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Residual stress distribution in rabbit limb bones

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ABSTRACT

The presence of the residual stresses in bone tissue has been noted and the authors have reported that there are residual stresses in bone tissue. The aim of our study is to measure the residual stress distribution in the cortical bone of the extremities of vertebrates and to describe the relationships with the osteon population density. The study used the rabbit limb bones (femur, tibia/fibula, humerus, and radius/ulna) and measured the residual stresses in the bone axial direction at anterior and posterior positions on the cortical surface. The osteons at the sections at the measurement positions were observed by microscopy. As a result, the average stresses at the hindlimb bones and the forelimb bones were 210 and 149 MPa, respectively. In the femur, humerus, and radius/ulna, the residual stresses at the anterior position were larger than those at the posterior position, while in the tibia, the stress at the posterior position was larger than that at the anterior position. Further, in the femur and humerus, the osteon population densities in the anterior positions were larger than those in the posterior positions. In the tibia, the osteon population density in the posterior position was larger than that in the anterior position. Therefore, tensile residual stresses were observed at every measurement position in the rabbit limb bones and the value of residual stress correlated with the osteon population density ($r=0.55$, $P<0.01$).

1. Introduction

Living tissue, like blood vessels, is subject to residual stresses (Fung, 1990). The presence of residual stresses in bone has also been noted (Tadano and Okoshi, 2006). A $\sin^2\psi$ method of X-ray diffraction as the measurement method of the residual stress in bone tissue has been proposed and residual stresses in the bone tissue of bovine femurs have been reported (Yamada and Tadano, 2010). The residual stress is defined as the stress that remains in bone tissue without any external forces. This previous study of bovine femoral diaphyses showed that the residual stresses in the bone axial direction were tensile, and the residual stresses in the bone tissue were discussed as a factor in the tissue strength.

Cortical bone has a hierarchal and composite structure formed by hydroxyapatite (HAp) like mineral particles and collagen matrix. The HAp in bone tissue has a hexagonal crystalline structure, and X-ray diffraction can be used to measure the interplanar spacings of HAp crystals (Fujisaki et al., 2006; Gupta et al., 2006; Almer and Stock, 2007; Fujisaki and Tadano, 2007; Tadano et al., 2008; Giri et al., 2009). When bone tissue deforms, the displacement of the lattice planes of the HAp crystals change almost proportionally. It has been shown that the distance between the lattice planes of the HAp crystals change proportionally to the deformation of the bone tissue (Fujisaki and Tadano, 2007). The HAp crystal strain can be calculated by the deformation of the interplanar spacing compared with a reference state (Fujisaki et al., 2006; Tadano et al., 2008). Based on this, the residual stresses in bone tissue can be measured using the $\sin^2\psi$ method of X-ray diffraction.

In general, residual stress is generated in a material by the indeterminate structure. It is well known that bone is usually replaced by new bone tissue with constructing osteon structures (Currey, 2002; Fung, 1990). Since the new tissue develops under in vivo loadings as the non-deformed state, an indeterminate structure may be generated by the difference of the deformation between the old and new phases. Further, the mechanical properties (e.g. elastic modulus) are also different in these phases (Gibson et al., 2006; Rho et al., 1999). Due to the nonuniform structures in bone tissue, residual stress may remain around the replaced region without any external forces.

The aim of this study is to measure the residual stress distribution in the cortical bone of the extremities of vertebrates and to describe the relationships with the osteon structures and mechanical loadings in vivo. In the experiments, the study used the bones of rabbit extremities and measured the residual stresses in the bone axial direction at anterior and posterior

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