Research paper

Non-destructive characterization of microdamage in cortical bone using low field pulsed NMR

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ABSTRACT

The microcracking and damage accumulation process in human cortical bone was characterized by performing cyclic loading under four-point bending at ambient temperature. A non-destructive nuclear magnetic resonance (NMR) spin–spin (T2) relaxation technique was applied to quantify the apparent changes in bone porosity as a function of cyclic loading and prior damage accumulation, first to unloaded cortical bone to quantify the initial porosity and then to fatigued cortical bone that was subjected to cyclic loading to various levels of modulus degradation and microdamage in the form of microcracks. The NMR T2 relaxation time and amplitude data of the fatigued bone were compared against the undamaged state. The difference in the T2 relaxation time data was taken as a measure of the increase in pore size, bone porosity or microcrack density due to microdamage induced by cyclic loading. A procedure was developed to deduce the number and size distributions of microcracks formed in cortical bone. Serial sectioning of the fatigued bone showed the formation of microcracks along the cement lines or within the interstitial tissue. The results on the evolution of microdamage derived from NMR measurements were verified by independent experimental measurements of microcrack density using histological characterization techniques. The size distribution and population of the microcracks were then utilized in conjunction with an analytical model to predict the degradation of the elastic modulus of cortical bone as a function of damage accumulation.

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1. Introduction

Bone damage has been implicated as a contributing factor governing bone fragility in diseases such as osteoporosis and in repetitive loading injuries such as stress fractures. Bone microdamage occurs naturally (in vivo) (Burr et al., 1997; Frost, 1960; Norman and Wang, 1997). Laboratory experiments, both in vitro and in vivo, where bone is cyclically loaded at physiological levels of stress or strain, have produced microdamage (Burr et al., 1985; Schaffler et al., 1989). Bone microdamage is typically defined as bone matrix failure detectable by light microscopy (Burr et al., 1997) in the form of microcracks. Microcracks have been defined as cracks that can be detected using relatively low magnification (>250×) and are usually of the order of 30–100 µm in length.

Fatigue loading has been shown to affect the mechanical properties of bone. Fatigue loading causes decreases in both bone stiffness, and residual strength (Carter and Hayes, 1977; Hoshaw et al., 1997; Pattin et al., 1996; Schaffler et al., 1989). Not surprisingly, fatigue loading of bone also produces