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Modeling of load transmission and distribution of deformation energy before and after healing of basal dental implants in the human mandible

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Abstract

The purpose of this study was to present the amount and distribution of pressure, stress, and deformation energy when basal implants in the mandible are restored with a bridge which is loaded at two different stages of bone healing. The model geometry and material properties of the mandible were gained from CT scans of a human mandible. The material model used in this study defined bone as an inhomogeneous, linear elastic isotropic material. The masseter and temporal muscles were considered as rigid connections between the bones in typical positions and directions. The rotation axis was simulated in the temporomandibular joint. The loading force of 450 N was assumed to be in the middle between the left molar and left canine implant. In freshly operated bone, the total deformation energy is 30% higher than in healed bone, due to the defined energy absorbing soft bone areas. Approximately 90% of the deformation energy is absorbed by the bone, regardless of the healing state of the bone. The immediate rigid implant splinting distributes peak forces. To cope with these energies, the necessity of a reduction of total masticatory forces or the use of additional implants for force distribution should be considered individually.

Keywords: bone healing; deformation energy; dental implantology; finite element analysis (FEA).

Introduction

Finite element analysis (FEA or FEM) is a useful tool in dental medicine for predicting stress on materials. The prediction of events as well as the re-evaluation of known medical phenomena can help to improve methods and materials. As dental implants can be immediately loaded by prosthetic constructions, specific calculations are needed. Adequate FEM models have been established, to describe stress distribution within the implants and at the bone interface. The distribution of deformation energy between bone, implants, and the bridge especially in loaded and healed bone has never been investigated.

A realistic FEM model of a human mandible with four implants connected by a bridge is investigated. A simpler model has been used for earlier investigations for determining stresses within basal implants and the bones interface adjacent to basal implants [8–10].

The purpose of this study was to calculate the amount and distribution of pressure, stress and deformation energy when basal implants in the mandible are loaded at two different stages of bone healing. Thus, the clinically proven good results in immediate implant loading need to be supported by biomechanical facts. It was hypothesized that deformation energies in immediate loading scenario can be higher than in healed bone due to softer bone around fresh inserted implants. Thus, improved primary stability by the early application of a bridge instead of no external splinting could lead to correct appliance of Wolff's law to the correct amount of bone remodeling stimulation forces and deformation energy distribution in the whole system and prevent failures.

Materials and methods

The geometry for the FEA model of the mandible was obtained from CT scans of a human mandible (edentulous, female, 73 years old) [5, 6, 18]. The resolution of the CT scan was 512×512 pixels, where pixel size is 0.414 mm. Slice increment was 0.5 mm. From a CT scan, the natural distribution between cortical and spongiosis bone and the degree of mineralization inside the mandible were evaluated and integrated in a FEM model. The bone was modeled by 25 different materials with Poisson ratio $\mu = 0.32$ for all Young modulus linearly altering from 1 GPa (1st Material) to 19.5 GPa (25th material) corresponding to experimental found values for cortical bone between $E = 4.9 \pm 1.1$ GPa and $E = 20.9 \pm 1.7$ GPa [17, 19]. These ranges should simulate empty spaces, spongiosis, as well as cortical bone by different sum properties rather than simulating trabecular structures itself [5]. The soft bone areas should represent the force induced (by microcrack) activation and orientation of secondary osteons, where primarily a hard tissue softening takes

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place by activated osteoclasts right after the implant placement as well as woven bone [4].

The mesh of the mandible was created in the ABAQUS 6.7-3 computer system by the C3D4 element type [1]. In this study bone was defined as an inhomogeneous, linear elastic isotropic material (Figure 1). The implant material (Titanium grade 2; E = 105 GPa; $\mu = 0.37$; yield strength = 320 MPa) was considered to be linear elastic. The improvement of this model compared to prior models is the inclusion of muscles. The masseter and temporal muscles were considered as rigid connections between the bones in typical position and direction (blue dot line in Figure 2). The rotation axis (yellow line in Figure 2) was simulated in the temporomandibular joint. The boundary conditions and loading force are shown in Figure 2.

A typical implant situation with four basal implants in strategic implant position for a circular bridge was assumed. Single base-plate implants (Type: BOI® BAST 9/16 h6 by Dr. Ihde Dental AG, Uetliburg, Switzerland) were placed in the areas of the second molars, while canine regions were equipped with triple base-plate implants (BOI® BBBS 7h6) [7]. All implants have the abutment as an integral part of the implant, meaning single-piece design. The implants reached bicortical engagement at least with one base-plate each [8, 9]. All implants were rigidly connected by a rectangular bridge (CoCrMo alloy; E = 194 GPa; $\mu = 0.3$), which was considered linear elastic. The dimension of the bridge was 4 mm height × 2.5 mm width. Material properties of CoCrMo alloy were taken from Ihdentalloy K® (Dr. Ihde Dental AG, Uetliburg, Switzerland; yield strength = 570 MPa). The model based on the splinting of the implants with a circular bridge, with the implants being more elastic than the bridge core.

The loading force of 450 N was assumed to be located in the middle between the left molar and left canine implant and is oriented in vertical direction (Figure 2).

The healing process was investigated at two stages: (1) Bone as completely healed and remineralized: the scanned degree of mineralization was assumed for the whole mandible. For this case ''Hard'' contact definitions were assumed. (2) Early phase of bone healing with a 2-mm thick layer of softer bone around the surfaces of the implants: a low degree of mineralization was assumed to be present there (structure modulus = 1.0 GPa). ''Hard'' contact definitions between the implant and the bone were assumed nevertheless.

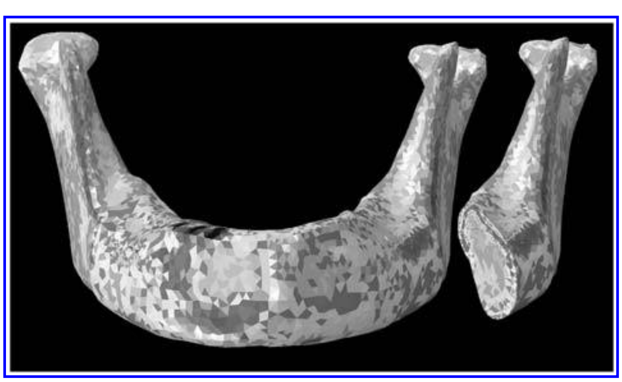


Figure 1 Material properties of bone taken from the CT scan. The darker gray corresponds to higher modulus.

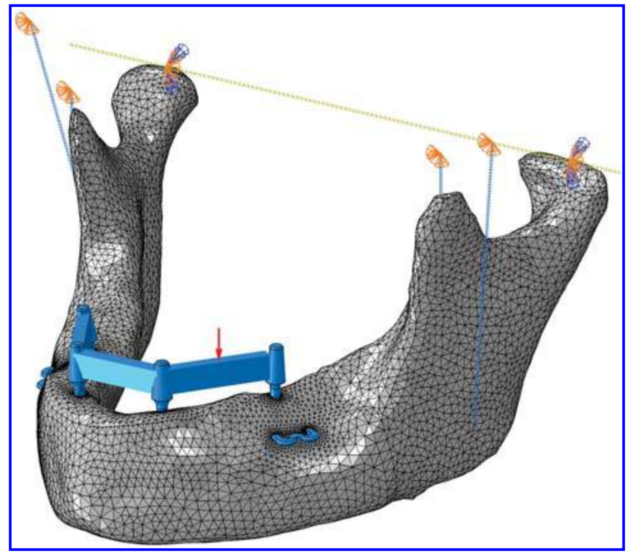


Figure 2 Model of mandible with implants, bridge and with marked muscles, boundary conditions and loading force.

Results

The distribution of stress was calculated for the whole model. The von Mises stress magnitudes in implants, bridge and mandible were calculated for both cases and compared with their limits. For cortical bone, a maximum stress for repetitive loading of 105 MPa was chosen as a limit for load bearing capability [2]. The limits for bridge and implants are their yield strengths (570 MPa and 320 MPa, respectively).

The highest values of von Mises stress in mandible do not exceed 105 MPa for both scenarios; the highest values are around 50 MPa. In the ''healed bone scenario'', the stress is concentrated around the shafts of implants on the loaded side. In freshly operated bone scenario, the stress is concentrated in cortical bone near the 2-mm thick layer with low mineralization (Figure 3).

Figure 4 shows contours of von Mises stress in implants for both scenarios. The implants on the non-loaded side carry some amount of load. However, the implants on loaded side carry the most of the load. The maximum value achieved the yield stress limit in single base-plate implant shaft in the freshly operated bone scenario. Nevertheless, the volume of material exceeding this limit is very low and elastic shakedown can be expected.

The highest values of von Mises stress in bridge are approximately 160 MPa for both cases which is safely under limit. The most loaded part of the bridge is situated in loading point.

To quantify the difference between scenarios, the deformation energy was computed both for the whole model and particular components. On the non-loaded side the decrease

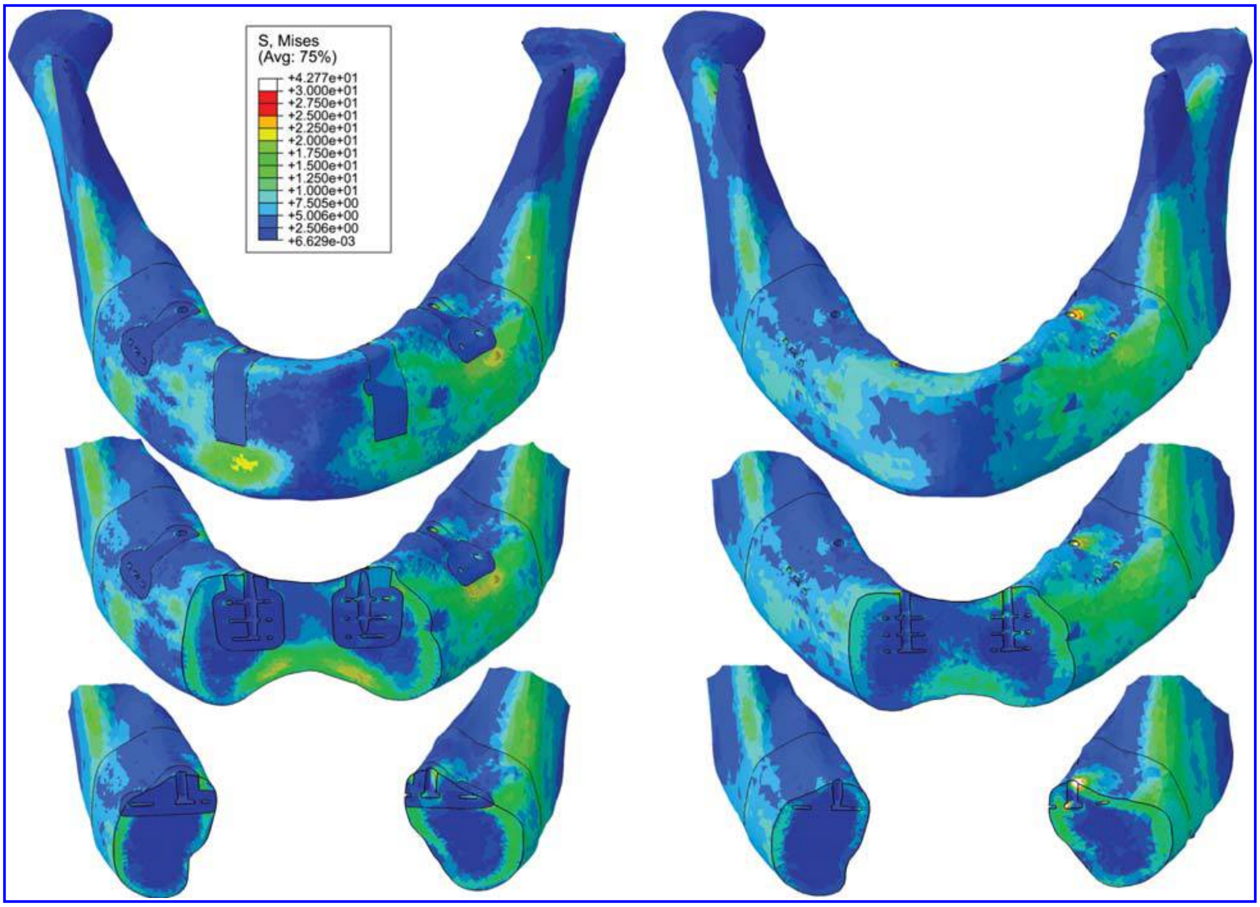


Figure 3 von Mises stress contours. Compilation of whole mandible and vertical cross-sections through the mandible in the area of the implants. Left, fresh operated; right, healed bone.

in deformation energy during the healing time is higher than on the loaded side even if the absolute values are very low (Figure 5).

In freshly operated bone, the total deformation energy is 30% higher than in healed bone (Figure 6). The increase of deformation energy has been observed in all analyzed components.

Stress and deformation energy absorbed by the implants are always higher on the loaded than on the unloaded side (Figures 4–6). Although unilateral loading was assumed, the almost rigid bridge led to a shift of the masticatory forces to the unloaded side, even with small (5.3–6.3 mJ) deformation energy uptake in the bridge itself (Figures 5 and 6). The maximum stress within the bridge core was located on the loaded side between the two adjacent implants and there is actually nearly no difference between the scenarios (Figure 4).

Discussion

A FEA model considering a gradual integration of basal dental implants distinguishing five separate stages (1–5) has been described in the literature [10]. The present calculation represents stages 2 and 5 of the bone healing process cited in [10]. The improved FEA model and the contact definitions used here are more realistic. Furthermore, the bone around the implants was assumed to have less rigidity compared to the rest of the mandible, which resembled to natural predicate better. By using ''Normal'' contact definition, the bone provided a considerable resistance. Compared to other FEA models, this is advanced, because muscle attachments are considered and the splinting and loading through a bridge is performed [9].

The results of this evaluation show the dependence of total deformation energies from the state of bone healing. The total deformation energy in immediate loaded scenario is 30% higher than in loaded healed bone. To cope with these energies, the necessity of a reduction of the total masticatory forces or the use of additional implants should be considered individually. Limits of deformation energies probably hindering hard tissue formation and inducing soft tissue formation should be evaluated clinically and implied in future models.

The better performance of immediate implant loading than in a two-stage procedure was found in FEA [14].

The implants on the non-loaded side of the mandible are bent and the bone on this side is subjected to stresses during mastication. Thus, by external implant splinting load and energy peaks are distributed in the whole system and energy

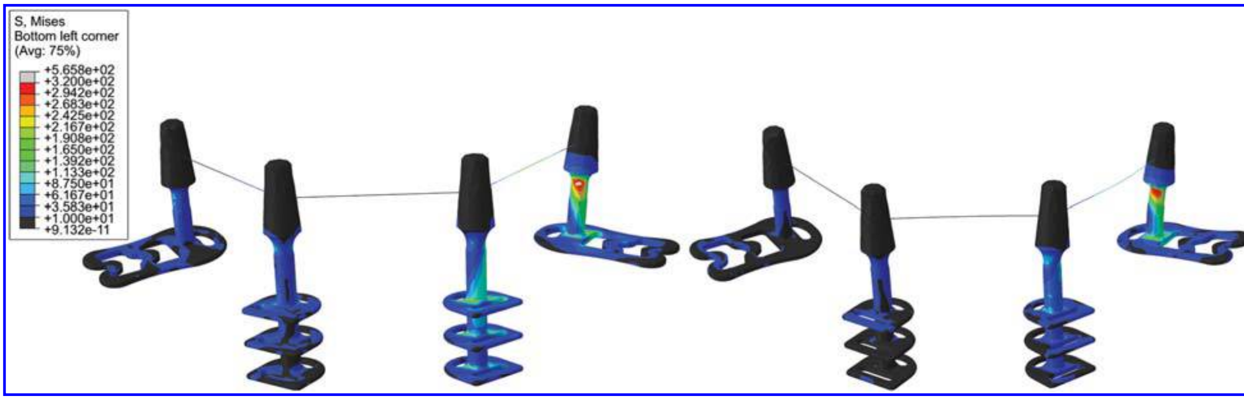
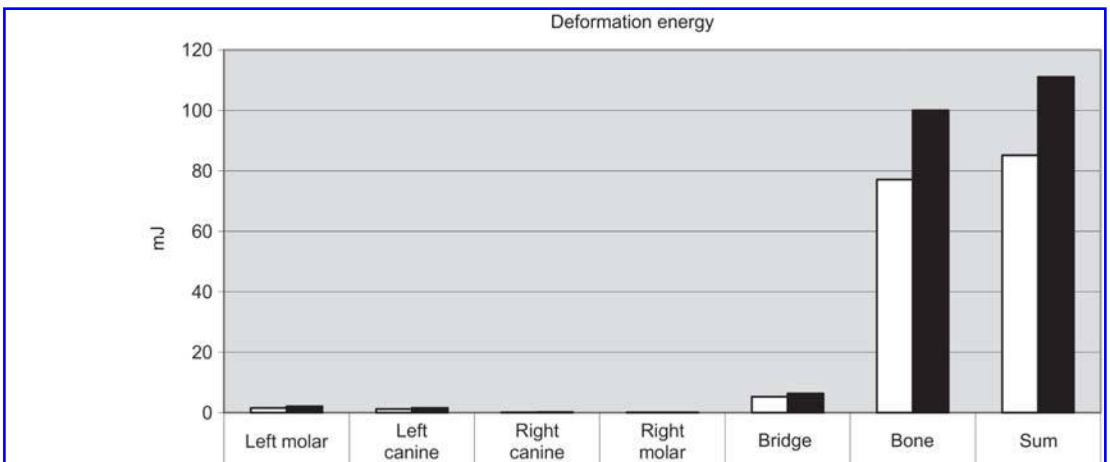
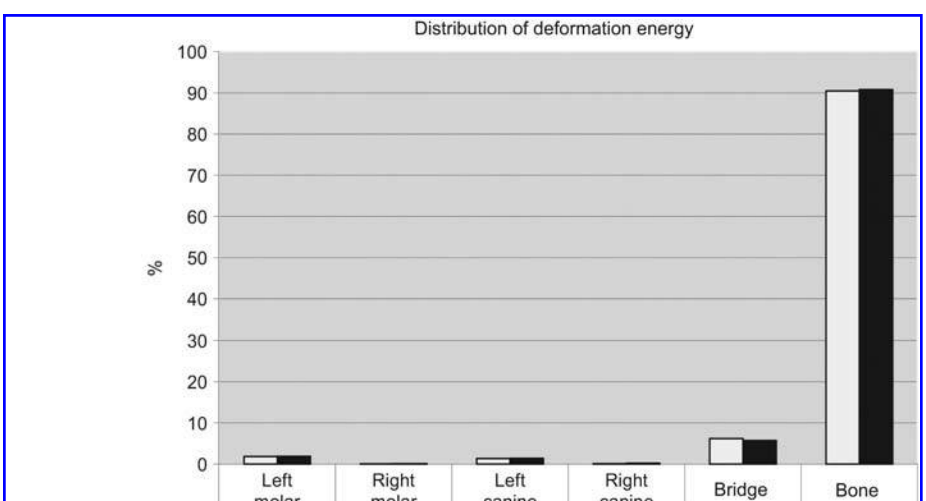


Figure 4 von Mises stress contours in all implants. Left, fresh operated; right, healed bone.



	Left molar	Left canine	Right canine	Right molar	Bridge	Bone	Sum
□ Healed bone	1.54	1.15	0.070	0.050	5.28	77.1	85.1
■ Freshly operated bone	2.05	1.53	0.200	0.110	6.30	100	111

Figure 5 Absolute deformation energy stratified for healing state and components.



	Left molar	Right molar	Left canine	Right canine	Bridge	Bone
□ Healed bone	1.81	0.060	1.35	0.080	6.21	90.5
■ Freshly operated bone	1.86	0.100	1.39	0.180	5.69	90.8

Figure 6 Relative deformation energy distribution stratified for healing state and components.

absorption takes place in all partaking components. The energy uptake in the bridge is around three times higher than in the implants itself (5.3–6.3 mJ), which probably helps to reduce bone disturbing peak forces. The highest ratio of deformation energy (approx. 90%) is channeled through the metal parts (bridge and implants) to the bone and has to be absorbed here regardless of its healing state. The absolute number decreases from 100 mJ right after implantation to 77 mJ in the remodeled bone. Even if there are no absolute limits of energy acceptance to be found in the literature, clinical experience proves the acceptance of this constellation by human bone [11–13]. The often performed but not calculated here ''all on four constructions'' (full arch bridge on four implants) with implant placement right into fresh extraction sockets (immediate implant placement) clinically led to no significant increase of failure rate compared to delayed implant placement or primary use of more than four implants (Figure 7) [12]. Absolute values of deformation energy uptake limits for bone should be found *in vitro* in further evaluations.

The results cannot generally be transferred to crestal dental implants (i.e., screws), because these implants differ in design and utilize different bone areas for load transmission. These results are only valid for cases where all implants are inserted at the same time. If only several implants are added or if, e.g., by earlier extractions the state of healing of the mandible is not uniform all over the horizontal part, resistance of single regions can differ considerably.

These results might not be generalizable for cases of extreme mandibular atrophy, where the body of the mandible will consist almost only of cortical bone [11, 12, 15].

Regardless of the healing state, 90% of the deformation energy turned out to be within the bone side of the model. Even the distribution of the deformation energy between the bridge and the implants was nearly the same in both scenarios. Future studies should show if this is a constant ratio for such systems or with a larger or smaller number of implants stress and deformation energies ratios differ.

Conclusion

Approximately 90% of the deformation energy in mandibular constructions on four basal implants is absorbed by the bone, regardless of the healing state of the bone. The established distribution and deformation energy uptake reduces peaks and distributes forces mainly to the adjacent implants, even if there are deformations in the whole bridge and in remote implants. This indicates that immediate external implant splinting by a circular bridge results in distributed and decreased stress and deformation energy, even with high (450 N) unilateral occlusal force input inside the supporting polygon marked by the implants [3]. Additional splinted implants can, however, lead to reduced deformations in the implant-to-bone interface, because more implant-to-bone interface surface would be available. This could also reduce susceptibility of the system against lateral masticatory forces. Immediate implant loading by external splinting is helpful in appliance of Wolff's law for force guided bone remodeling and has no influence on the fraction of the deformation energy to be absorbed by the bone, which is approximately 90% during the whole healing process.

Figure 7 Panoramic view of a mandible equipped with four basal implants and an immediate fixed bridge 5 years post-surgery.

Although the total deformation energy decreases during the healing process by approximately 30%, the highest risk in immediate loaded scenarios is in the initial first months. Surviving this period leads to even better prognosis due to lower deformation energy uptake needed afterwards [16].

This could also be partially true for closed healed implants with delayed prosthetical loading due to the induced forces, leading to bone remodeling.

Acknowledgements

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