Prediction of Local Elastic Modulus of Bovine Cortical Bone Using Microhardness Testing

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Introduction
Hardness is a reflection of the resistance to penetration by an indenter. Two types of hardness tests are recognized based on the magnitude of the indentation load. Macrohardness testing involves using loads greater than 1 kgf, while microhardness tests use loads less than 1 kgf. Microhardness test of bone permits quantification of the mechanical properties of local variation in the composition of bone. Studies have shown the correlation between microhardness and mineral content [1, 2], and microhardness and elastic modulus on extensive scale [3, 4, 5]. However, only limited information is presently available on relationship between microhardness and local elastic modulus of cortical bone because of the lack of appropriate local elastic modulus measuring technique. The objective of this study was to predict a local elastic modulus (Young’s modulus) of bovine cortical bone utilizing microhardness testing and Scanning Acoustic Microscope (SAM).

Materials and Methods
Ninety cortical bone specimens were obtained from nine bovine femora. Cortical bone specimens from the anterior and posterior mid-diaphysis were transversely sliced into thin layers approximately 1.5 mm thick with a microcutter and polished with a buffing machine. The 5×15×1.5 mm rectangular specimens were cut from the plates under constant water irrigation using a drill as shown in Fig.1. The perpendicular direction of specimen was aligned with the longitudinal axis of bone. The anterior and posterior specimens of bovine femoral cortical bone used here were plexiform and Haversian bone, respectively. These specimens were scanned with a peripheral Quantitative Computed Tomography (pQCT; XCT-960, Norland-Stratec) to estimate the volumetric Bone Mineral Density (BMD).

In the pulse echo mode of the SAM, the time delay is measured from the reflected wave on the top bone surface to the reflected wave on the bottom bone surface as shown in Fig.2. The ultrasonic velocity is equal to twice the thickness of the specimen divided by the time delay.

Figure 1: Schematic representation of bovine femoral cortical bone specimens preparation process.
Figure 2: Schematic diagram of the scanning acoustic microscope.
The cortical bone specimens were nondestructively measured local elastic moduli of specimens using the SAM (Uh3, Olympus). A 50 MHz ultrasonic transducer and lens (V390, Panametrics) of SAM were used to transmit, and receive acoustic waves in pulse echo mode. Delay time between acoustic waves reflected from the bottom of the specimens was measured using a digital oscilloscope (VC-7104, Hitachi). The elastic wave propagation theory predicts relations between the elastic modulus, $E$, bone specimen density, $\rho$, and acoustic velocity $c$, of the following form:

$$E = (1 + \nu)(1 - 2\nu)\rho c^2 / (1 - \nu),$$

where $\nu$ is the Poisson’s ratio.

All the bone specimens were also tested on a Vickers microhardness tester (MVK-H1, Akashi), equipped with a diamond pyramid indenter, using 200 gf (1.96 N), 500 gf (4.9 N) and 1000 gf (9.8 N) applied loads for 30 seconds. Each specimen was indented 10 times, the diagonals of the indents being measured at 400x magnification. The Vickers microhardness number $H_v$ is defined as the applied load divided by the surface area of the indentation and may be expressed as follow:

$$H_v = 0.189F / d^2,$$

where $F$ is applied load in N and $d$ is the average length of two diagonals in mm.

**Results & Discussion**

Figure 3 is an optical micrograph of Vickers microindentation made in one of the bovine femoral cortical bone specimens. It was noted that pilling up of specimen around an indent was not noticeable.

Figure 4 shows the relationship between local elastic modulus (Young’s modulus) $E$ and Vickers microhardness number $H_v$ using 200 gf load. The $H_v$ number of plexiform bone is higher than that of Haversian bone. The elastic modulus of plexiform bone is also higher than that of Haversian bone. The elastic modulus is highly correlated with microhardness, and the relationship is essentially linear.

Figures 5 and 6 show the relationship between elastic modulus and microhardness number using 500 and 1000 gf loads, respectively. Likewise, a correlation also existed between elastic modulus and microhardness of two different loads. Ramarakhiani et al. [6] measured $H_v$ values using 5, 10, 20, 30, 50, 75, 100, 130, 150 gf loads and found that $H_v$ increased with loads to 50 gf, and then became independent of load in subsequent

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**Figure 3**: The optical micrograph of Vickers microindentation in bovine cortical bone.

**Figure 4**: The relationship between elastic modulus and Vickers microhardness number using 200 gf load.

\[ E = 0.4212H_v + 6.7506 \]

\[ r = 0.845 \]
measurements. In this study, loads of 200, 500 and 100 gf are not reveal statistically significant differences in $H_v$ values of bovine cortical bone. Currey and Brear [4] shown that the value of elastic modulus was about 24 GPa at $H_v$=60 from the mammalian mineralized tissue. In our study, the value of elastic modulus is about 32 GPa at $H_v$=60 from the bovine cortical bone. The relationship in plexiform and Haversian bone specimens between volumetric Bone Mineral Density (BMD) and microhardness is shown in Fig. 7, and that between elastic modulus and BMD in Fig. 8. It is clear that there is a good relationship between BMD and each of two variables.

**Figure 5**: The relationship between elastic modulus and Vickers microhardness number using 500 gf load.

**Figure 6**: The relationship between elastic modulus and Vickers microhardness number using 1000 gf load.

**Figure 7**: The relationship between bone mineral density and Vickers microhardness number using 200 gf load.

**Figure 8**: The relationship between bone mineral density and elastic modulus.

**References**

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