Advanced Materials Research Vols. 79-82 (2009) pp 2167-2170
© (2009) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.79-82.2167

Multiscale Bone Remodeling Prediction for Fully Porous-Coated (FPC) Dental Implant Supported Prosthesis

Chaiy Rungsiyakull[1a] , Qing Li[1b], Wei Li[1], Michael Swain[2]

[1]School of Aerospace, Mechanical and Mechatronic Engineering

[2]Faculty of Dentistry

The University of Sydney, Sydney, NSW 2006, Australia

[a]c.rungsiyakull@usyd.edu.au, [b]q.li@usyd.edu.au

Keywords: Dental implant, Coating, Osseointegration, Finite element analysis, Bone remodelling

Abstract

This paper aims at providing a preliminary understanding in biomechanics with respect to the effect of FPC dental implants on bone remodelling. 2D multi-scale finite element models are created for a typical dental implantation setting. Under a certain mastication force (<200N), a global response from a macro-scale model (without considering coated surface morphology details) is first obtained and then it is transferred to the micro-scale models (with coated surface morphology details and various particle sizes) for micro-scale analysis. A strain energy density (SED) obtained from 2D micro-scale Finite Element Analysis (FEA) is used as a mechanical stimulus to determine the bone remodeling in term of the change in apparent bone densities for cancellous and cortical bones. The change in bone densities is examined as a result of bone remodelling activities over a period of 48 months.

Introduction

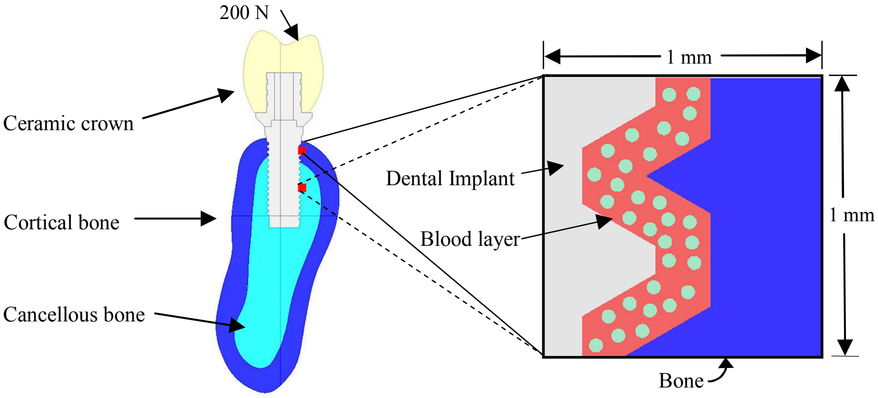
Osseointegrated dental implants have been accepted as clinically desirable restorative device and have predictable outcomes for the management of partially and fully edentulous patients. Osseointegration becomes one of critical factors to determine the success of implantation as it directly affects the stresses acting on the peri-implant bony tissues. A better osseointegration is believed to be able to improve adaptive remodelling process and minimise healing time. In this regard, fully porous coated (FPC) implant has been making significant success in implantation *in-vivo* over the last decade and there has been clinical evidence that these coatings create a better osseointegrating environment [1]. However, it still remains unclear how the implant biomaterials and corresponding surface morphologies would affect the bone remodelling activities.

Concurrently with the osseointegration process, bone regulates itself in response to mechanical loads by adapting its internal morphology and properties for accommodating the fundamental loading environment, knowing as “bone remodeling” [2]. In this regard, the bone remodels in line with the change of mechanical loading induced by implant. As bone remodels positively, the better quality of bone can be achieved, which leads to the stabilization of the dental implant. As a general remodelling rule, a decrease in mechanical strain may cause bone disuse and resorption, whereas an increase may lead to bone apposition where bone is more engaged to stabilise the dental implant.

However, the relation between the existing surface coating and dental bone remodeling has not been well reported. This preliminary study will explore the effect of two-unit cantilever fixed dental prostheses on bone remodelling by using the finite element method (FEM) as a tool for remodelling simulation. The role of cantilever bridge on a bone’s response is justified and therefore to provide a new and effective approach to the improvement of restorative longevity.

Materials and Methods

Two 2D microscopic models that have 1mm × 1mm dimension were created based on the information of 2D macro scale model from previous study [3], representing the localized cortical or cancellous regions in Models I and II, respectively. Each microscopic model consists of three parts: threads of dental fixture; localized cortical or cancellous bone and a blood layer where the bony tissue shows the most significant change during the osseointegration healing processes after the insertion of the implants. The spherical-shaped, atomized particles of Ti6A14V alloy porous coating with diameter 50 µm and 25 % porosity were also modelled in blood layer.



a) 2D - macro scale model b) 2D - micro scale model

Fig. 1 Multiscale finite element model

Initially, a mechanical load of 200N was applied on top of the crown at a 2 mm offset from the centre to the buccal side in the perpendicular direction to the crown surface of the macro-scale model. Then the displacement field was extracted from the macroscopic model (Fig. 1a), which was used as the kinematic constraint for the microscopic models (Fig. 1b). Finally, strain energy density (SED) was evaluated for accessing the mechanical response in the microscopic model.

All the biomaterials associated were presumed to be linear elastic, homogenous, and isotropic for sake of simplification in this multiscale analysis. The corresponding properties such as Young's modulus and Poisson ratio were obtained from the literature [4]. The analyses were performed in ABAQUS version 6.7.1.

In order to perform bone remodeling analysis, the SED was used as a mechanical stimulus for evaluating the bone remodeling processes. The SED model has been successfully used in many remodelling studies in the long bone scenarios, e.g. [5-7]. According to Weinans et al [5] the change in bone density (ρ) can be expressed as a function of the mechanical stimulus:

$$\frac{d\rho}{dt} = B(\frac{U}{\rho} - k), \qquad 0 < \rho \le \rho_{cb} \tag{1}$$

where B is a constant, U is the strain energy density (strain energy per unit of volume) and ρ is the local density (bone mass per unit of volume), k is the threshold value and ρ_{cb} is the maximum density of bone.

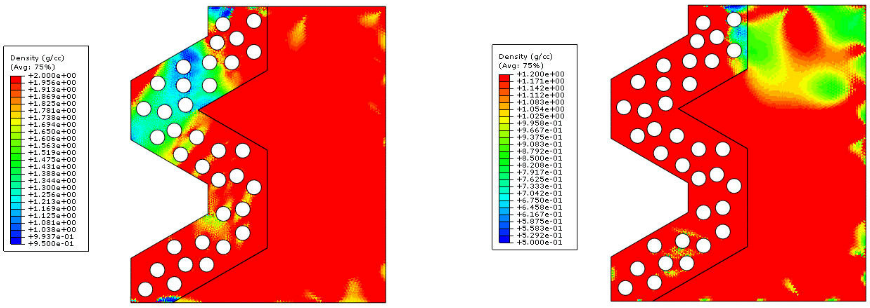
In the FE framework, SED can be calculated from averaging the strain energy density values at all the integration points of an element from

$$U = \frac{1}{2}\{\sigma_{ij}\}\{\varepsilon_{ij}\} \tag{2}$$

These formulations have been implemented in an ABAQUS environment by using Python scripting language for facilitating the bone remodelling calculation.

Results and Discussions

In this study, the 48 month period is considered as the remodeling period, in which the change in the density is chosen to monitor the bone remodeling activities. Fig. 2 plots the overall density distributions of Models I and II at the end of 48 months remodeling duration. Overall, it can be clearly seen that the majority of bone in Models I (cortical, Fig. 2a) and II (cancellous, Fig. 2b) has been occupied by the dense bone over the 48 month healing period, which is similar to the density distributions obtained from macro-scale analysis. This also provides the evidence to confirm the bone remodeling activities. It is found that the cancellous region remodels more in the blood layer whereas the most concentrate density in cortical region is in the bone. This implies that the bone in cancellous region is more sensitive to mechanical loading than that in the cortical area. Therefore, a shorter healing time is required for the blood layer in the cancellous region.

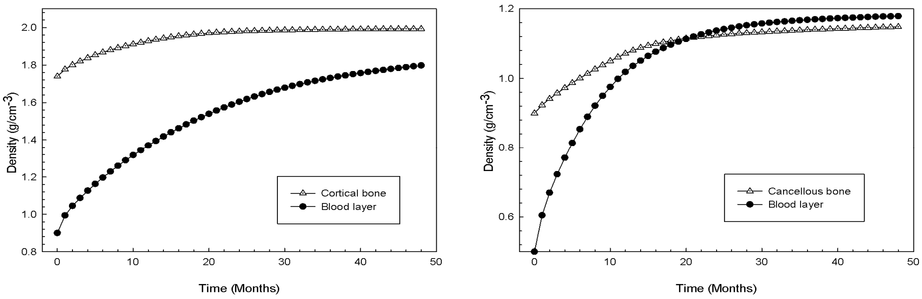


a) Model I (Cortical) b) Model II (Cancellous)

Fig. 2 Density contour of Models I and II after month 48

Fig. 3a represents the progression of the density in cortical region over the 48-month period. The density in both blood layer and cortical bone increases throughout the remodeling period which also indicates the degree of osseointegration. In general, the greater the bone density, the denser the bone and the better the implant stability. The increase rate of density within the cortical bone region is high in the first few months and reaches an equilibrium after month 20, where the average bone density of 1.99 g/cm^3 can be achieved while those of blood layer continues increasing until month 48 with a final density of 1.79 g/cm^3

The change of the density of Model II shown in Fig 3b also exhibits a similar magnification pattern to that in Model I. Overall, the average density increases sharply within the first 14 months and then the rate gradually decreases until the end of the remodelling period. It is interesting to note that the density in blood layer after month 20 onward is greater than those in cancellous bone region, confirming that the most concentrate mechanical stimulus can be found in the region. The average density after month 48 reaches 1.17 g/cm^3 and 1.14 g/cm^3 in blood layer and cancellous bone region respectively.



a) Model I (Cortical) b) Model II (Cancellous)

Fig. 3 Density progression of Model I and II

Conclusions

This numerical simulation provided the preliminary results on micro-scale bone remodeling prediction of FPC implant supported crown. Overall, the remodeling rates in both Models I and II are relatively high in the first few months which represents the healing period for the bone to initiate an osseointegration after implantation. The remodeling analysis shows that the blood layer in the cancellous bone region is more sensitive to the mechanical load than that in the cortical region. The comparative analysis with different size and porosity of the coating surface may need to be incorporated in the further studies in order to facilitate the effect of porous coating structure.

Acknowledgements

This study has been supported by Australian Research Council (ARC) and the first author is grateful the Faculty Scholarship at The University of Sydney.

Reference

1. Xiropaidis, A.V., et al., *Bone-implant contact at calcium phosphate-coated and porous titanium oxide (TiUnite (TM))-modified oral implants.* Clinical Oral Implants Research, 2005. **16**(5): p. 532-539.
2. García, J.M., M. Doblar, and J. Cegoino, *Bone remodelling simulation: a tool for implant design.* Computational Materials Science, 2002. **25**(1-2): p. 100-114.
3. Rungsiyakull, C., et al., *Effect of Fully Porous-Coated (FPC) Technique on Osseointegration of Dental Implants.* Advanced Materials Research, 2008. **32**: p. 189-192.
4. Vaillancourt, H., R.M. Pilliar, and D. Mccammond, *Finite-Element Analysis of Crestal Bone Loss around Porous-Coated Dental Implants.* Journal of Applied Biomaterials, 1995. **6**(4): p. 267-282.
5. Weinans, H., R. Huiskes, and H.J. Grootenboer, *The behavior of adaptive bone-remodeling simulation models.* Journal of Biomechanics, 1992. **25**(12): p. 1425-1441.
6. Mellal, A., et al., *Stimulating effect of implant loading on surrounding bone - Comparison of three numerical models and validation by in vivo data.* Clinical Oral Implants Research, 2004. **15**(2): p. 239-248.
7. Huiskes, R., et al., *Adaptive bone-remodeling theory applied to prosthetic-design analysis.* Journal of Biomechanics, 1987. **20**(11-12): p. 1135-1150.