Influence with Pressure of the Bone Fluid in Inclination of Osteon

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ABSTRACT

Cortical bone is composed of an osteon, which is a subunit of the cortical bone. At the center of the osteon, Haversian is located and it consists of blood vessels and nerves. Osteon is known to be inclined 5 to 15 degrees with respect to the long axis of a cortical bone, but the reason why it is inclined is not clear. Using the poroelastic calculation provides the pore pressure varies at the lacunar-canalicular network from -200KPa to 200KPa. This estimation is close to the result shown in the previous literature and it helps further cell culture experiment for elucidating the bone remodeling process.

Key Words : Osteon, Bone Fluid, Cortical Bone, Haversian, Lacunar-Canalicular

I. INTRODUCTION

Human is always subjected to the external mechanical loading. As they walk or do exercise, the reaction occurs at the road or other supports. It produces the repetitive loading stimulating the musculoskeletal system. The weight lifting is also subjected to the mechanical loading and these mechanical loading is strong enough to generate the musculoskeletal deformation.

It is noted that the musculoskeletal system is composed of bone, tendon, and ligament. However the word, "bone" mostly represents the musculoskeletal system because bone is stronger than tendon and ligament, working as the supporting structure of human body.

Although bone is a hard tissue, bone cells live in the space in the bone matrix and communicate with adjacent bone cells via tiny tunnels called "canaliculi." One type of bone cells, "osteocytes" are living in the ellipsoidal cavity, called "lacunae", which are connected to the adjacent lacunae by canaliculi. Osteocytes in the lacunar space need nutrients for their survival. Bone fluid is filled within the lacunar-canalicular space for osteocytes' survival.

The repetitive mechanical loading induces bone fluid flow in the canalicular space [1]. As the mechanical loading is induced to the bone matrix, bone is subjected to bending.

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The bending moment generates the pressure gradient from one side of bone to the other. The built-up pressure gradient induces the bone fluid flow.

It is believed that bone fluid flow plays an important role in bone adaptation [2,3]. Bone adaptation is that new bone is formed by the orientation of mechanical loading. However the mechanism of bone adaptation is unclear.

Since bone is a porous material, proelastic models are developed to elucidate the bone fluid flow phenomena as well as bone adaptation [2,3,4]. Pressure gradient is an important parameter to determine the bone fluid flow phenomena. Pressure gradient profile shows the osteocytic cell membrane is faced with the shear stress induced by bone fluid flow.

Another model explaining the bone fluid flow phenomena at the cellular level [5] shows that bone fluid flow deforms the cell membrane and amplifies the hoop strain of the cell membrane. The strain at the tissue level, or at the bone matrix is hundreds smaller than the strain at the osteocytic cell membrane. This model explains the phenomena how bone cells respond to the low amplitude and high frequency mechanical stimulus.

The geometry or orientation of a lacunar space influences the pressure built-up at the lacunar-canalicular space. The orientation of ellipsoidal lacunar space aligned in the longitudinal direction has less pressure built-up than that aligned in the transverse direction because the lacunar space deforms differently.

The Haversian canal located at the center of the osteon, which is a subunit of bone structure, contains the blood vessels and nerves. Blood vessel in the Haversian canal generates a little pressure alteration due to blood flow. However the inclination of Haversian canal may affect the pressure built-up at the lacunar-canalicular space, which inclined 5 to 15 degrees [6]. Thus the pressure distribution around the Haversian canal in the osteon is examined by employing the borehole problem, which is widely used in the old and gas industry [7].

II. METHOD

Cui et al. [7] provides an analytical solution for a circular, infinite long borehole, embedded in a linear and homogenous isotropic poroelastic medium. It is usually used in the old and gas industry, but it may be employed for the bone flow flow in the cortical bone because the cortical bone is also a porous material.

Three governing equations, [a] equilibrium equations, [b] compatibility equations, and [c] diffusion equation, are required for analyzing the pressure built-up in the lacunar-canalicular space.

[a] Equilibrium equations

$$\sigma_{ij,j} = 0 \quad (1)$$

[b] Compatibility equations

$$\nabla^2\sigma_{ij} + \frac{1}{1+\nu}\sigma_{kk,ij} + 2\eta\left(\delta_{ij}\nabla^2 p + \frac{1-\nu}{1+\nu}p_{,ij}\right) = 0 \quad (2)$$

[c] Diffusion equations

$$\nabla^2(\sigma_{kk}+\frac{3}{B}p)=\frac{1}{c}\frac{\partial p}{\partial t} \quad (3)$$

For the analysis, the Cartesian coordinate system x'y'z' is chosen to coincide with the principal axes of the compressive stresses, S_x, S_y, and S_z. The inclined borehole is defined by a local coordinate system xyz with the borehole axis is coincident with the z-axis. Thus x'y' plane is rotated by the angle jz' about the z'-axis, and then by an inclination of a angle jy toward the x-axis.

The boundary conditions at the far field (or $r\rightarrow\infty$), where r is the radial distance from the borehole axis, are

$$\sigma_{xx}=-S_x;\sigma_{yy}=-S_y;\sigma_{zz}=-S_z;\sigma_{xy}=-S_{xy}; \quad (4)$$

$$\sigma_{yz}=-S_{yz};\sigma_{zx}=-S_{zx};p=p_o,$$

where p_o is the original pore pressure. Those at the borehole wall, $r=R$, where R is the borehole radius, surface tractions and pore pressure are to vanish instantly,

$$\sigma_{rr}=-S_r H(-t);\sigma_{r\theta}=-S_{r\theta}H(-t); \quad (5)$$

$$\sigma_{rz}=-S_{rz}H(-t);p=-p_oH(-t),$$

where H is the Heaviside unit step function and $H(-t)=1-H(t)$ such that $H(-t)=1$ for $t\leq 0$, and $H(-t)=0$ for $t>0$. These boundary conditions, Eqs (4) and (5) are decomposed for the boundary conditions for three fundamental problems, [i] a poroelastic plane-strain, [ii] an elastic uni-axial, and [iii] an elastic antiplane shear problem.

[i] The boundary conditions for a poroelastic plane-strain

In the far field (or $r\rightarrow\infty$),

$$\sigma_{xx}=-S_x;\sigma_{yy}=-S_y; \quad (6)$$

$$\sigma_{zz}=-\nu(S_x+S_y)-\alpha(1-2\nu)p_o;$$

$$\sigma_{yz}=-S_{yz};\sigma_{zx}=-S_{zx};p=p_o,$$

At the borehole (or $r=R$),

$$\sigma_{rr}=-S_r H(-t);\sigma_{r\theta}=-S_{r\theta}H(-t); \quad (7)$$

$$\sigma_{rz}=0;\ p=p_oH(-t),$$

[ii] The boundary conditions for an elastic uni-axial

In the far field (or $r\rightarrow\infty$),

$$\sigma_{zz}=-\nu(S_x+S_y)-\alpha(1-2\nu)p_o; \quad (8)$$

$$\sigma_{xx}=\sigma_{yy}=\sigma_{xy}=\sigma_{yx}=\sigma_{xz}=p=0.$$

At the borehole (or r = R),

$$\sigma_{rr}=\sigma_{r\theta}=\sigma_{rz}=p=0. \quad (9)$$

[iii] The boundary conditions for an elastic antiplane shear problem

In the far field (or $r\rightarrow\infty$),

$$\sigma_{xx}=\sigma_{yy}=\sigma_{zz}=\sigma_{xy}=p=0 \quad (10)$$

$$\sigma_{yz}=-S_{yz};\sigma_{xz}=-S_{xz}.$$

At the borehole (or r = R),

$$\sigma_{rr}=\sigma_{r\theta}=p=0;\sigma_{rz}=-S_{rz}H(-t). \quad (11)$$

Note that a in Equations (6) and (8) are Biot effective stress coefficient. After employing three boundary conditions, the solution of inclined borehole problem is given by

$$\sigma_{rr}=-P_o+S_o\cos 2(\theta-\theta_r)+\sigma_{rr}^{(1)}+\sigma_{rr}^{(2)}+\sigma_{rr}^{(3)}, \quad (12)$$

where

$$P_o = \frac{S_x + S_y}{2}, \quad (13)$$

$$S_o = \sqrt{(\frac{S_x + S_y}{2})^2 + S_{xy}^2}.$$

$$\sigma_{\theta\theta} = -P_o - S_o \cos 2(\theta - \theta_r) + \sigma_{\theta\theta}^{(1)} + \sigma_{\theta\theta}^{(2)} + \sigma_{\theta\theta}^{(3)}. \quad (14)$$

$$\sigma_{zz} = \nu[\sigma_{zz} + \sigma_{\theta\theta}] - \alpha(1-2\nu)(p_o + p^{(2)} + p^{(3)}) \quad (15)$$
$$- S_z + [\nu(S_x + S_y) + \alpha(1-2\nu)p_o].$$

For numerical calculation, 1000 microstrain is used for the bone whose elastic modulus is 20 GPa because the normal activity deforms the bone less than 1000 microstrain.

The angle between the borehole axis and the mechanical loading is set to be 15 degrees. Previously it is estimated that 19% of applied stress is transferred to the pressure in the Haversian canals [8].

In this calculation, the pressure alteration due to the osteon inclination is examined, where the poroelastic constants for bone are given by [3] $\nu = 0.32$, $\nu\mu = 0.33$, $B = 0.40$, $\alpha = 0.14$. Fig1 shows an osteon inclined 15 degrees from the long axis of bone.

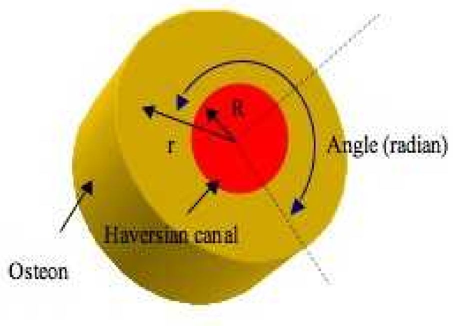

Figure1. The defined angle and location (r/R) are shown in the schematic diagram of an inclined osteon.

III. RESULT AND CONCLUSION

The local pore pressure in the osteon is not uniform because osteons are inclined up to 15 degrees from the long bone axis (Fig2). If the repetitive mechanical loading is a sinusoidal type, the pore pressure profile shows similar patterns as increases the loading time. The pore pressure varies from the 200KPa to -200KPa around the Haversian canal. It means that osteocytes are stimulated by the pressure variation around the Haversian canal.

Similarly Figure 3 shows the pore pressure is increased or decreased as increases the repetitive loading time and the radius of the osteon (r/R). For example, where the location is twice the radius of Haversian canal (r/R=2), the pressure varies from -200 KPa to 200 KPa. Osteocyte far from the Haversian canal faces greater pressure than that near the Haversian canal.

Zhang et al. [8] estimate the pore pressure at the lacunar-canalicular porosity generated at the cement line, which is the most outside of an osteon, is to be 0.27MPa or 270KPa. This estimation is close to our calculation, 200 KPa. However the pressure variation from -200 KPa to 200 KPa at the cement line first appears in this paper and provides an insight in cell culture experiment.

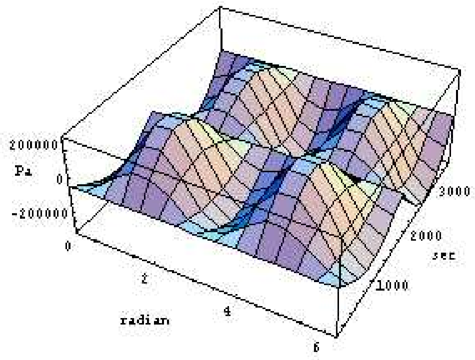

Figure2. Pressure variation against the defined angle (radian) and the loading time (sec)

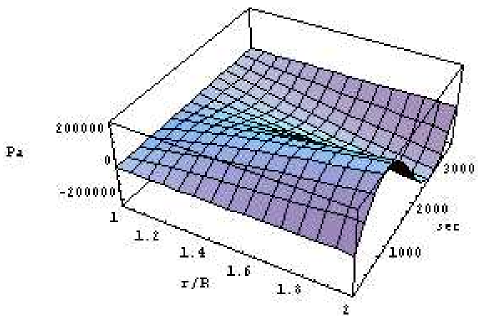

Figure3. Pressure distribution against the defined location (r/R) and the loading time (sec). Pi/4

The continuously applied compressive pressure (CCP) at 1 atm on the growth and differentiation of osteoblast-like cells (MC3T3-E1) increased the production and secretion of prostaglandin E2(PGE2) and suppressed alkaline phosphatase activity. The CCP treatment also suppressed collagen synthesis and calcification [10]. Thus we think that osteocytes near the cement line suppress collagen synthesis and calcification because the osteocytes are derived from the osteoblasts.

In order to elucidate the further phenomena, for example osteocytes to osteocytes communication, a new bone adaptation model is to be developed by combining with the neural network.

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