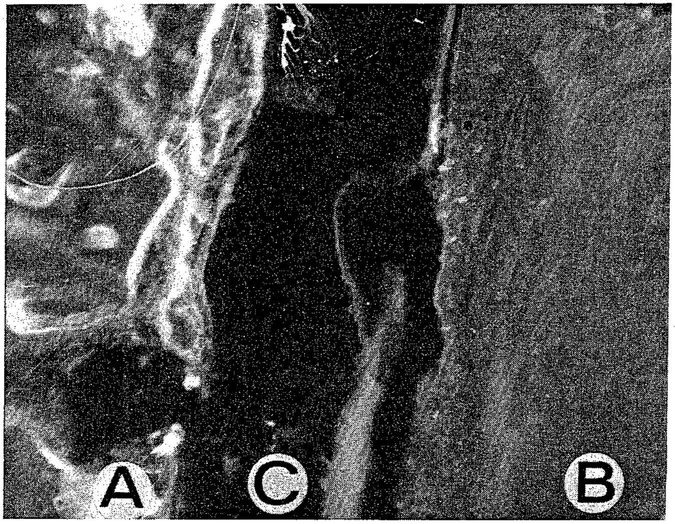


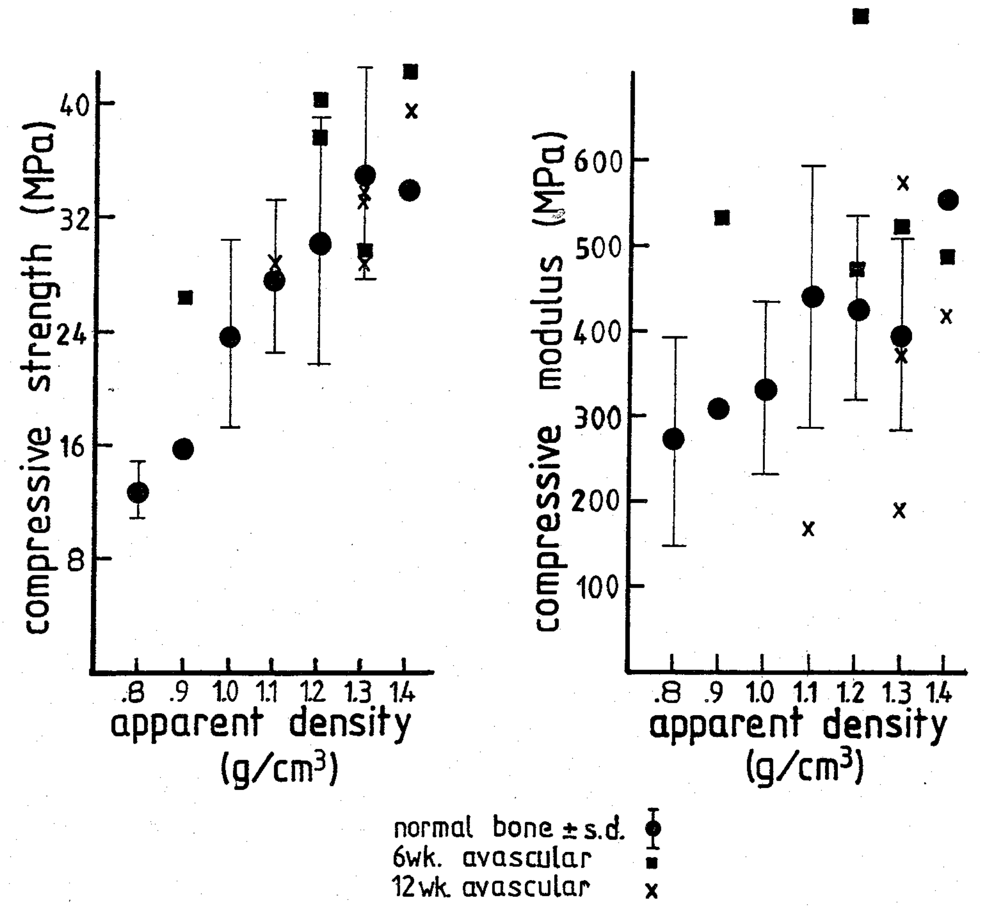
Figure 3

A. vital bone with tetracycline
B. avascular bone
C. acrylic cement

100µm section, undecalcified, UV light, 25x

The yield strength (σ_y) and stiffness (Young's modulus, E) of cancellous bone in both normal and avascular goats varied with apparent density (ρ_A) such that increases in apparent density produced increases in these material properties (fig. 4). What is of particular interest is that the ranges of these three variables (ρ_A, σ_y, E) were two to three times greater than reported ranges of human cancellous bone for the respective variables.[4] Thus, data were obtained in a previously untested range of the material property—apparent density relations.

The strength of cancellous bone demonstrated no significant change with avascularization. The values of the six-week avascular specimens appeared slightly higher than the averaged values for normal bone at the corresponding apparent densities but generally fell within the calculated standard deviation for normal bone (fig.4). This is a foreseeable result if one assumes that bone matrix strength is generally derived from the inorganic composition of the bone. By avascularizing and isolating the bone, therefore, one maintains the same inorganic composition yet prevents both resorption and revascularization, which have been suggested to be causes of femoral head collapse during necrosis.[1] The material properties of the inorganic matrix thus remain indifferent to the blood supply and the matrix simply continues to function in a load-bearing, shock-absorbing



capacity. A major influence of avascularization on the bone's material properties would probably be revealed in fatigue studies. Carter and Hayes determined that fatigue life (cycles to failure) of cortical bone tissue is a function of stress amplitude, temperature, and bone density.[3] Carter et al maintained, however, that slowly accumulating trabecular failures are easily contained by normal bone remodeling processes.[2] Hence, in accordance with Brown and Ferguson, where it was theoretically demonstrated that clinically observed femoral head collapse in necrotic tissue was due to accumulated fatigue failures of individual trabeculae, it can be concluded, with respect to the present work, that in an avascular segment remodeling cannot occur; thus, micro-damage accumulates until macro-failure occurs.[1]

Stiffness values were more difficult to interpret because of their greater scatter. The absolute values in the avascular specimens were of the same order of magnitude as normal bone, although in two of the twelve-week specimens the Young's moduli were observed to be substantially lower than the corresponding normal values. The aforementioned scatter, as seen in figure 4, is in agreement with reported findings.[4] An obvious explanation of this observation is that stiffness is, besides apparent density, also highly sensitive to trabecular orientation and to the degree of mineralization of bone tissue for a given individual.

CONCLUSIONS

A surgical method of avascularizing and isolating cancellous bone in situ has successfully been demonstrated. Comparisons of the yield strength and the Young's modulus of such bone with normal cancellous bone indicated no significant variational trends. Scatter was present in the data but did not mask the increases in material properties with respect to increases in apparent density. Cancellous bone of goat femoral heads was found to be stronger and stiffer than human and bovine cancellous bone, due to its higher apparent density.

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