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Predicting time-dependent remodeling of bone around immediately loaded dental implants with different designs

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ABSTRACT

The purpose of this study was to predict time-dependent biomechanics of bone around cylindrical screw dental implants with different macrogeometric designs under simulated immediate loading condition. The remodeling of bone around a parallel-sided and a tapered dental implant of same length was studied under 100 N oblique load by implementing the *Stanford theory* into three-dimensional finite element models. The results of the analyses were examined in five time intervals consisting loading immediately after implant placement, and after 1, 2, 3 and 4 weeks following implantation. Maximum principal stress, minimum principal stress, and strain energy density in peri-implant bone and displacement in *x*-(implant lateral direction with a projection of the oblique force) and *y*-(implant longitudinal direction) axes of the implant were evaluated. The highest value of the maximum and minimum principal stresses around both implants increased in cortical bone and decreased in trabecular bone. The maximum and minimum principal stresses in cortical bone were higher around the tapered cylindrical implant, but stresses in the trabecular bone were higher around the parallel-sided cylindrical implant. Strain energy density around both implants increased in cortical bone, slightly decreased in trabecular bone, and higher values were obtained for the parallel-sided cylindrical implant. Displacement values slightly decreased in time in *x*-axis, and an initial decrease followed by a slight increase was observed in the *y*-axis. Bone responded differently in remodeling for the two implant designs under immediate loading, where the cortical bone carried the highest load. Application of oblique loading resulted in increase of stiffness in the peri-implant bone.

1. Introduction

Bone is an extremely complex tissue that changes its form, mass and internal structure under load upon a cascade of re/modeling processes ruled by a physiological control system [1,2]. While the process of mechanically mediated bone adaptation to stimuli that deviate from the homeostatic level could be studied by in vivo experiments, another valid approach is to use computer simulations based on implementation of remodeling theories. Current bone remodeling theories differentiate between external modeling, relating to apposition and resorption of bone at the periosteal and endosteal surfaces, and internal modeling, which depends on time-dependent changes in apparent bone density. There are two isotropic bone adaptation remodeling hypotheses dedicated to predict changes in bone shape and density based on mechanical stimuli like strain, stress or strain energy density in accordance with the "Wolff's Law" [3]. In these models, strain energy density is used as a feed-back control variable for functional adaptation of bone, whereby homeostatic strain energy density distribution is assumed as the remodeling objective. The first approach under the direction of Huiskes [4–6] assumes that, the variation of the elastic modulus is proportional to the difference between the actual strain energy density and a referential strain energy density. The second hypothesis, proposed by Carter and Beaupre [7–9] establishes as stimulus a certain effective stress, being the apparent density related to this effective stress. Both theories allow the combined formulation of external and internal adaptation and the outcomes are very similar, being almost indistinguishable in internal remodeling. These theories have been basically originated from the long-bone community and have proven success in remodeling driven orthopedic design. There are few studies available in the literature to predict dental bone remodeling using finite element method [10–15]. All those previous studies are based on algorithms that actually originated from the long-bone community. Although there is no dental

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implant induced remodeling theory, the study of Reina et al. [14] and Li et al. [15] show that the prediction of bone remodeling for mandible bone by using long-bone remodeling can have significant consistency with clinical studies.

Recently, the increasing clinical applications of immediate loading of dental implants to support removable and fixed prostheses [16,17] stimulated the need to unravel the time-dependent mechanobiology of bone around such implants [10,11]. It is often pronounced that good primary stability and low micromovement of implant in bone are the most critical elements cultivating a safe mechanical environment for uneventful healing [18]. This becomes even more crucial for single-tooth replacements, because immediate loading of single-tooth implants is not recommended as a routine clinical approach. Therefore, additional insights into complex biomechanical mechanism of time-dependent skeletal tissue differentiation around immediately loaded single-tooth implants are needed for correct clinical interpretations. In this regard, application of bone remodeling theories to dental implants could be considered as a useful tool to predict these changes [13,19]. The purpose of this study was, therefore, to predict the time-dependent changes in cortical and trabecular bone around immediately loaded implants with different macrogeometric designs by application of the *Stanford theory* [8].

2. Materials and methods

2.1. Application of the Stanford theory

For the remodeling of bone around implants, the theory of Beaupre and Carter [8], so-called *the Stanford theory*, is selected as the mathematical model. The theory is based on a daily stress stimulus which is defined by

$$\psi_b = \left(\sum_i n_i \sigma_i^m\right)^{1/m} \tag{1}$$

where n_i is the number of cycles of load type i which is assumed to be 1 in this study, and σ_i is a continuum level effective stress defined as

$$\sigma = (2EU)^{1/2} \tag{2}$$

where E is the continuum elastic modulus and U is the continuum strain energy density. The level of the daily stress stimulus ψ_b determines the bone remodeling process. Under normal loading conditions daily stress stimulus ψ_b remains in a determined range and bone remodeling does not occur. This range is named as "lazy" or "dead" zone by Carter et al. [7].

The mathematical expression of the apposition-resorption rate of the bone by considering this "dead" zone is modeled as

$$\dot{r} = \begin{cases} c(\psi_b - \psi_{bas}) + cw & (\psi_b - \psi_{bas}) < -w \\ 0 & -w \le (\psi_b - \psi_{bas}) \le +w \\ c(\psi_b - \psi_{bas}) - cw & (\psi_b - \psi_{bas}) > +w \end{cases} \tag{3}$$

where $\dot{r}$ is the apposition-resorption rate (μm/day), ψ_b is the daily tissue level stress stimulus (Eq. (1)), ψ_{bas} is the attractor state stress stimulus (the level of daily stress stimulus in which bone mass change does not occur), c is an empirical rate constant and w is the half-width of the central, normal activity region (dead zone).

The attractor stress stimulus ψ_{bas} is determined from the graph of cyclic energy stress magnitude and equivalent cyclic normal strain magnitude versus the number of cycles per day, as reported by Beaupre et al. [9]. The number of daily load cycles used in the present study was 2778. Equivalent cyclic normal strain value was 225 $\mu\varepsilon$ and obtained from strain-gauge analysis of a buccal marginal cortical bone of natural maxillary canines of human cadavers [20]. Assuming the empirical constant, m, to be equal to 4, attractor state stress stimulus of 23 MPa/day were selected for 100 N loading [9]. The numerical value of c is assumed to be 0.02 (μm/day)/(MPa/day) while the value of w is assumed to be equal to the 10% of the attractor stress stimulus which is 2.3 [9]. The initial elastic modulus for cortical and trabecular bone were 15 GPa and 1 GPa, respectively and Poisson's ratio was 0.3 for both [21]. Dental implant was titanium with an elastic modulus of 110 GPa and a Poisson's ratio of 0.35 [12].

After determining apposition-resorption rate (μm/day), the new density of the bone can be calculated as follows:

$$\rho = \dot{r} S_v \rho_t \Delta_t + \rho_o \tag{4}$$

where ρ_o is the density of the bone in previous stage which is for the first step after osseointegration for cortical bone equals to the 1.5818 g/cm^3 and 0.6414 g/cm^3 for trabecular bone, S_v is the bone surface area per unit tissue volume and ρ_t is the true density of the bone tissue (which is assumed to be equal to the density of fully mineralized tissue). The constants S_v and ρ_t are selected to be 4 μm^{-1} and 1.58 g/cm^3 as in Beaupre et al. [9].

The density (apparent density) of the bone can be related to the elastic modulus of the bone through the equation from Weinans et al. [6]:

$$E = 3790\rho^3 \tag{5}$$

The equation above is used for both cortical and trabecular bone, as the bone remodeling takes place on bone surfaces of marrow spaces/voids in cancellous bone and haversian canals in cortical bone [8]. In Eq. (5), the density is in g/cm^3, the elastic modulus is in MPa, and the corresponding constant (3790) has the unit 10^3 m^2/s^2. Using the above relation, the new elastic modulus can be calculated for each step. The new elastic modulus is used for the next simulation of bone–implant structure under the load. The number of iterations for the time periods is estimated using the convergence criteria of the change in apparent density for every element to be less than 0.02 g/cm^3 to achieve a homeostatic state similar to Beaupre et al. [9]. In this sense, the material properties of bone were updated (i.e., remodeled) considering the results of the previous analysis by the program, *Remodel*, developed by the authors [13].

2.2. The computer program: Remodel

The computer program *Remodel* was run after the completion of the first finite element analysis of the bone–implant structure under load, using MSC.Marc (MSC.Marc-Mentat 2005, MSC. Software Corporation, Los Angeles, CA) with constant elastic moduli for cortical and trabecular bone. *Remodel* reads the input file of the finite element analysis, which contains information about the geometry, boundary conditions, the *initial* material properties and output file generated by the finite element analysis code MSC.Marc that contains the calculated parameters like stresses, strains, and strain energy densities at various finite numbers of locations within the geometry due to applied load. Using the calculated continuum strain energy density, U (available in the output file) and the corresponding elastic modulus E (available in the input file), the continuum level effective stress, σ_i, can be calculated for every bone finite element by using Eq. (2). After achieving effective stress σ_i where $i = 1$ for one load type, the daily stress stimulus ψ_b is calculated by *Remodel* by using Eq. (1) with the referenced values of $m = 4$ and $n = 2778$. In the next step, the program calculates the apposition-resorption rate, $\dot{r}$, for every element using the values of daily stress stimulus ψ_b from the previous step and by the referenced values of $c = 0.02$ (μm/day)/(MPa/day) and $w = 2.3$ MPa using Eq. (3). *Remodel* uses the value of $\dot{r}$ in Eq. (4) to calculate the