Cortical Bone Remodeling Due to Implants by Finite Element Analysis

Hsuan-Yu Chou and Sinan Müftü
Northeastern University, Department of Mechanical Engineering, Boston, MA

Poster No: 543
Corresponding Author:
Professor Sinan Müftü, Ph.D.
Department of Mechanical Engineering
Northeastern University
334 SN, Boston, MA, 02115
Email: s.muftu@neu.edu, Phone: 617-373-4743

Objective

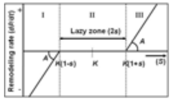
- The goal of this work is to provide a computational tool to predict bone remodeling around dental implant systems due to direct occlusion. This work will eventually lead to design of optimal implant shapes, sizes and materials.
- Significant bone remodeling is observed near the bone implant interface, and such activity decreases away from the implant surface.[1] In this regard, we hypothesize:
  - Attractor stimulus is a localized variable and can be obtained from a model consisting of the natural tooth prior to implantation.
  - A virtual bone graft after implant placement is needed and the attractor stimulus of bone graft has significant influence on predictions.

Background & 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 often been used to study the bone strength in dental implant treatment scenarios. In most of these models, bone quality has been assumed to be "static." On the other hand, according to Wolff's law[2], 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. However, application of such models to implant dentistry is still limited.[3-5]
- A mathematical model considering how the bone would possibly remodel around a dental implant would potentially reduce the need for in vivo experiments

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 ***attractor stimulus*** (*K*).[7]
- Bone remodeling is represented graphically as shown



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

$$\frac{d\rho}{dt}=\begin{cases} A[S-K(1+s)]^2 & S\geq K(1+s) \quad \text{(1a)}\\ 0 \quad , & K(1+s)>S>K(1-s) \quad \text{(1b)}\\ A[S-K(1-s)]^3 & K(1-s)\geq S \quad \text{(1c)}\end{cases}$$

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

Mathematical model of bone remodeling

- Eq. (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 $A\Delta t$ can be found from:

$$\rho^{(new)}=\begin{cases} \rho^{(old)}+A\Delta t\left[S^{(old)}-K(1+s)\right]^2 & S^{(old)}\geq K(1+s) \quad \text{(2a)}\\ 0 \quad , & K(1+s)>S^{(old)}>K(1-s) \quad \text{(2b)}\\ \rho^{(old)}+A\Delta t\left[S^{(old)}-K(1-s)\right]^3 & K(1-s)\geq S^{(old)} \quad \text{(2c)}\end{cases}$$

- Remodeling stimulus *S* is strain energy per unit mass

$$S=\frac{SED}{\rho} \quad (3)$$

is a function of time and location; and it is calculated at each mesh point.
- The apparent bone density is related to its elastic modulus according to8:

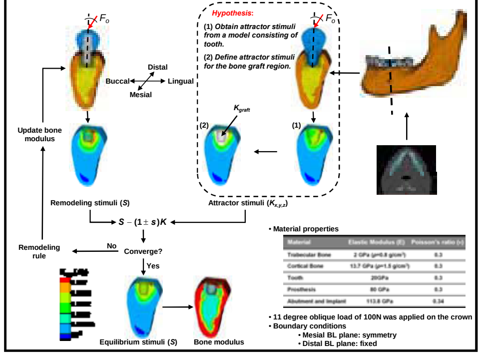
$$E=C\rho^3 \quad (4)$$

- 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
  1. Time integration constant : $A\ \Delta t$ = 1x10-11
  2. Width of lazy zone : s = 0.75

Flow chart of remodeling algorithm

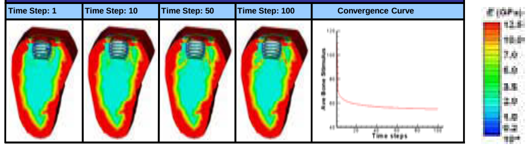


- Material properties

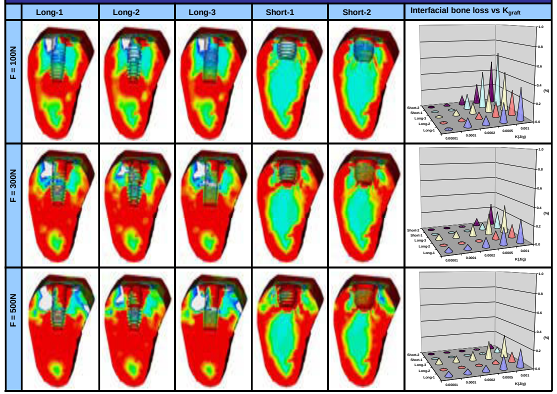
Material	Elastic Modulus (E)	Poisson's ratio (ν)
Trabecular Bone	2 GPa (ρ=0.8 g/cm³)	0.3
Cortical Bone	13.7 GPa (ρ=1.5 g/cm³)	0.3
Tooth	20GPa	0.3
Prosthesis	80 GPa	0.3
Abutment and Implant	113.8 GPa	0.34

- 11 degree oblique load of 100N was applied on the crown
- Boundary conditions
  - Mesial BL plane: symmetry
  - Distal BL plane: fixed

Transient results



Effects of implant designs (K_{graft}=0.0005 J/g)



Histologic studies reported in literature

- Osseointegration of a bar connected titanium plasma-sprayed screw after 12 years of function in human.[9]
- Osseointegration of sandblasted and acid-etched titanium implants after 15 months (12 months loaded) in the canine mandible.[9]
- Osseointegration of an unloaded titanium implant after 6 months in the monkey mandible.[10]
- Osseointegration of a titanium implant after 27 months (18 months loaded) in the monkey mandible.[11]

Results and Discussion

Clinical significance of the findings

- Significant peri-implant bone remodeling is predicted as a result of dental implantation.
- The effect of implant on bone remodeling decreases gradually away from implant.
- The implant size has a significant influence on the remodeling.

Long implants
  - Significantly change bone density distribution with respect to natural tooth, especially near the implant apex
  - Cortical bone loss on the buccal side is predicted

Short & wide implants
  - Peri implant bone density is similar to that of a natural tooth
  - Bone loss is predicted to occur between the threads.

- The degree of interfacial bone loss (BIC) depends on
  1. Implant size and shape: Interfacial bone loss of short implant is more sensitive to occlusal load than that of long implants.
  2. External load: Reduced bone loss is predicted as the magnitude of occlusion increases
  3. K_{graft}: More bone loss is predicted as the K_{graft} increases.
- The predicted bone loss could be correlated to the bone-implant-contact reported in histologic studies.
- The inherent bone density distribution, where the inner trabecular bone is surrounded by a cortical layer is maintained without considering the effect of the general loading on the jaw.
- The lack of global loading on jaw results in less stimulation in bone. This could possibly generate additional remodeling error and cause significant bone densification near the apex of long implants.

Computational convergence

- In this study, the number of total iterations is set to be 100 as a result of expensive computational time.
- The validity of the equilibrium (100th iteration) result is verified by the transient study that shows there is no significant change after 50th iteration.
- The average bone remodeling stimulus illustrates a good convergence trend.

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