Journal of Biomechanics 46 (2013) 871–878

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Simulation of peri-implant bone healing due to immediate loading in dental implant treatments

Hsuan-Yu Chou, Sinan Müftü *

Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA 02115, United States

ARTICLE INFO

Article history:
Accepted 21 December 2012

Keywords:
Dental implants
Tissue differentiation
Fracture healing
Immediate loading

ABSTRACT

The goal of this work was to investigate the role of immediate loading on the peri-implant bone healing in dental implant treatments. A mechano-regulatory tissue differentiation model that takes into account the stimuli through the solid and the fluid components of the healing tissue, and the diffusion of pluripotent stem cells into the healing callus was used. A two-dimensional axisymmetric model consisting of a dental implant, the healing callus tissue and the host bone tissue was constructed for the finite element analysis. Poroelastic material properties were assigned to the healing callus and the bone tissue. The effects of micro-motion, healing callus size, and implant thread design on the length of the bone-to-implant contact (BIC) and the bone volume (BV) formed in the healing callus were investigated. In general, the analysis predicted formation of a continuous layer of soft tissue along the faces of the implant which are parallel to the loading direction. This was predicted to be correlated with the high levels of distortional strain transferred through the solid component of the stimulus. It was also predicted that the external threads on the implant, redistribute the interfacial load, thus help reduce the high distortional stimulus and also help the cells to differentiate to bone tissue. In addition, the region underneath the implant apex was predicted to experience high fluid stimulus that results in the development of soft tissue. The relationship between the variables considered in this study and the outcome measures, BV and BIC, was found to be highly nonlinear. A three-way analysis of variance (ANOVA) of the results was conducted and it showed that micro-motion presents the largest hindrance to bone formation during healing.

1. Introduction

The two-stage dental implant placement protocol introduced by Brånemark (1983) requires dental implants to remain submerged and unloaded during a healing period of three to six months. A second stage surgery is necessary to uncover the dental implants before attaching the prostheses. On the other hand, the immediate loading protocol in which the restoration is performed at the time of implant surgery, considerably shortens the treatment duration and reduces the number of operations (Misch et al., 2004). Clinical studies have documented satisfactory survival rate of immediately loaded implants (Chiapasco et al., 1997; Testori et al., 2004). However, it is also indicated that the failure rate is relatively high when the conditions of recipient site are compromised (Lekholm, 2003), when the implant is placed in a high loading region, such as a molar site (Romanos and Nentwig, 2006), and when a single implant is used instead of splinted implants (Malo et al., 2003).

A successful dental implant treatment relies on maintaining the stability of the implant within the host bone site. This condition is achieved through osseointegration, which consists of healing and remodeling phases (Brånemark, 1983). The bone trauma caused by the implant placement surgery triggers the bone healing process (Davies, 2003). Tissue regeneration involves a reparative phase, where mesenchymal stem cells differentiate into different progenitor cells, and result in the development of different skeletal tissues such as fibrous tissue, cartilage tissue, and bone tissue (Prendergast and van der Meulen, 2001). During the peri-implant bone healing, osteoprogenitor cells derived from bone marrow and endosteal bone surfaces migrate to the healing callus. They proliferate and differentiate into osteoblasts, which then begin to lay down new bone on the existing bone surface, or on the implant surface (Davies, 2003). Random and unorganized woven bone forms as a scaffold to bridge the gap at a relatively rapid rate (Schenk and Buser, 1998). The loading condition should be well controlled throughout the process for successful bone formation. Otherwise, soft tissue develops and provides minimal mechanical stability. This can lead to implant loosening, which is recognized as a common symptom of implant failure (Huiskes et al., 1987).

* Corresponding author. Tel.: +1 617 373 4743; fax: +1 617 373 2921.
E-mail addresses: smuftu@coe.neu.edu, s.muftu@neu.edu (S. Müftü).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2012.12.023

The biological processes in the bone implant interface have been revealed by extensive experimental studies. Nevertheless, numerical simulations can provide a detailed window into the complex phenomenon taking place in the bone-implant interface and help the interpretation and explanation of the underlying mechanisms. Most of the previous work focused on investigating the effects of biomechanical factors on the mechanical state around a dental implant including implant and abutment designs, bone morphology and loading conditions (Bozkaya et al., 2004; Chou et al., 2010; Faegh and Müftü, 2010). Others evaluated long term peri-implant bone evolution in response to mechanical loading by incorporating a bone remodeling algorithm into the computer simulations (Chou et al. 2008, 2012; Crupi et al. 2004; Li et al., 2007; 2012; Lin et al., 2009). Only a few studies simulated the bone healing around dental implants (Ambard and Swider, 2006; Amor et al., 2009; Moreo et al., 2009; Vanegas-Acosta et al., 2011). These studies evaluated peri-implant healing from the point of view that tissue regeneration is a complex biological process involving a cascade of coordinated cellular events and the interaction of biochemical compounds (Bailon-Plaza and van der Meulen, 2001) without considering the influence of functional loads on bone healing. In order to investigate the effect of immediate loading on the peri-implant bone healing, the mechano-regulatory tissue differentiation model proposed by Huiskes et al. (1997) and Prendergast et al. (1997) is adopted in this study.

2. Materials and methods

Biphysical stimuli with both solid and fluid loading components have been proposed as the regulators of the tissue differentiation pathway (Prendergast et al., 1997). Huiskes et al. (1997) defined a healing stimulus S that governs the tissue differentiation by taking into account the distortional strain (γ) and the interstitial flow velocity (v) as follows,

$$S=\frac{\gamma}{a}+\frac{v}{b} \tag{1}$$

where $a=0.0375$ and $b=3$ μm/s are empirically determined constants. Depending on the value of healing stimulus (S), cells inside the callus are able to differentiate into different phenotypes. High stimulus ($S>3$) is associated with the development of fibrous tissue. Intermediate stimulus ($1<S<3$) is in favor of chondrocyte differentiation, which forms fibrous cartilaginous tissue. Low stimulus ($S<1$) promotes the osteoblast differentiation and results in woven bone. At very low stimulus ($S<0.2667$), mature (cancellous) bone instead of immature (woven) bone is generated.

Mechanisms with which the mesenchymal stem cells spread out within the healing callus involve migration and proliferation. These mechanisms are complex and unclear. Lacroix and Prendergast (2002) assumed random and nondirectional movement of cells resulting in the net effect that cells advance into the regions with lower cell concentration. Such a description of cell distribution can be modeled by the diffusion equation as follows,

$$D\nabla^2 n_{cells}=\frac{dn_{cells}}{dt} \tag{2}$$

where n_{cells} is the local cell concentration and D is a diffusion constant. For numerical implementation D is determined so that the entire healing callus reaches the maximal cell concentration after a preset healing time (Lacroix and Prendergast, 2002).

As the production of new tissue depends on the temporal evolution of mesenchymal cell concentration, at a given time the healing compartment will simultaneously have callus and differentiated tissue. Therefore, a rule of mixture is used to account for local material property in this transient state as follows,

$$E_{new}=\frac{n_{cells}}{n_{\max}}E_{tissue}+\frac{n_{\max}-n_{cells}}{n_{\max}}E_{callus} \tag{3}$$

where E_{new} is the local elastic modulus of the new tissue, n_{cells} is the local cell concentration determined by Eq. (2), n_{max} is the maximal cell concentration, E_{tissue} is the elastic modulus determined by the mechano-regulatory models described in Eq. (1), E_{callus} is the elastic modulus of callus tissue. The local material properties including Young's modulus, Poisson's ratio and permeability are also determined by the rule of mixture. Table 1 lists the material properties used in this work. In addition, a gradual change of material properties toward the phenotype is assumed in the process. To avoid numerical instability caused by too much

Table 1
Material properties used in the study (Misch and Bidez, 1999; Geris et al., 2003).

	Young's modulus (MPa)	Poisson's ratio	Permeability (m^4/Ns)
Implant	113×10^3	0.3	NA
Callus tissue	0.2	0.17	10^{-14}
Fibrous tissue	2	0.17	10^{-14}
Cartilage tissue	10	0.17	5×10^{-15}
Immature bone	1000	0.3	10^{-13}
Cancellous bone	6000	0.3	3.7×10^{-13}
Cortical bone	20×10^3	0.3	10^{-17}

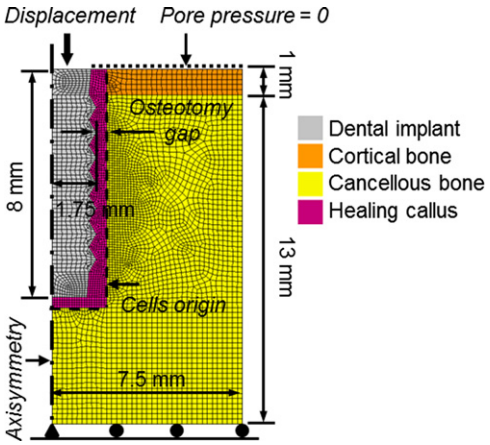

Fig. 1. A 2D axisymmetric finite element model consists of a screw thread dental implant, the cortical bone region, the cancellous bone region, and the osteotomy gap.

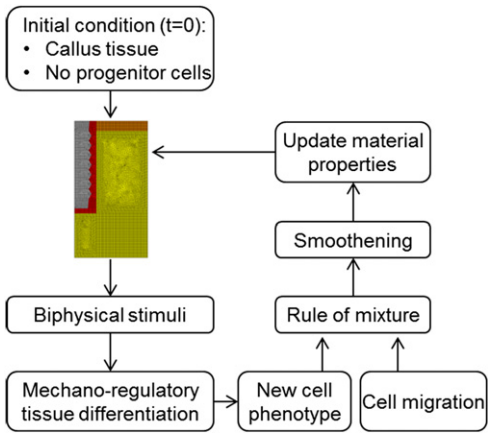

Fig. 2. Flow chart of peri-implant bone healing simulation.

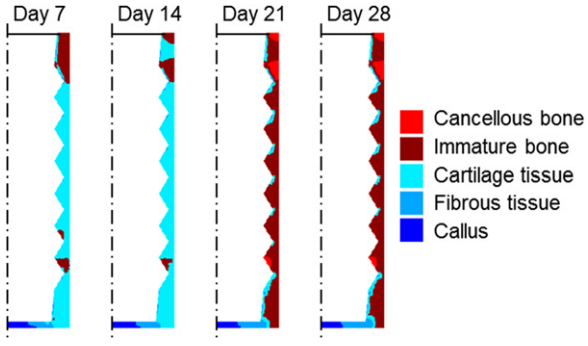

Fig. 3. Transient results of tissue differentiation for a healing period of 28 days. The results are obtained for 10 μm of micro-motion, 0.2 mm of osteotomy gap, and 14 days of cell migration period.