INTRODUCTION

Viscoelastic properties of materials can be measured by analysis of forced oscillations using a dynamic mechanical analyzer (DMA). Dynamic mechanical analyzers have the advantage of measuring viscoelastic properties in a controlled environment non-destructively, by applying very small loads (in the order of Newtons), therefore, making it possible to study very small or soft specimens. DMA has been shown to be a promising tool for studying properties of bone cement [Yang et al., 1999] and cortical bone [Yamashita et al., 2001].

The viscoelastic properties measured by a DMA, typically at a frequency range of 0.1 to 100 Hz, are associated with the amount of elastic energy stored (E1; storage modulus), elastic energy dissipated by viscoelastic mechanisms (E2; loss modulus) and a phase angle between the stress and strain waveforms, indicative of the ratio of lost and stored energy (tan δ, loss factor) [Menard, 1999]. The purpose of this study was i) to measure viscoelastic properties of cancellous bone using DMA and ii) to examine whether parameters measured with DMA can predict mechanical properties of cancellous bone during compressive failure.

METHODS

A bovine tibia was obtained from a local slaughterhouse and a 10 mm thick transverse section was cut at the proximal epiphysis using a diamond blade band saw (EXAKT). Five 8.255 mm diameter cylinders were cored from this section using a coring drill bit (Starlite). Storage modulus, loss modulus and loss factor were measured for a frequency range of 1-10 Hz using a Dynamic Mechanical Analyzer (Perkin Elmer DMA 7e) while the specimens were compressed in the supero-inferior direction under a sinusoidal load waveform with an amplitude of 3N. The specimens were submerged in normal saline at 37 °C during DMA measurements. Any third parameter can be derived from the other two viscoelastic parameters, therefore, we focused on storage modulus and loss factor in the current study.

Following DMA measurements, each specimen was compressed to 5% strain and then unloaded between unlubricated platens under strain control with a strain rate of 1% s^-1 using a servohydraulic testing machine (Instron 8501). Displacements were measured with an extensometer (±5mm range, Instron) attached to the platens. From stress-strain data, apparent stiffness, E, yield and ultimate stress, σy and σu, respectively, residual stress at 5% strain, σr, residual strain, εr, and elastic energy, Ue, yield-to-ultimate energy, U_y, ultimate-to-5% energy (sum of the last three was recorded as total energy), Ure, and the recovered energy, Ur, upon unloading were calculated (Figure 1).

RESULTS

The frequency (f) dependence of storage modulus was in the form of $E1=Af^m$ (Figure 2) whereas tan δ had a linear relationship in all specimens for the range of frequencies examined. The coefficient A and the power exponent m from the E1-frequency relationship and the mean value of tan δ and the slope of tan δ-frequency relationship were analyzed for correlation with the properties from mechanical testing.

The energy absorbed from yield to ultimate stress (Figure 3), and the total energy absorbed to 5% strain significantly increased with increasing power exponent m in the E1-frequency relationship ($r_{adj}=0.89, p<0.02$ and $r_{adj}=0.74, p=0.04$, respectively).

DISCUSSION

A dynamic mechanical analyzer was utilized for the measurement of bovine tibial cancellous bone viscoelastic properties. Viscoelastic parameters measured using the DMA were correlated to mechanical properties measured by conventional mechanical testing. The nature of the frequency dependence of storage modulus and loss factor was consistent between specimens (Figure 2).

Our results (Figure 3) indicate that the energy absorbed by cancellous bone during yield increases with increasing frequency dependence of storage modulus. The ability to predict a post-yield mechanical property from a viscoelastic parameter is important in that post-yield energy absorption can be predicted using non-damaging DMA results. It is possible that dynamic analysis can be extended to in vivo use to predict the post-yield properties of bone.

A greater frequency dependence is indicative of a more viscoelastic material. This is analogous to increased sensitivity of elastic modulus to strain rate suggesting that the post-yield energy absorption is related to the strain-rate sensitivity of the material. The yield region of bone's load-deformation behavior has been characterized by microcracking events [4]. The result that the energy absorption during microcracking events is related to the viscoelastic properties of bone (Figure 3) suggests that the crack tip strain rates associated with microcracking are large enough that strain rate stiffening is a toughening mechanism that slows microcrack growth.

REFERENCES


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