

COMPARISON OF MECHANICAL QUANTITIES AT SINGLE TRABECULAR LEVEL AS CANDIDATES FOR BONE REMODELING STIMULI

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INTRODUCTION

In computational simulation for trabecular structural adaptation, it is important to quantify the mechanical stimulus that can account for the biological response to the mechanical factors in the remodeling process. An intensity of mechanical quantity has been used as a mechanical stimulus in macroscopic bone remodeling models in which trabecular bone is regarded as a continuum [1]. Recently, the mechanical stimulus has begun to be expressed by integration of the mechanical quantities considering actual biological systems such as networks for intercellular communication [2,3]. The purpose of this study is to clarify the local and integral mechanical quantities at a single trabecular level as candidates for remodeling stimuli, and to discuss the mechanisms of trabecular bone adaptation by remodeling from a mechanical viewpoint.

METHODS

The mechanical quantities on a trabecular surface were evaluated using a digital image-based finite element model of a rat L1 vertebral body under the normal loading state, as shown in Fig. 1. Based on image data obtained by X-ray micro CT, the model was constructed using about 4.6 million elements of which the size was 12.8 μm . The bone was assumed to be a homogeneous and isotropic material with Young's modulus $E = 20 \text{ GPa}$ and Poisson's ratio $\nu = 0.3$. The marrow was regarded as a cavity and neglected in finite element analysis. Compressive loading $f = 10 \text{ N}$ along the axial direction was

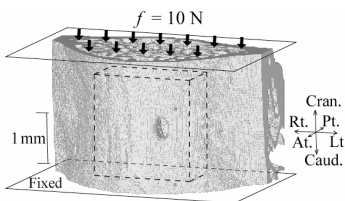


Figure 1. Digital image-based finite element model of a rat vertebral body under compressive loading

applied as a representative daily loading condition. To neglect artificial effects of the boundary condition, simulation results were discussed only for the central hexahedral region of $2 \times 1 \times 2 \text{ mm}^3$ in trabecular bone.

As representative mechanical quantities proposed for trabecular remodeling stimuli, strain energy density (SED) $U [\text{J/m}^3]$ and von Mises equivalent stress $\sigma [\text{MPa}]$ were considered for local mechanical quantities, and SED integration with a decay function and nonuniformity of von Mises equivalent stress for integral mechanical quantities. In SED integration with a decay function [2,4]:

$$P = \sum_{i=1}^n f_i(\mathbf{x}) \mu_i U_i \quad [\text{J/m}^3], \quad (1)$$

the role of osteocytes is considered as mechanosensors. Here, U_i is SED in the location of osteocyte i , μ_i is the mechanosensitivity of osteocyte i , $f_i(\mathbf{x})$ is an exponential decay function between osteocyte i and surface location \mathbf{x} , and n is the number of osteocytes in the neighborhood of the surface location \mathbf{x} . In nonuniformity of equivalent stress [3,5,6]:

$$\Gamma = \ln(\sigma_c / \sigma_d), \quad (2)$$

surface remodeling is assumed to seek a uniform state of the mechanical stimulus. Here, σ_c is stress at point \mathbf{x}_c on the trabecular surface, and σ_d is representative neighbor stress to the point \mathbf{x}_c . The representative neighbor stress σ_d is defined as

$$\sigma_d = \int w(l) \sigma_r dV / \int w(l) dV, \quad (3)$$

where σ_r is the stress at point \mathbf{x}_r , l is the distance between points \mathbf{x}_c and \mathbf{x}_r , dV is the trabecular volume, and $w(l)$ is decreasing function with distance l . The model parameters in the integral formulae were the number of osteocytes $n = 10000 \text{ mm}^{-3}$ in Eq. (1) and characteristic decaying distance $D = 100 \mu\text{m}$ [2] for SED integration P , and the sensing distance $l_l = 200 \mu\text{m}$ [3] for stress nonuniformity Γ .

RESULTS

It was shown that distribution of mechanical quantity in the trabecular bone region was different in the four quantities, as shown in Fig. 2, in which the frequency was defined using trabecular surface area A , normalized by total surface area A^{total} , to the mechanical quantities. The mechanical quantities were SED $U = 0.29 \pm 0.33$ [kJ/m³] (mean \pm s.d.), equivalent stress $\sigma = 2.6 \pm 1.5$ [MPa], SED integration $P = 19 \pm 7$ [kJ/m³], and stress nonuniformity $\Gamma = -0.13 \pm 0.55$. Modes of the mechanical quantities were $U^{mo} = 9.0$ [J/m³] for SED, $\sigma^{mo} = 1.9$ [MPa] for equivalent stress, $P^{mo} = 17$ [kJ/m³] for SED integration, and $\Gamma^{mo} = 0.10$ for stress nonuniformity.

Regarding each mechanical quantity U , σ , P , and Γ as a bone remodeling stimulus S , frequency A/A^{total} to each normalized mechanical stimulus \hat{S} is illustrated in Fig. 3. Normalized stimulus \hat{S} was defined as $\hat{S} = (S - S^{mean})/S^{s.d.}$, where S^{mean} and $S^{s.d.}$ are the mean and standard deviation of stimulus S in the trabecular bone region, respectively. Defining \hat{A}^- as the total surface area for $\hat{S} < \hat{S}^{mo}$ and \hat{A}^+ as that for $\hat{S} > \hat{S}^{mo}$, the ratio of the surface area \hat{A}^- to \hat{A}^+ was $\hat{A}^- : \hat{A}^+ = 4\% : 96\%$ for SED \hat{U} , 36% : 64% for equivalent stress $\hat{\sigma}$, 43% : 57% for SED integration \hat{P} , and 63% : 37% for stress nonuniformity $\hat{\Gamma}$. The difference between surface areas \hat{A}^- and \hat{A}^+ for equivalent stress $\hat{\sigma}$ was smaller than that for strain energy density \hat{U} in the case of local mechanical quantities, and smaller for SED integration \hat{P} than for stress nonuniformity $\hat{\Gamma}$ in the case of integral mechanical quantities. Comparing the local mechanical quantities and integral mechanical quantities, the differences between surface areas \hat{A}^- and \hat{A}^+ for both local quantities \hat{U} and $\hat{\sigma}$ became smaller when those quantities were integrated to \hat{P} and $\hat{\Gamma}$, respectively.

DISCUSSION

The trabecular bone is maintained by well-balanced bone formation/resorption under the remodeling equilibrium state in normal bone. Therefore, it would be a natural assumption that the frequency of the actual mechanical stimulus can be plotted in Fig. 3 with the mode of normalized stimulus $\hat{S}^{mo} = 0$, with a symmetric distribution pattern,

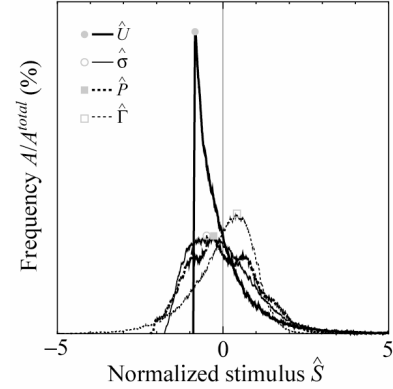


Figure 3. Comparison of distribution of mechanical stimuli

and with no difference between the surface areas \hat{A}^- and \hat{A}^+ ($\hat{A}^- : \hat{A}^+ = 50\% : 50\%$). The result might suggest that equivalent stress is the more likely candidate for the bone remodeling stimulus than SED in the case of local mechanical quantities.

The differences between surface areas \hat{A}^- and \hat{A}^+ for the local mechanical quantities became smaller when these quantities were integrated, indicating that integration of the local mechanical quantity resulted in a more realistic distribution pattern of mechanical stimuli than the local mechanical quantity itself. This result supports that the concept of the integral formulae proposed for the bone remodeling stimulus corresponds not only to the actual biological system but also to the observed phenomenon of trabecular adaptation to the mechanical environment. Comparing SED integration and stress nonuniformity, the difference between surface areas \hat{A}^- and \hat{A}^+ for SED integration was smaller than that for stress nonuniformity. However, stress nonuniformity seems to be a possible candidate for a bone remodeling stimulus because stress nonuniformity was more smoothly distributed than SED integration. One possible hypothesis is that the stress/strain nonuniformity more strongly influences the bone cells in sensing the spatial distribution of mechanical environment than does the mechanical intensity, and that the intensity more strongly influences the time-course changes in a mechanical environment [4,6]. For further investigation, simulation study for the more realistic complicated loading condition is under way for multiple specimens.

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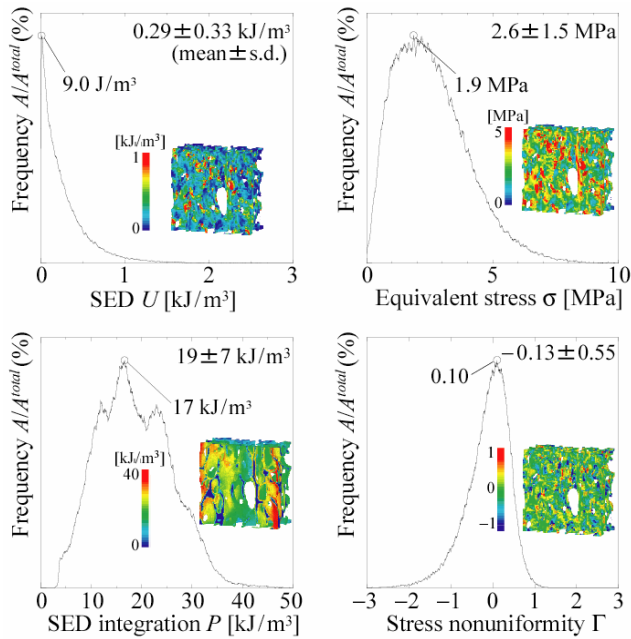


Figure 2. Distribution function of mechanical quantities at single trabecular level