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# POST-OPERATIVE REMODELLING OF THE MANDIBULAR BONE ALLOWS THE INCORPORATION OF STIFF CIRCULAR BRIDGES ON FOUR STRATEGICALLY PLACED BASAL IMPLANTS IN AN IMMEDIATE LOAD PROTOCOL

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# Post-operative remodelling of the mandibular bone allows the incorporation of stiff circular bridges on four strategically placed basal implants in an immediate load protocol

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## Abstract

Aims: The relationship between bridge-core diameters, the resistance of peri-implant bone and stresses around the endosseous base plates of immediately loaded basal implants were simulated.

Methods: Von Mises stresses appearing around the base plates of four basal implants supporting a circular mandibular bridge were calculated using the finite element method. Using different bridge-core dimensions starting from 1.5 mm x 2.5 mm for various types of loading, stress values on the bone side of the interface and within the bridge-core as well as in the implants were calculated.

Results: Only if SOFT contact definitions between implants and bone were applied, acceptable values for stresses were found on the bone side of the interface. This indicates, that the stiffness of the constructions and the reduction of the mineralization of the bone are prerequisites for the uneventful integration of basal dental implants into the bone.

Conclusions: The success of a treatment with immediately loaded basal implants in strategic positioning depends strongly on the rigidity of the bridge, i.e. on the bridge-core diameter. Dimensions of 2.5 mm x 3.5 mm or more for the bridge-core are required for treatment in immediate load protocols.

**Keywords:** finite element model; von Mises stresses; basal dental implants; bone-implant interface; SOFT and TIED contact definitions; post-operative remodelling; mineral content.

## Introduction

The number of implants and prosthetic constructions which are necessary to equip the edentulous mandible with fixed prosthetics has been largely discussed, because the flexion of the mandible under function could prevent or endanger osseointegration if this bone is splinted overly by few stiff bridge segments[1]. While increasing the number of implants may increase the treatment success, this approach consequently increases the demands for technical precision as well as the requirement for bone substance and the costs, respectively. This is especially true, when separate bridges are planned in one jaw, because each bridge requires a separate stable endosseous anchorage and the masticatory forces must be balanced. The constructive advantage of a self-stabilizing full-arch bridge approach is thereby surrendered. The placement of four strategically placed basal implants as shown in (Fig. 1) is not only the most minimal approach for a treatment: this treatment is available for all patients, regardless of the available amount of bone. Although the basal treatment concept has proven to be successful in prospective[2,3] and retrospective[4] studies, a number of questions still remain to be answered as both the treatment approach and the design of the implants differ from conventional concepts. One of the questions raised frequently is why so extremely reduced intra-osseous load transmission areas as shown in Fig. 1 are capable of creating immediate and long term stability.

Basal implants have skeletonised design, with a polished vertical implant part and one or several supportive ring base-plates anchored trans-osseously on the vestibular and lingual cortical bone. They provide transmission of masticatory forces not to cancellous bone as conventional cylindrical/screwed implants, but to the stable cortical bone[5]. In the early phase of function, the base-plates of these implants direct the masticatory forces exclusively onto supporting cortical areas. The void osteotimized spaces in the vicinity of the implants fill with blood which later forms a callus. Both the cortical areas and the callus undergo remodelling until the site is finally healed and the implants are fully integrated. This modus of implant integration was described as «dual integration»[5].

The purpose of this study was to calculate stresses occurring within bone, the bone interface and within the bridge-core, and to suggest the diameter of the bridge-core that should be used for mandible full-arch bridges supported only by four basal implants. It is known, that the investigated treatment approach is successful in the clinical reality[4,5,6]. Adequate contact definitions had to be defined, taking into consideration that these constructions work successfully in the clinical reality[6,7]. The influence of the bridge core diameter under immediate load conditions has never been investigated.

## Material and Method

The geometry of the mandible was gained from CT-scans of a human mandible (edentulous, male, 80 years old).

The 3D-Model based on the CT-data was created using the technique of rapid prototyping (Stratasys Prodigy Plus, USA). Typical insertion slots in 3D-model were prepared by an experienced implantologist to enable the insertion of two different basal implants into this model. Single base-plate implants (TOI® brand: TAS 9/16 h6, Biomed Est., Liechtenstein) were placed in the areas of the second molars, while the canine regions were equipped with triple-base-plate implants (TOI® brand: TTTS 7 h6, Biomed Est., Liechtenstein). The implants placement followed the instruction of the manufacturer: bi-cortical support and a correct trans-osseous position were achieved. The relative positions of the implants towards each other, their relative angulations, the necessary bending of their shafts to achieve a uniform direction of insertion for the bridge were copied from this 3D-model to finite element (FE) model through precise measurements (Fig. 1a and 1b).

The FE-model assumed the mandible to consist of a 1.5 – 2.5 mm thick cortical ring, with a cancellous bone filling (Fig. 1a). The FE mesh of this mandible was created in system ABAQUS 6.7-3 (Abaqus Inc., Providence, RI 02909-2499, USA; Abacus manual5) by the C3D4 element type. The material model used in this study defined bone as a homogeneous, linear elastic isotropic material. The implant material, titanium Grade 2 was considered to be linear elastic. Material properties of both cortical and cancellous bone as well as properties of other materials (implants, bridge-core, etc.) are represented in Table 1. All implants included the abutment as an integral part (single piece design).

Basal implants are primarily anchored at the base-plates within the cortical areas of the bone. In order to reflect the changing material properties of bone during the healing process, different contact definitions available in the ABAQUS were used. Most appropriate are the contact definitions TIED for healed (mineralized) bone and SOFT for bone under remodelling[9,10].

For all calculations the bridge was assumed to be of the BEAM-type in ABAQUS (with rectangular cross-section, one dimensional mesh) with material properties of CoCrMo alloy considering the typical yield strength of 570 MPa (Tab. 1a).

The distribution of von Mises stress patterns was calculated for CoCrMo alloy bridge-core as well as for the implants displayed in their relative position and for the osteotomized bone site around each implant. The scaling was set differently for the bone and titanium, in order to make stress graduations visible. To assess lifetime and limiting state of bridges the ultimate strength was used (Tab. 1a), because this is the limiting value determining elastic behaviour of materials. For cortical bone a maximum stress for repetitive loading of 105 MPa was chosen as a limit for load bearing capability[8].

The system, consisting of four basal dental implants implanted in edentulous mandible and a rigidly connected bar (representing the bridge-core), was loaded under different conditions and assumptions:

Case 1 – Different diameters of bridge-cores: loading force 450 N on tooth 36:

The first series of calculations using the model described above considered different dimensions of metal bridge-cores, while assuming TIED contact definition conditions in the shaft and base-plates area of the implant under repetitive unilateral vertical loading of 450 N at the area of tooth 36. This situation resembles healed and mineralized bone around the whole endossous interface of the implant.

Case 2 – One diameter of bridge-cores, different loading forces:

For comparison, the same model as in the Case 1 was calculated, but with bridge-core of constant dimensions of 1.5 mm x 2.5 mm, observing stresses within bridge-core, implant body and the bone facing the implant, under different values of bilateral vertical loading (200 N, 350 N and 450 N). This calculation assumed TIED contact definitions between the endosseous implant surface.

Case 3 – Clinical situation:

The model situation during bony healing based on histological and clinical observations[2] was assumed: SOFT contact definition allowing vertical movements of the shaft and elastic deformation of the base plates7 were thus assumed possible, with the implant being supported only by rigid cortical areas of the bone. This situation was calculated for different bridge-bar cross-sections and a bilateral vertical load of 450 N.

**Results**

The results are presented in tables 2 to 4. Red coloured values represent critical values exceeding the elastic range of the bridge-core material.

Case 1: Repetitive chewing forces of 450 MPa applied unilaterally on one molar (36) led to exceeding of the load bearing capability of the bone for all cross-sections of bridge-cores calculated in this study (Table 2). However, stresses acting within the bridge-core reach an acceptable range for bridge-bars larger than 2.5 (width) x 4 mm (height), while the stresses acting within the implant are acceptable if the bridge-core is larger than 1.5 mm (width) x 2.5 mm (height).

Case 2: When bilateral loads of 200 N, 350 N and 450 N were applied to a bridge-core with cross-section of 1.5 x 2.5 mm, von Mises stresses on the bone side of the interface reached unbearable values, which are exceeding the strength limits of the bone. Stresses within the implants however were acceptable (Tab. 3). This may result in a localized overload osteolysis and in a failure of integration of all or single implants. Only 200 N was the acceptable load for the CoCrMo alloy bridge-core. For this case TIED contact definitions was assumed just as for Case 1.

Case 3: Results of the calculations (Tab.4) in this case were different in comparison to the Case 1 (Tab. 2). When assuming SOFT contact definition conditions, maximum von Mises stress on the bridge-core decreased to 978 MPa. Maximum stress at the bone interface decreased to 70 MPa whereas the maximum von Mises stress within the implants almost remained constant. Those stresses are in the acceptable range for the bone interface even for all bridge-core cross-sections under consideration, while the values of von Mises stress for the bridge-core are acceptable only for larger cross-sections above (3.0 mm x 4.5 mm).

**Discussion**

Comparing mineral content and different properties of bone with the functional designation, Currey 13 found that even bone with a modulus of elasticity of 30 GPa can be functional although its fracture resistance will decrease significantly. Cortical bone has a very broad spectrum of functional adaptive mineralizations (Tab. 1b[13]). Besides the function, also injuries and age influence the local mineral content of bone: during the insertion of basal dental implants, vertical and horizontal slots have to be prepared. The subsequent repair within the bone requires a complete remodelling of at least the horizontal part of the mandible[11]. In order to simulate the healing process as well as the mechanism of gradual osseo-integration from a mechanical point of view, various contact definitions of FE model have been used. The contact definition SOFT appears to resemble the osteotomized healing bone around basal implants best[9, 14]. Stresses on implants and bridges which are in the elastic range, i.e below the limits of yielding, indicate that these structures will resist the mechanical loading without damage. Values near the limit of the material tensile strength indicate the increase of the risk of damage for the bridge as well as for the implant. A limit for bone (105 MPa)[12] is an average value, because cortical bone in nature is found to be functional within large range of values for mineralization[12,13]. The distribution of the mineralisation in non-injured human mandibles depends largely on the functional pattern[15].

Before the insertion of basal dental implants into the mandible, vertical and horizontal slots have to be prepared. These trans-osseous slots may be considered to be four semi-fractures. Their repair leads to a full remodelling of at least the crestal horizontal part of the mandible and this remodelling is accompanied by an overall softening of the bone[11]. Attention must be paid not only to the material properties of implants but also to their structural design, the area of placement and the loading area and to how they are connected with the bridge. The conventional screw implant technique would be to treat the edentulous mandible with separate bridges, requiring e.g. three implants in the lateral segments and 2-4 implants in the frontal segment. If the alternative «all on four» concept is applied, the posterior screw implants are placed in a tilted manner and only between the mental nerves.

The model used for the calculation considered a mandible with a mild atrophy consisting of cortical and spongeous bone. In cases of extreme atrophy however, the body of the mandible will consist pre-operatively almost only of cortical bone. After the implants are inserted, massive remodelling will occur, leading to a considerable decrease in mineralization. This and the altered function must result in changes in the jaw's bone elasticity[15, 16]. According to our findings, this decrease in mineralization promotes stress free integration of the basal dental implants. The mineralization will later increase to pre-operative values, with the implants remaining integrated.

Under conditions of an «all on four basal dental implants» treatment approach, a considerable part of the mandible's task to resist macro-trajectorial forces may be temporarily taken over by the splinting bridge-core. The situation resembles one of a circular mandibular fracture plate. Therefore, and not only with respect to the occlusal loading, bridge-core dimensions are crucial for treatment of edentulous mandible in respect to the bone overloading and fracture resistance of the implant body.

From the initially obtained results (Cases 1 and 2) it was deducted, that the TIED contact definition would cause significant overloading onto the peri-implant bone areas if only four implants are used to equip an edentulous mandible. At the same time it would require large bridge-cores and very low masticatory forces. When using TIED contact definitions, larger parts of the implant's interface must be considered as rigidly osseo-integrated (at a high degree of mineralisation). Transmitting loads only through those parts of the implants which are cortically anchored would lead to unacceptably high forces, if both the bridge and the contact between bone and implant are stiff.

When searching the currently available literature describing FE models concerning dental implants, only concepts applying TIED contact definitions were found. This is probably due to the fact, that cylindrical/ screwed dental implants are used after the completion of the bone's healing, when the bone's mineralization at the implant's interface has reached at least preoperative values again. Because the bone is considered static, these calculations do not consider the strong altering effect of the osteonal remodelling on the force distribution along the interface of the implants.

When considering treatment modalities of an «immediate loading», SOFT contact definition conditions are in our view more suitable, because this condition resembles better the resistance of osteonal bone under strong remodelling[9], a state known as post-surgical osteoporosis[17].

Creating a balanced, bilateral pattern of chewing seems a critical factor to the success of the treatment, because repetitive unilateral loading may result in overloading the bone interface on the chewing side (Case 1).

**Conclusion**

When elastic designs of basal dental implants are combined with the concept of strategic implant placement, the dimension of the metal bridge-cores is of large importance. Only sufficiently rigid bridge-cores allow a distribution of masticatory forces on all implants. The dimensions of the bridge-core have to be chosen appropriately, in order to avoid overloading of single implants, prosthetic structures and the bone's interface around the base-plates. Bridges made out of CoCrMo alloy should provide a minimum size of 2.5 mm (width) to 3.5 mm (height). The influence of a plastic or ceramic covering of the metal bridge-core on the rigidity of the bridge was not taken into account.

Assuming TIED contact definitions for elastic bone-to-implant systems has led in our calculation to unacceptable values of von Mises stress at the bone's side of the interface. It seems therefore justified to apply SOFT contact definitions for basal dental implants placed in an immediate load protocol in the mandible. Our findings imply also that the use of SOFT contact definitions is a realistic scenario when it comes to determine details of and changes in stress distribution around basal dental implants, for example for evaluating changes in the macro-design of implantable devices in the future.

Future studies of borderline situations like unilateral or anterior patterns of chewing or asymmetries in the morphology of the bones will help to understand more about the stress distribution between basal implants and the bone's interface.

Future research using the same model could address the question, in how much the later replacement of one basal implant only (with the strong remodelling taking place around the new base plate only) is advisable in an immediate load protocol, or if in this case the replaced implant should remain without loading until the mineralisation around the interface has increased again. Likewise the influence of unintentional malpositioning of single base-plates in a non-bicortical manner could enlighten the question, in how much the cortical engagement of basal implants is a prerequisite to a successful treatment.

Our calculations refer only to vertical mouth closing during mastication. The influence of the deformation of the mandible on the bone's interface and the bridge during forced mouth opening and lateral masticatory movements remains to be investigated.

If basal implants are loaded after the bone's healing (i.e. not in an immediate loading protocol), TIED contact definitions may be applicable and bridge-core dimensions are less critical.

## Tabels

| Material | Type | E (GPa) | μ | RM (MPa) | RE (MPa) | A (%) |
|---|---|---|---|---|---|---|
| Bridge – Ihdedentalloy k | Isotropic elasto-plastic | 194 | 0.3 | 734 | 570 | 10 |
| Implants – Ti Grade 2 * | Isotropic elasto-plastic | 105 | 0.37 | 490 | 300 | 10 |
| Implants – Ti6Al4V | Isotropic elasto-plastic | 113.8 | 0.342 | 950 | 880 | 14 |
| Cortical bone | Isotropic linear elastic | 13.7 | 0.3 | | | |
| Cancellous bone | Isotropic linear elastic | 2.3 | 0.4 | | | |

Table 1a: Mechanical properties of the materials under investigation.

| | Elk antlers | Cow femur | Whale bulla |
|---|---|---|---|
| Fracture resistance (J/m$^2$) | 6190 | 1710 | 200 |
| Flexural strength MPa | 247 | 179 | 33 |
| Elasticity mod. Gpa | 7.4 | 13.5 | 31.3 |
| Acoustic impedance | 3.71 | 5.27 | 8.79 |
| Mineral content (wt %) | 59.3 | 66.7 | 86.4 |

Table. 1b: Properties of cortical bone according to Currey[13]

| Bridge Crossectional Area mm$^2$ | Size of Frame (mm; b x h) | Max, Values in bridge (MPa) | Max, Values within implant (MPa) | Max, Values at bone interface (MPa) |
|---|---|---|---|---|
| 3,75 | 1,5 x 2,5 | 2182 | 490 | 562 |
| 4,5 | 1,5 x 3,0 | 1555 | 482 | 446 |
| 5,25 | 1,5 x 3,5 | 1195 | 470 | 392 |
| 6 | 1,5 x 4,0 | 962 | 462 | 365 |
| 5 | 2,0 x 2,5 | 826 | 452 | 332 |
| 6 | 2,0 x 3,0 | 1076 | 464 | 377 |
| 7 | 2,0 x 3,5 | 826 | 452 | 332 |
| 8 | 2,0 x 4,0 | 662 | 442 | 303 |
| 7,5 | 2,5 x 3,0 | 816 | 448 | 329 |
| 8,75 | 3,5 x 3,5 | 622 | 435 | 291 |
| 10 | 2,5 x 4,0 | 494 | 422 | 264 |
| 10,5 | 3,0 x 3,5 | 493 | 419 | 261 |
| 12 | 3,0 x 4,0 | 386 | 402 | 236 |
| 14 | 3,5 x 4,0 | 323 | 386 | 217 |
| 11,5 | 2,5 x 4,5 | 244 | 409 | 244 |
| 13,5 | 3,0 x 4,5 | 321 | 389 | 218 |

Table 2: Repetitive chewing forces of 450 MPa applied unilaterally on one molar (36) led to exceeding of the load bearing capability of the bone for all cross-sections of bridge-cores calculated in this study.

| Load (MPa) | Max. Values in bridge (MPa) | Max. Values within implant (MPa) | Max. Values at bone interface (MPa) |
|---|---|---|---|
| 200 | 612 | 409 | 197 |
| 350 | 1199 | 465 | 374 |
| 450 | 1640 | 481 | 467 |

Table 3: When bilateral loads of 200 N, 350 N and 450 N were applied to a bridge-core with cross-section of 1.5 x 2.5 mm, von Mises stresses on the bone side of the interface reached unbearable values, which are exceeding the strength limits of the bone. Stresses within the implants however were acceptable.

| Bridge Crossectional Area (mm²) | Size of Frame (mm; b x h) | Max. Values in bridge (MPa) | Max. Values within implant (MPa) | Max. Values at bone interface (MPa) |
|---|---|---|---|---|
| 3.75 | 1.5 x 2.5 | 978 | 479 | 54 |
| 4.5 | 1.5 x 3.0 | 950 | 466 | 58 |
| 5.25 | 1.5 x 3.5 | 827 | 432 | 60 |
| 6 | 1.5 x 4.0 | 846 | 436 | 58 |
| 5 | 2.0 x 2.5 | 774 | 425 | 45 |
| 6 | 2.0 x 3.0 | 853 | 446 | 70 |
| 7 | 2.0 x 3.5 | 778 | 428 | 62 |
| 8 | 2.0 x 4.0 | 635 | 405 | 49 |
| 7.5 | 2.5 x 3.0 | 642 | 400 | 50 |
| 8.75 | 2.5 x 3.5 | 587 | 391 | 45 |
| 13.5 | 3.0 x 4.5 | 333 | 354 | 43 |

Table 4: When assuming SOFT contact definition conditions, maximum von Mises stress on the bridge-core decreased to 978 MPa. Maximum stress at the bone interface decreased to 70 MPa whereas the maximum von Mises stress within the implants almost remained constant. Those stresses are in the acceptable range for the bone interface even for all bridge-core cross-sections under consideration, while the values of von Mises stress for the bridge-core are acceptable only for larger cross-sections above (3.0mm x 4.5mm).

**Declarations**

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