Cortical Bone Remodeling Due to Implants by Finite Element Analysis

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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. In this regard, we hypothesized:
  - Attractor stimulus is a localized variable and can be obtained from a model consisting of the natural tooth prior to implantation.
  - A virtual graft after implant placement is needed and the attractor stimulus of bone graft has significant influence on predictions.

Mathematical model of bone remodeling
- Eq. (1) is solved by forward Euler time-integration. For convenience, Adt can be treated as one term, as a time integration parameter. The density change per time step Adt can be found from:
  \[ \rho = \begin{cases} 
  0 & S < K_s + \Delta S, \\
  \left[S^1 \Delta t - K_s \Delta S \right] & K_s + \Delta S \leq S < K_b + \Delta S, \\
  \left[K_b + \Delta S \right] & S \geq K_b + \Delta S.
\end{cases} \] (24)
- Remodeling stimulus \( S \) is strain energy per unit mass
  \[ S = \int_{V} \sigma \cdot \varepsilon \, dV \]

Remodeling parameters
- Chosen after extensive numerical tests
  1. Time integration constant \( A \Delta t = 1 \times 10^{-11} \)
  2. Width of lazy zone \( \alpha = 6.75 \)

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, 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 promises in the long bone community. However, application of such models to implant dentistry is still limited. 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 Hilgers and Weisgerber's bone remodeling theory is that each sensor in the bone stress to bring its remodeling stimulus (2) to the present value of the attractor stimulus (3).
- Bone remodeling is represented graphically as shown:

\[ \frac{dS}{dt} = \begin{cases} 
  0 & S < K_s + \Delta S, \\
  (S - K_s - \Delta S) / A & K_s + \Delta S \leq S < K_b + \Delta S, \\
  (K_b - S) / A & S \geq K_b + \Delta S.
\end{cases} \] (26)

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where \( A \) is a constant, \( t \) is time and \( \alpha \) is the width of dead zone.

Equations of constants
- Eq. (2) is solved by forward Euler time-integration. For convenience, Adt can be treated as one term, as a time integration parameter. The density change per time step Adt can be found from:
  \[ \rho = \begin{cases} 
  0 & S < K_s + \Delta S, \\
  \left[S^1 \Delta t - K_s \Delta S \right] & K_s + \Delta S \leq S < K_b + \Delta S, \\
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Flow chart of remodeling algorithm

Transient results

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

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

- Long implants: More bone loss is predicted as the occlusion increases.
- Cortical bone loss on the buccal side is predicted significant bone densification near the apex of long implants.

Histologic studies reported in literature

Conclusions of histological and histomorphometric analyses
- The degree of interfacial bone loss (BIC) depends on the implant size and shape. Interfacial bone loss of short implant is more sensitive to occlusal load than that of long implants.
- Reduced bone loss is predicted in the magnitude of the interfacial bone loss is reduced as the implant size is increased.
- More bone loss is predicted as the graft density increases.
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Computations 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.

References


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