

ANALYSIS OF BONE STRENGTH USING ULTRASOUND SYSTEM

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INTRODUCTION

There is currently no acceptable diagnostic technique to accurately separate patients having high risk of fracture from normal age-matched controls. All available noninvasive, in vivo, techniques to assess fracture threshold measure either bone density or bone mineral content.

Studies aimed at predicting fracture risk have related the breaking strength of bone evaluated in vitro to its mass and have shown good correlation (Smith, 1976; Dalen, 1976; Smith, 1972). However, in vivo, while some individuals with fracture had lower bone mass than those without fracture, considerable overlap between fracture and control groups was found when bone mass was measured in the radius of patients with and without vertebral collapse fracture (Dalen, 1976); in the femoral neck of patients with and without fracture of the proximal femur (Smith, 1972); in vertebrae removed postmortem from those with and without collapse fracture (Arnold, 1965); and in the opposite radius of patients with and without colles fracture. Blacks in South Africa have been found to have at least a 10 fold lower incidence of femoral neck fracture than South African whites, yet the bone density in these whites was greater, as determined by measuring cortical thickness (Solomon, 1979). Clearly these data could result from insufficiently sensitive methods or measures not taken at the fracture site, however, a more likely explanation is that bone density is not the sole determinant of fracture risk (Hayes, 1983; Solomon, 1979; Johnston, 1981).

Current clinical methods for measuring bone mineral content are: radiogrammetry, single photon absorptiometry, dual photon absorptiometry, CAT scan, and neutron activation analysis (which actually measures whole body calcium). Single photon absorptiometry, offering 2-4% error with good reproducibility, does not provide information about the axial skeleton, which is

80% trabecular bone and can not be assessed with single photon techniques (Dalen, 1974; Seeman, 1981; Riggs, 1980). The value of CAT scanning for measurement of vertebral bone density has been questioned because of potential inaccuracies caused by interspersed marrow fat in areas of trabecular bone. Dual energy CAT scanning is generally not available, and in general CAT scanning is expensive and associated with a relatively large radiation exposure. Dual photon absorptiometry, which uses a ^{153}Gd source, relies on estimation of the two separate energy levels and subtracts their difference to eliminate soft tissue error providing trabecular (spine) bone mineral content. Error of measurement is 2-4% and reproducibility is 2%, however, the instrumentation is expensive and does deliver low doses of radiation.

Biomechanical research has demonstrated that the elastic properties of bone offer a more effective measure of bone strength than bone mineral content (Abendschein, 1970; Craven, 1973; Greenfield, 1975; Reilly, 1974; Schryver, 1978; Andre, 1981; Pratt, 1981; Carter, 1977; Carter, 1976). Elastic modulus which relates stress to strain in a viscoelastic, anisotropic material, such as bone, is a measure of these elastic properties. Both elastic modulus and the compressive strength of bone are proportional to the strain rate raised to the 0.06 power (Carter, 1977; Carter, 1976). Thus the velocity of ultrasound transmission in bone, which provides a measure of elastic modulus, may determine fracture threshold. The following relationship applies:

$$V_B = \text{Elastic modulus } (E_M) / (P) \text{ density}$$

$$E_M = \text{Elastic modulus of bone}$$

$$P = \text{Bone density}$$

$$V_B = \text{Velocity of sound transmission}$$

As it can be seen the elastic modulus relates directly to the velocity of sound squared.

$$E_M = \sqrt{V_B^2 \times P}$$

Further work has shown a direct relationship between V_B^2 and compressive strength, which for our purposes empirically relates to breaking strength (Pratt, 1981).

Abendschien and Hyatt (1970) have demonstrated a high degree of correlation between the ultrasound transmission velocity and the measurement of mass density, the modulus of elasticity, and the mathematical formulation of the breaking strength of human bone. Their work established that the mechanical modulus, determined by static loading, correlated to ultrasonic velocity ($r = .885$, $p < .001$); that the mechanical modulus correlated to density ($r = .9376$, $p < .0001$); and finally that the mechanical modulus correlated to elastic modulus ($r = .9093$, $p < .001$), showing a high correlation of the velocity of sound transmission in bone to the elastic modulus and ultimate breaking strength.

A reliable non-invasive method for monitoring fracture threshold, in vivo, is of considerable significance to the sportsmedicine practitioner involved in the study and treatment of stress related injuries to bone, as well as to all areas of medicine concerned with bone diseases. More clinical study is necessary to evaluate the role of ultrasound velocity measurement in this area, however, the equipment necessary to conduct such study requires operation by technicians trained in the use of electronic instrumentation for time measurement. Our goal is to develop equipment to make clinical study of ultrasonic velocity measurement more practical.

EQUIPMENT

An industrial quality electronic digital caliper accurate to 0.025mm was used to measure the transmission path distance. The caliper incorporated a push button zeroing function making it unnecessary to read the distance measurement during actual ultrasound transmission. Two 1.25 MHz quartz piezoelectric ultrasound transducers were mounted on the digital caliper for transmission and reception of the ultrasound signal through the bone. Signal generation and amplification of the received signal was accomplished through the use of a broadband ultrasonic pulser/receiver producing large amplitude electrical pulses of one micro second duration. The signal processing portion of the system consisted of an 8 bit analog to digital converter interfaced to an 8 bit micro computer.

The 8 bit resolution of the analog to digital converter allowed the continuous analog signal to be sampled and quantized into a string of 256 binary values. Since the signal presented by the ultrasonic pulser/receiver was both repetitive and periodic and was followed by a trigger point, equivalent time sampling was possible. Equivalent time sampling makes it possible for an analog to digital converter to appear to record information at a higher sampling rate than designed by acquiring only one binary sample after each trigger. Following each subsequent trigger the time between the trigger and the sample point is incremented a precise amount and this will continue until all 256 sample points have been acquired.

Under normal conditions the approximate range for time measurements was determined to be 10-30 microseconds. A time delay was built in so that sampling began at 10 microseconds and with an equivalent time sampling rate of 12.5 MHz the last acquired sample point in a sweep would be 30.48 microseconds. The 12.5 MHz equivalent time sampling rate was acceptable according to the Nyquist criterion (Heyberger, 1983).

Waveform averaging was performed to reduce the signal to noise ratio and software was developed to mathematically determine the time of the first arriving signal to the receiving transducer. Additional features included 5.25 inch floppy disk



Fig. 1. Instrumentation setup for measurement of ultrasonic velocity through bone.

storage of measurement data, velocity, date and clinical comments. Software was also available for statistical analysis and plotting of data and patient histories.

TESTING

A preliminary testing procedure was arranged in which the analog data signal from the ultrasound pulser/receiver was presented simultaneously to both the micro computer signal analysis system and a 15 MHz oscilloscope operated by a trained technician. Each of the 42 different sample sites were analyzed during four separate trials by both systems. Considerably more time and effort was required for the technician-oscilloscope system to recognize and record the point of the first arriving ultrasound signal. Additionally, data gathered using the technician-oscilloscope system had to be at a later time entered into a computer for velocity calculation and data reduction.

Statistical analysis was performed on the range of readings for each site. The micro computer signal analysis system showed an average 40.89% increase in data reproducibility over the technician-oscilloscope system. No tests have yet been performed to determine accuracy of the systems, however, before use the micro computer velocity measurement system was calibrated to velocity measurements made in distilled water.

CONCLUSION

Experimental in vitro studies indicate that an empirical relationship exists between the velocity of sound and fracture threshold of the bone. Clinical study is necessary to fully

evaluate the usefulness of ultrasound velocity measurement for purposes of diagnosis of fracture threshold. The instrumentation presented here is intended to aid such clinical study by simplifying data collection and reduction. Evaluation of the instrumentation is currently underway at a number of institutions involved in research of diseases and stress related injuries of bone.

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