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SIMULATION OF BONE HEALING PROCESSES AROUND DENTAL IMPLANTS DURING THE HEALING PERIOD

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Abstract: *The healing process of dental implants after insertion is complex. It was assumed that implant healing is comparable to indirect fracture healing of long bones. Hence, the aim of the present study was to simulate the remodelling process of the bone bed surrounding dental implants, considering different tissue layers until the osseointegrated state is reached. A two-dimensional model was created in a bone segment which has 1.0 mm layer of cortical bone surrounding a core of trabecular bone. Three different layers with three different thicknesses were added around the implant in the models. New bone formation was observed with a layer of 0.1 mm thickness. With a layer of 0.3 mm simulation resulted in bone resorption. A stable region for all remodelling parameters could be determined such that bone density resulted in an equilibrium state with a soft tissue layer of 0.1 mm, which is in accordance with clinical findings. Similar boundary conditions will be applied in future 3D modelling.*

1. INTRODUCTION

Bone seems to be static but is a dynamic and complex organ system. It consists of cortical and spongy parts. Bone mainly consists of two different cell types called osteoblasts and osteoclasts. Osteoclasts mainly remove bone tissue, while osteoblasts are specialised to create new bone tissue. Bone density has different values in the range of 1.7-2.0 g/cm^3 and 0.2-1.0 g/cm^3, for cortical bone and spongy bone respectively. Bone remodelling is a mechanical adaptation during all our life, which includes bone formation and bone resorption. Bone formation also occurs in fracture healing.

Basic aspects of a theory to describe bone remodelling processes and bone adaptation were presented by Wolff [15], and the process of bone modelling and remodelling is called 'Wolff's Law'. Although he did not formulate a quantative law, he described a relationship between bone loading and bone structure. In 2003, Frost defined that an equilibrium exists between resorption and formation, which are balanced such that old bone is replaced by new bone, adapting to mechanical loading. Bone remodelling occures over a long period of time in a combination of resorption and formation. This process was described by numerous researchers using different mechanical parameters to stimulate bone remodelling [2,5,14].

In last decades, different mathematical models have been presented to simulate bone behaviour and mechanics to predict the density change in long bones like femur and tibia. Typically finite element methods are used as simulation tool [1,7]. Some of the recent models tried to explain the bone remodelling process around dental implants [6,12,13].

It was the aim of this numerical study to simulate the bone remodelling around dental implants including the osseointeration phase during the healing period with regard to biomechanical aspects. A previously presented mathematical model [12] was used to simulate the bone remodelling in the two dimensional finite element model of the bone around dental implant with special focus on the tissue behaviour at the implant surface as a time dependent function in response to local mechanical stimulus.

2. MATERIALS AND METHODS

A bone remodelling theory for the early healing phase of dental implants in the surrounding bony tissue based on previously developed bone remodelling theories was implement . When a mechanical load is applied to a bony structure, the bone responses to this load and it is remodelled depending on the magnitude of the load. This remodelling process can change the density of existing bone and/or change the geometry of the bone. The models used in this study consider only the change of bone density.

In 2007 Li et al. described the change in bone density as a function of mechanical stimulus. They expanded the equation by a term [14] to include the overload resorption:

The next example is a multi-line equation:

$$\begin{aligned} \frac{d\rho}{dt} &= B(\frac{U}{\rho} - k), \qquad 0 < \rho <= \rho_{cp}, \\ \frac{d\rho}{dt} &= B(\frac{U}{\rho} - k) - D(\frac{U}{\rho} - k)^2, \qquad 0 < \rho <= \rho_{cp}, \end{aligned} \tag{1}$$

where B and D are constants, k is the reference stimulus, ρ_{cb} is maximal denstiy (i.e. cortical bone density), U is strain energy density, ρ is density of bone and U/ρ is the mechanical stimulus.

Several authors suggested that a certain amount in over- or underloading must be exceeded before the bone remodelling occurs. The loading area between this threshold levels is often referred to as the 'lazy zone' or 'dead zone' [4,10,12]. The dead zone (w) was considered with % 20 in this study. In 1977 Carter et al. derived the upper limit by using the inverse function to the formula $E(\rho) = C\rho^3$ with a maximum Young's modulus of 20.000 GPa, where C is a constant and has the value of 3790 $MPa(gcm^{-3})^{-3}$. The Euler method was used to solve the ordinary differential equation numerically as described by Li et al. 2007. In order to be able to model the osseointegration process, the remodelling of different tissue types had to be considered. We distinguished between four different tissue types during remodelling:

- Stiff Callus (SC), i.e. cortical bone
- Connective Tissue (CT), i.e. blood, bone marrow and bone fragments directly after insertion of the implant
- Soft Callus (SOC)
- Intermediate Soft Callus (MSC)

These tissue types are added around the implant as three separated diferent phases. The two dimensional model was implemented into the commercial FE software MSC.Marc/Mentat. The Young's modulus of cortical bone was 20 GPa and for spongy bone was 100 MPa. Bone remodelling parameters were set as follows: constant k 0.0001 Jg^{-1}, constant D 19.48 $(gcm^{-3})^{-3}$ $MPa^{-2}(timeunit)^{-1}$, B=1.0 $(gcm^{-3})^{2}$ $MPa^{-1}(timeunit)^{-1}$ according to Li et al. 2007, w was $\%20$ of k. The dental implant ($\emptyset = 3mm, L = 11mm$) was inserted into the two dimensional model to test the bone remodelling with osseointegration. The applied boundary conditions to the model are shown in Table 1.

BOUNDARY CONDITIONS	VALUES
Element edge length (mm)	0.5 and 0.2
Fixation of the model in three degrees of freedom.	
Muscle pressure (MPa)	2
Young's Modulus of spongious bone (initial values before starting remodelling process)(MPa)	20, 50,...500
3 Phase with 3 different tissue types:	Phase1: CT
	Phase2: CT,SOC,MSC
	Phase3: SOC,MSC,SC
All tissue types with different thickness (mm):	0.1 , 0.2 , 0.3
Total Force:	100 N with 20

Table 1. Boundary Conditions which are used in the remodelling models with osseointegration.

Table 2 shows parameters for tissue types which are used during bone remodelling with osseointegration. Figure 1(a) shows the situation immediately after implant insertion to two weeks, Figure 1(b) displays the geometry after two months and Figure 1(c) after four months [9].

Figure 2 shows three different phases that are used to simulate osseointegration during bone remodelling with different tissue types within different thickness of this tissue types.

In Figure 3 the red, yellow and blue parts are cortical bone, spongy bone and implant, respectivelly. The model was subjected to a compression pressure on the lingual and the buccal

Material Name	Young's Modulus (MPa)	Poisson's Ratio
Initial Connective Tissue (CT)	1	0.17
Soft Callus (SC)	1.000	0.3
Intermadiate Stiffness		
Callus (MSC)	6.000	0.3
Stiff Callus (SC)	10.000	0.3

Table 2. Parameters for Tissue Types *[9, 11]

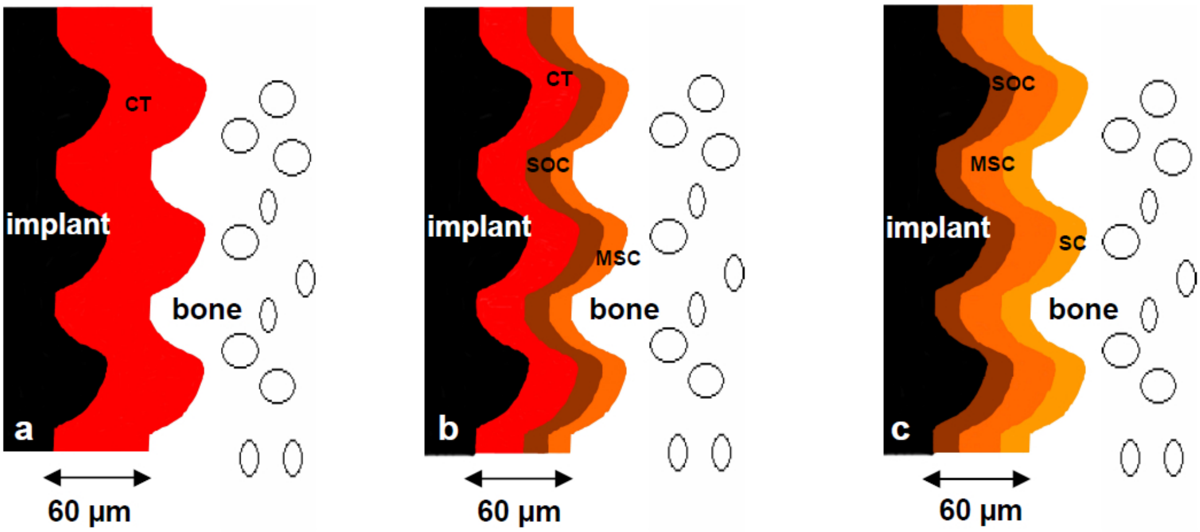

Figure 1. Healing Phases.

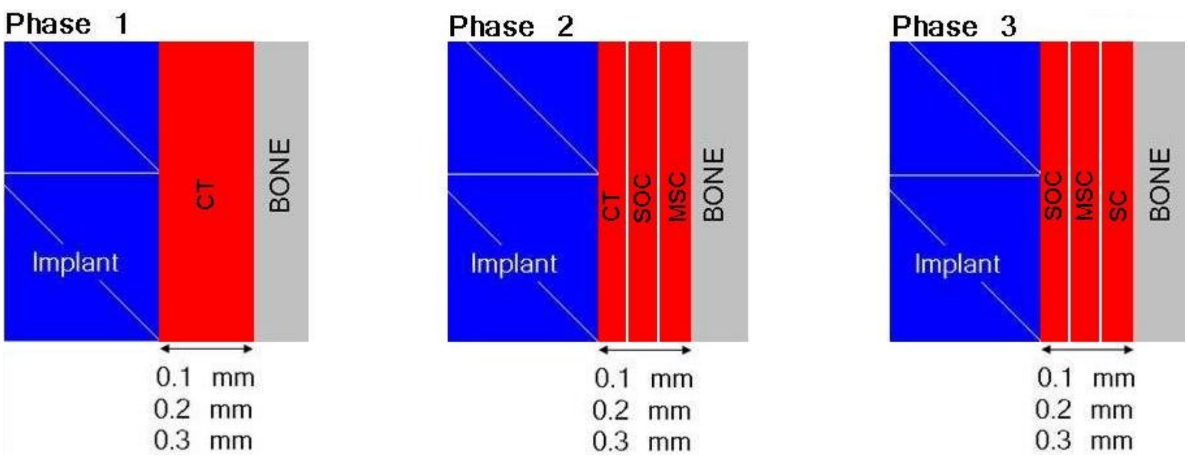

Figure 2. Bone Remodelling with Osseointegration.

side to simulate muscle loading.

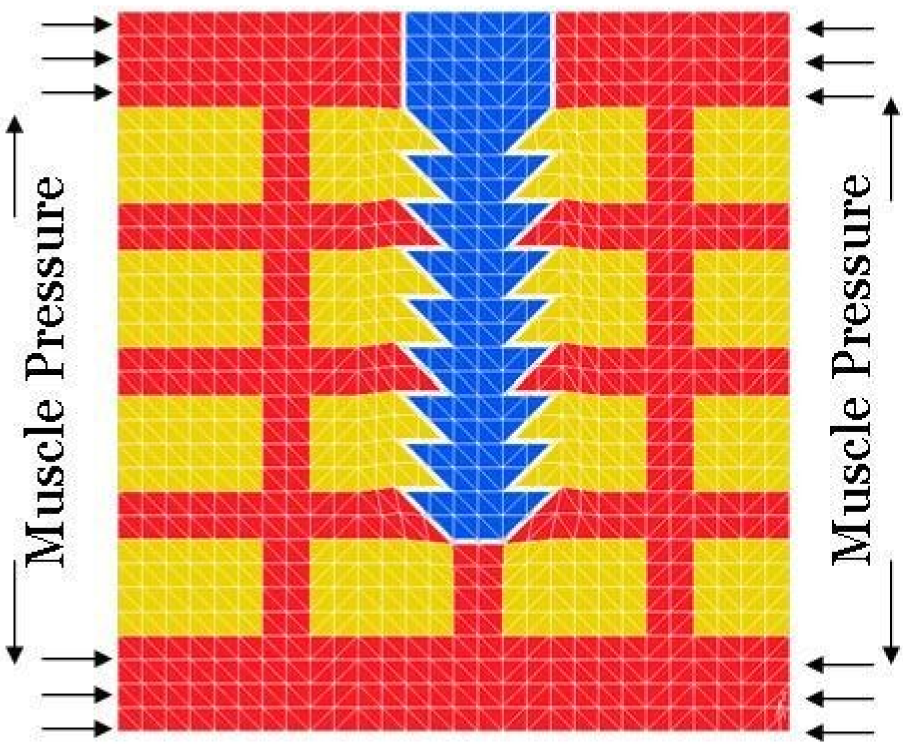

Figure 3. 2D FE model with different tissue types.

3. RESULTS

Bone density changes with different parameters are presented after 300 time steps. The two dimensional models are used to simulate bone remodelling with osseointegration. Density distribution within the range of 0.0-1.74 g/cm^3 was used to demonstrate the results. Figure 4 shows simulation results by applying the bone remodelling simulation with osseointegration in the 2D model after 300 time steps. In the blue parts the density was below 0.4 g/cm^3, which means that bone resorption took place in that region. In the yellow part the density was higher than 1.74 g/cm^3 and thus bone formation was obtained around the implant and some part of the bone region during all phases with a 0.1 mm soft tissue thickness. New bone formation was obtained with 0.2 mm as well but it was less then with 0.1 mm during all phases. In contrast, overload resorption was obtained with 0.3 mm thickness during all osseointegration phases.

4. CONCLUSIONS

A two dimensional bone remodelling simulation was performed under varying mechanical conditions and bone remodelling parameters for the healing around dental implants. Using a two dimensional FE model, a stable region for all remodelling parameters could be determinded such that bone density resulted in an equilibrium state with a soft tissue layer of 0.1 mm, which is in accordance with clinical findings. In the future, similar boundary coundations will be applied with different layers in 3D modelling. The results from 3D modelling will be validated with results from sika deer animal experiments. Then the numerical results will be compared

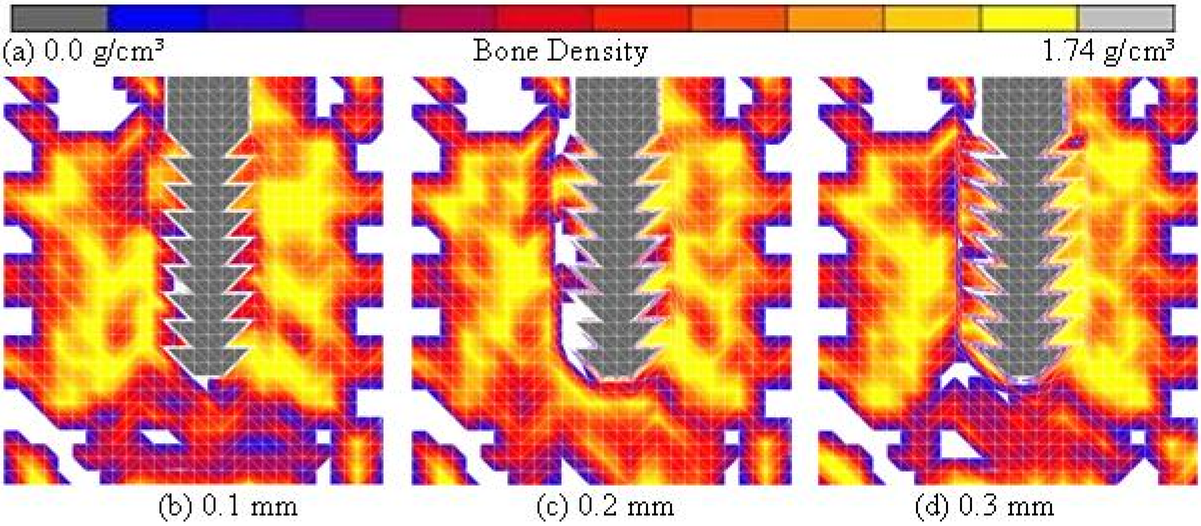

Figure 4. Density distribution with different thickness of tissue types within Phase 2.

with clinical findings.

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