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Simulation of bone modeling around a screw implant in the mandible

On the basis of a biomechanical model for the bone healing process around a dental implant, the attainable degree of ossification in two-phase implantation is studied for a screw implant and compared with corresponding results for a cylinder implant. It is shown that a screw implant delivers a better ossification of the repair zone than a cylinder implant which is in accordance with clinical observation.

1. Introduction

Due to mechanical and thermal damage of the bone during the insertion process, a necrotic repair zone containing demineralized bone matrix and coagulum is produced around a dental implant. In the so-called two-phase implantation the implant remains hidden underneath the mucosa for a healing period of about three months (primary phase) before it is finally connected to a suprastructure (crown, bridge, prosthesis) in a subsequent surgical step (secondary phase). Thus, during the healing period, the implant is not exposed to direct loading, i.e. the repair zone experiences solely stresses caused by deformations of the mandible under functional movements (chewing, biting etc.) which is simulated by periodic bending. Using FEM the bone modeling processes around a screw implant (diameter: 4 mm, insertion length: 14 mm) in the primary and secondary phase are investigated under the following conditions: 1) Bone apposition in an element is only allowed if the response (von Mises stress) falls into a certain "response window"; 2) otherwise bone resorption occurs; 3) the modeling process proceeds from the intact bone in direction to the implant, thus following revascularization.

2. Biomechanical Modeling

In the simulation of the mechanobiological healing process a screw implant (diameter: 4 mm) made of titanium was considered at the site of a premolar (insertion depth: 14 mm). The (atrophied) mandible was modeled as a straight inhomogeneous beam (length: 90 mm) with realistic dimensions concerning the cross-section (maximum diameter: 23 mm) as well as the distribution of cortical and trabecular bone in the cross-section (Fig. 1). The repair zone had a thickness of 500 μm, and was supposed to be perfectly bonded to the implant. All materials involved were assumed to be linear-elastic and isotropic. Young's modulus of titanium was chosen as $E_t = 110$ GPa, the (apparent) moduli of cortical and spongy bone as $E_c = 18$ GPa and $E_s = 2$ GPa, respectively. For all three materials Poisson's ratio was taken as $\nu = 0.3$. Since under chewing a mandible is predominantly subject to bending, in the primary phase the beam model was loaded with a periodically applied bending moment M = 4,000 N·mm, which, in the model without the implant, would lead to a clinically realistic deflection of 25 μm. In the secondary phase the implant was periodically exposed to a combination of axial forces $F_a = 100$ N and alternating lateral forces $F_{ll} = F_{lb} = 30$ N (l: lingual, b: buccal) which corresponds to realistic (moderate) chewing stimuli (Fig. 1).

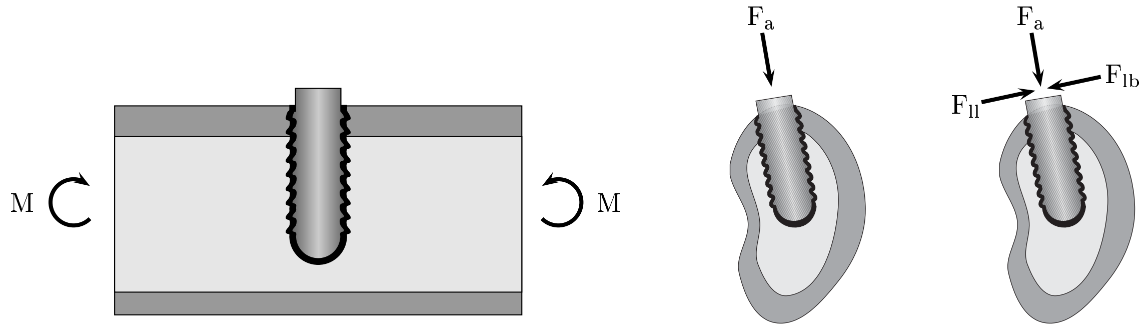

Fig.1 Beam model and loads applied to the repair zone.

For the three-dimensional FE analysis carried out with ANSYS 5.5.3, the beam was discretized in 34,481 elements, corresponding to 20,671 nodes. An especially fine mesh consisting of five thin layers was used for the repair zone

(Fig. 2). The response window for the von Mises stress was chosen as [0.16 MPa , 5.50 MPa]. In the initial configuration Young's modulus was set to 500 MPa which roughly corresponds to the stiffness of connective tissue. Bone apposition in an element was characterized by an incremental increase of Young's modulus in the cortical and spongy section of the repair zone (ΔE_c = 50 MPa, ΔE_s = 100 MPa, respectively) if the von Mises stress fell into the response window. Otherwise (over- and underloading) bone resorption of identical magnitude ΔE_c and ΔE_s was postulated. An increase of Young's modulus was, however, only allowed in an element if it was connected over at least one node via a "bridge" with surface elements of the intact bone and if these "bridging elements" had experienced at least one increase of Young's modulus under preceding stimuli (revascularization). The degree of ossification was defined as

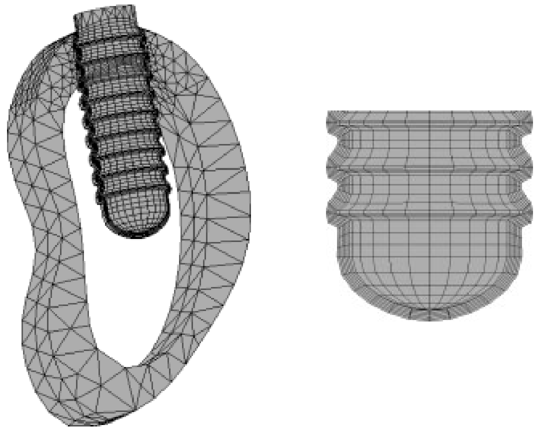

Fig.2: FE mesh of the screw implant and the repair zone.

$$\kappa_c(n) = \sum \frac{E_i(n)V_i}{E_c V_c} \quad , \quad \kappa_s(n) = \sum \frac{E_i(n)V_i}{E_s V_s}$$

in the cortical and in the spongy section of the repair zone, respectively. Here $E_i(n)$ denotes the Young's modulus of the i^{th} element after the n^{th} loading (iteration) step, V_i its volume, E_c and E_s the target values of the Young's moduli as given above, and V_c and V_s the total volume of the repair zone in the cortical and spongy section, respectively. In the primary as well as in the secondary phase the stimuli were repeated until either a total bone regeneration or asymptotically a stable non-complete degree of ossification was reached.

3. Results and Discussion

Fig. 3 shows, including a comparison with formerly obtained results for a cylindrical implant with identical dimensions [1], the degrees of ossification in the spongy and in the cortical section of the repair zone for the primary healing phase (H) and for the subsequent secondary functional phase. The latter case is subdivided into purely axial loading (F_a) and combined axial and lateral loading ($F_{a,l}$). At the end of the primary phase (H) the attainable degrees of ossification are nearly identical for the two implants (∼60% in the spongy, ∼90% in the cortical section), whereas at the end of the secondary phase (F_a and $F_{a,l}$) the screw implant shows a slightly lower degree of ossification in the spongy, yet a significantly higher degree in the cortical section. It becomes evident that the modeling processes in the functional period lead to a drastic increase of spongy bone and a dramatic loss of cortical bone, the latter being much more pronounced under additional lateral ($F_{a,l}$) than under purely axial stimuli (F_a). A detailed analysis of the distribution of Young's modulus in the repair zone proves that this bone resorption corresponds to the funnel-like crestal bone loss clinically often observed at the neck of implants. All together, the simulation shows that the overall degree of ossification attainable with a screw implant is better than that reached by a cylinder implant.

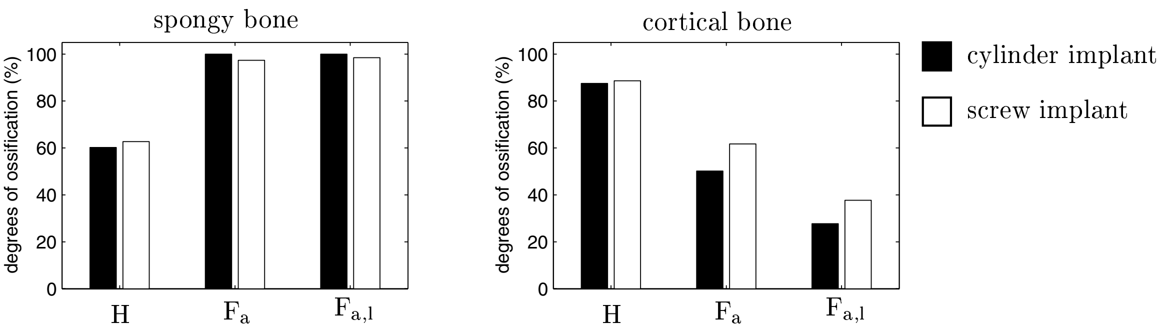

Fig.3: Comparison of the results for the screw and the cylinder implant.

4. References

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