

Motivation

- Clinical, histological and histomorphometric evaluations have shown insightful indications of bone response to dental implants. These studies usually involve in vivo experiments and the establishment of results is time-consuming.
- FEA has been used on many occasions to study the bone strength along with the presence of dental implant. In most of models, bone quality has been assumed to be "static." According to Wolff's law¹, bone undergoes a dynamic remodeling process as a result of physical loading.
- Mathematical models developed to study the phenomenon of bone adaptation to functional loading have shown promising prediction in the long bone community. In addition, same concept has been adopted to simulate the bone structure of the acetabulum, proximal tibia, metacarpal and calcaneus.²
- A mathematical model considering how the bone would possibly remodel around a dental implant would potentially reduce the need for in vivo experiments, and could reveal the effects of mechanotransduction in osseointegration of dental implants.

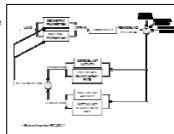
Objective

- The goal of this work is to provide a computational tool to predict bone remodeling around dental implant systems due to direct occlusion. This work will eventually lead to design of optimal implant shapes, sizes and materials.
- A recent histomorphometric study indicates significant bone remodeling is confined to the first millimeter from the implant surface, and that this activity decreases as a function of distance away from the implant surface.³ Such a suggestion leads to this study that attempts to implement a computational algorithm of bone remodeling only near the close proximity of implant surface.
- In the **first phase** of this study a comparative evaluation of stress/strain distributions due to a natural tooth, and short/long implant systems is made.
- In the **second phase** bone remodeling around various dental implant systems due to direct occlusion are investigated.

Mechanical bone adaptability

- Wolff's Law can be summarized as follows:
 - Bone in the body is designed to optimize strength with respect to weight.
 - Trabeculae are aligned with the principle stress directions.
 - Bone cells are capable of adjusting the bone in response to mechanical loading.

- Frost⁴ proposed mechanostat hypothesis that different bone response can be triggered as the strain thresholds are reached.



- A possible control mechanism embedded in bone to regulate bone remodeling can be illustrated⁵ as:

Mathematical model of bone remodeling

- The fundamental assumption of Huiskes and Weinans' bone remodeling theory is that each sensor in the bone strives to bring its remodeling stimulus (S) to the preset value of the reference stimulus (K).⁶

- The theory is given in terms of rate of change of bone mass density (ρ):

$$A_r[S - K(1+s)]^p \quad \text{if } S \geq K(1+s) \quad (1a)$$

$$\frac{d\rho}{dt} = 0 \quad \text{if } K(1-s) \leq S \leq K(1+s) \quad (1b)$$

$$-A_r[S - K(1-s)]^p \quad \text{if } S \leq K(1-s) \quad (1c)$$

where A is a constant, t is time and s is the width of dead zone.

- Eqn (1) is solved by forward Euler time-integration. For convenience, $A\Delta t$ can be treated as one term, as a time integration parameter. The density change per time step Δt can be found from:

$$\rho_n = \rho_{n-1} + A\Delta t[S_{n-1} - K(1+s)]^p \quad \text{if } S_{n-1} \geq K(1+s) \quad (2a)$$

$$\rho_n = \rho_{n-1} + A\Delta t[S_{n-1} - K(1-s)]^p \quad \text{if } S_{n-1} \leq K(1-s) \quad (2b)$$

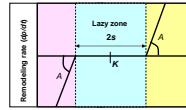
where m is the time iteration level.

- Remodeling stimulus S is strain energy per unit mass

$$S(x,t) = SED(x,t) / \rho(x,t) \quad (3)$$

is a function of time and location; and it is calculated at each mesh point.

- Bone remodeling is represented graphically as shown



- The apparent bone density is related to its elastic modulus according to:

$$E = C \rho^m \quad (4)$$

- Here, elastic modulus (E) is expressed in GPa. C is an experimentally determined constant which is found to be $C = 3.79$.

Remodeling parameters

- Chosen after extensive numerical tests:
 - Time integration constant : $A \Delta t = 1e-11$
 - Homeostatic stimulus : $K = 250$
 - Width of lazy zone : $s = 0.65$

Materials and methods

- Bone remodeling theory of Huiskes et al.³ is used and this iterative problem is solved by a text based command language, APDL programming language, embedded in commercial FE package, ANSYS 11.0.

- Four short implants including cylinder, truncated cone and two threaded implants with contours similar to commercially available ones were investigated as well as one long implant and the natural tooth.

- A buccal-lingual bone contour is obtained from a CT scan of the mandible by using Mimics 11. This contour is extruded to obtain a representative bone volume.

- Solid92 element is a 3D 10-node tetrahedral solid element with a quadratic displacement behavior and well suited to model irregular meshes.

- High mesh density is applied at region of interest (remodeling region) and approximately 135000 elements are used in each case.

- 100 N occlusal load is applied at 11° with respect to the axis of the tooth.

- All materials are assumed to be linear, homogenous and isotropic.

Material	Elastic Modulus (E)	Poisson's ratio (ν)
Trabecular Bone	2 GPa	0.3
Cortical Bone	13.7 GPa	0.3
Tooth	90 GPa	0.3
Abutment and Implant	113.8 GPa	0.34



- Initially, the implant and the bone are assumed to be perfectly bonded.

Results

von Mises Strain (and stress)

- The comparative evaluation of the strain (and stress) field around a natural tooth and a short dental implant show that the stress/strain distributions in region away from the root or implant are very similar to one another.

- The strain (and stress) patterns inside the bone are substantially altered by the placement of a long implant.

- The magnitude of the strain on the bone implant interface seems to be reduced by a long implant.

Elastic modulus/Bone density

- In the case of short implant systems, dense bone develops from the edge of the implant apex and the amount of the development varies from the implant geometry.

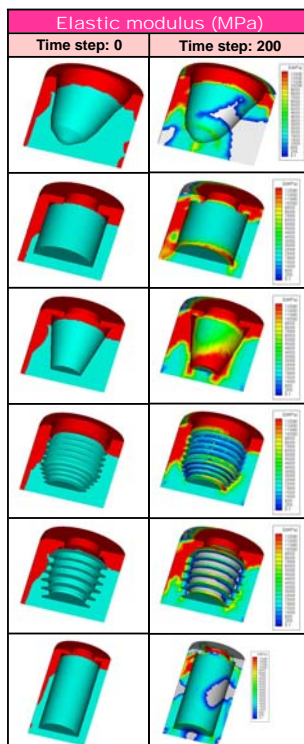
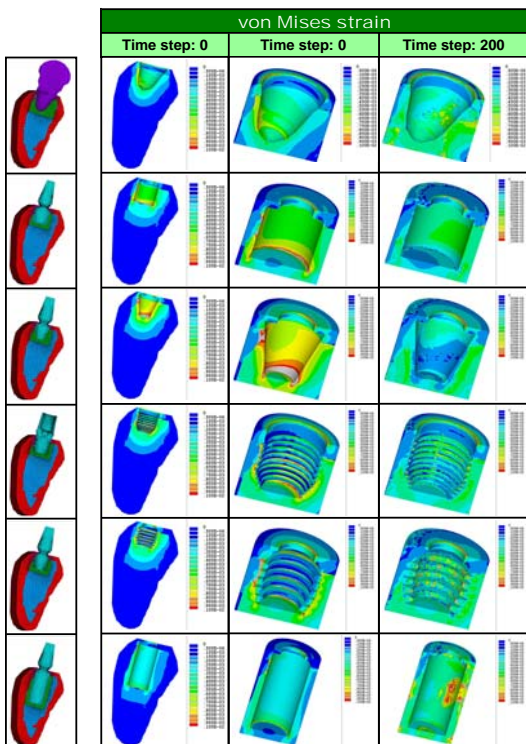
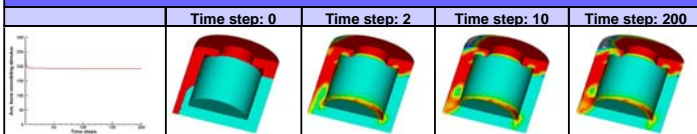
- Under current loading condition, 100N occlusion, thread design only favors the bone deposition at the tips close to apex, but loss of bone mass occurs within grooves.

- Around the implant collar, short implants are capable of maintaining quality bone regardless the diameter of post used in the system; however, serious bone resorption is predicted around the collar region of long implant.

- More bone loss is predicted on the bone-implant interface of long implant than short implant except the bone inside the grooves of threaded implant systems.

- Similar to our previous 2D prediction, bone resorption takes place at the implant apex of lone implant.⁴

Transient results



Discussion

Stress/strain analysis

- When a short implant is placed with its position and orientation close to the root of natural tooth, stress and strain field of the bone altered by implant design is limited to the close proximity of the implant surface. This characteristic could have positive implication on the overall bone health.

- The bone adaptation simply states that bone undergoes a process of structural optimization in order to adapt to changes of mechanical environment. According to our stress/strain analysis, one can argue that bone remodeling due to the direct effects of occlusion is confined to a close proximity of the implant and the tooth.

- Bone loss along the bone-implant interface can be attributed to the effect of stress/strain shielding, which possibly result in the lack of remodeling stimulus inside the grooves of threaded implants and along the surface of long implant.

Bone remodeling convergence

- Based on the bone adaptation theory, bone will not stop remodeling until equilibrium state is reached. In this study, the number of total iterations is set to be 200 as a result of expensive computational time.

- The validity of the equilibrium (200th iteration) result is verified by the transient study that shows there is no significant change after 10th iteration. In addition, the average bone remodeling stimulus illustrates good a convergence trend.

Site specific response

- Different mechanobiologic responses can be expected due to various local chemical environment and cellular activities.² In this regard, different remodeling rates should be applied to better describe the evolution of different bone site.

- Histologic observations show cell activities are vigorous close to bone implant interface and this implies high remodeling rate is suitable for this region. The choice of 1 mm distance from implant surface as the region of interest is a start point to represent this phenomenon and this should be studied closely with histologic and histomorphologic evaluations.

- Dramatic resorption around tooth can be attributed to this concern that a remodeling mechanism favors bone implant interface may not be suitable to bone tooth interface, since the biologic and chemical effects are various for these two interfaces.²

Development of remodeling algorithm

- Clinical studies have shown marginal bone loss is associated with occlusal overloading which is not considered here. Nevertheless no pathologic stress/strain is predicted due to direct occlusion applied in this study.

- Although current algorithm can predict the bone remodeling induced by normal occlusion, an algorithm including overloading resorption should be developed to account for more complicated mastication⁷, extreme loading caused by bruxism, or to study a bone model with initially poor quality.

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