

Finite element analysis of stress distribution around a dental implant with different amounts of bone loss: An in vitro study

Analiza metodą elementów skończonych rozkładu naprężeń dookoła implantu zębowego ze zróżnicowaną utratą kości – badanie in vitro

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Abstract

Background. The choice between reducing the bone height and inserting a shorter implant with a greater diameter or a longer and narrower implant without altering the bone height is a challenge in clinical practice.

Objectives. The purpose of this finite element analysis (FEA) was to compare the pattern and level of stress around implants with different lengths and diameters and with different amounts of bone loss, which changes the implant–crown ratio over time, depending on the available bone and the treatment modality.

Material and methods. The FEA was carried out to evaluate the stress distribution in bone around 3.25×13 mm and 4×11 mm 3i implants, and 3.3×12 mm and 4.1×10 mm Straumann® implants. A 3D segment of the mandible was reconstructed from a computed tomography image of the posterior mandible. Occlusal force was simulated by applying 200 N vertical and 40 N horizontal loads to the occlusal node at the center of the abutment. The pattern of stress distribution in bone was evaluated in 10 models for each implant, representing 0–9 mm of bone resorption.

Results. The results showed that along with decreasing the implant insertion depth, and consequently the implant–crown ratio, the amount of stress in bone increased. The amount of stress increased with an increase in depth of bone loss in all models, but there was no significant change in the amount of stress in the first several millimeters of bone loss.

Conclusions. The results suggest that in terms of stress distribution, it is better to reduce the bone height and insert shorter implants with a greater diameter than longer implants with a smaller diameter.

Key words: dental implant, finite element analysis, alveolar bone loss

Słowa kluczowe: implant zębowy, analiza metodą elementów skończonych, utrata kości wyrostka zębowożuchowego

Introduction

Marginal bone loss is a major concern in the long-term success and survival of dental implants.¹ Initially, bone loss may occur in the crestal area of the cortical bone and progress apically. It has been reported that during the first year of implant functioning, crestal vertical bone loss by 1 mm is not uncommon and is often followed by an additional 0.1 mm bone loss in every subsequent year.^{2,3} Crestal bone loss has been attributed to several factors. In an earlier report, microbial accumulation around the implant and in the peri-implant tissues, and inadequate mechanical stimuli/loading transferred to the crestal bone were considered as possible factors responsible for bone resorption.⁴

Bone quality and quantity have been shown to affect the stress/strain distribution in bone around dental implants. The level of strain around dental implants is higher in the low-density cancellous bone.⁵ The thickness of the cortical bone and the available bone height in relation to the size of the implant can also have an influence on the stress/strain distribution in bone.

Some researchers have tried to increase the bone-to-implant contact area to decrease stress in the cortical bone and minimize crestal bone loss. Attempts to increase the bone-to-implant contact area have focused on increasing the diameter and/or length of implants, or altering the fixture micro and/or macro design.⁶ Some researchers believe that the implant diameter is a more important factor in decreasing stress in bone,⁷ while according to others, the implant length has a more significant effect on the strain/stress distribution in bone around dental implants.⁸ On the other hand, it has been shown that neither the implant diameter nor its length are as important as the technique of surgery, sufficient primary stability, and pre- and postoperative oral hygiene.⁹

Larger implants, in terms of both diameter and length, improve the stress/strain distribution patterns; however, in many clinical situations, the alveolar bone does not have sufficient thickness or height for the insertion of such implants.⁶

There are cases in which the clinician must choose between inserting a longer implant with a smaller diameter or decreasing the bone height and using a shorter implant with a greater diameter. The subsequent crestal bone resorption is another concern in changing the stress/strain distribution pattern, as the crown–implant ratio changes over time.

Finite element analysis (FEA) allows the researchers to predict the stress/strain distribution patterns in the peri-implant bone.¹⁰ This FEA was designed to compare the pattern and level of stress around implants with different lengths and diameters, and simulate gradual crestal bone resorption.

Material and methods

The 3D geometry of the posterior segment of the mandible consisting of both the cancellous and cortical bone was reconstructed from a proper 2D image of computed tomography scans taken from an edentulous mandible. This 2D image was transferred to computer-aided design (CAD) software to extract the border contours and make a solid model by extruding the borders.

Different implant systems were evaluated: 2 regular neck 3i implants (Implant Innovations, Inc., Palm Beach Gardens, USA) – one with a diameter of 3.25 mm and a length of 13 mm, and the other one with a diameter of 4 mm and a length of 11 mm; and 2 Straumann® implants (Institut Straumann AG, Waldenburg, Switzerland) – one with a diameter of 3.3 mm and a length of 12 mm, and the other one with a diameter of 4.1 mm and a length of 10 mm. The implants were digitized using an optical digitizing system (ATOS® II; GOM GmbH, Braunschweig, Germany). This system digitizes objects with high accuracy and 3D local resolution in a short time. The measured data can be exported as a point cloud, sections or stereolithography (STL) data. Here, the STL data was imported to Rapidform® software (INUS Technology, Inc., Seoul, South Korea) to make solid models of the implant systems.

To imitate crestal bone resorption over time and altering the implant–crown ratio, the 4 implants were assembled over the bony part. From each of these 4 non-resorption (N-R) models, 9 or 10 resorption models (depending on the length of the implant) were generated, each with 1 mm more resorption than the previous model in a step-wise manner.

It was assumed that all the represented materials were isotropic, homogeneous and linearly elastic. The material properties were extracted from the literature^{11,12} and are listed in Table 1.

The different anatomical parts were meshed with linear tetrahedral solid elements. Each model was comprised of approx. 550,000 elements and 110,000 nodes.

It was assumed that the interface between the implant and bone was perfectly tight, and also the same type of contact was provided when the alveolar bone was resorbed at different levels.

The fixed boundary conditions included restraints in all 6 degrees of freedom, involving rotation and translation in 3 coordinate axes for the nodes located at the mesial

Table 1. Material properties

Material	Young's modulus [MPa]	Poisson's ratio
Cortical bone	13,700	0.30
Cancellous bone	1,370	0.30
Mucosa	1	0.37
Titanium	110,000	0.33

and distal surfaces of the bone. In all cases, a vertical load of 200 N (along the longitudinal axis of the implant) and a horizontal load of 40 N (buccolingually) at an angle of 15° were simultaneously applied to the occlusal node at the center of the abutment.¹³

The statistical analysis was done using a 3D FEA package (ABAQUS v. 6.9-3; Simulia Corp., Providence, USA).

Results

The amount of von Mises stress was calculated in the cortical and cancellous bone in all finite element models with different levels of bone resorption.

Stress distribution

Figures 1 and 2 show von Mises stress (MPa) in the crestal cortical and cancellous bone, respectively, with different implant systems and different levels of bone resorption. Each column demonstrates an implant system with a different level of bone resorption (rows). Row 1 shows the amount of von Mises stress in the models without bone resorption (depth of resorption: 0 mm), in the 3i implants with diameters of 4 mm and 3.25 mm, and the Straumann implants with diameters of 4.1 mm and 3.3 mm,

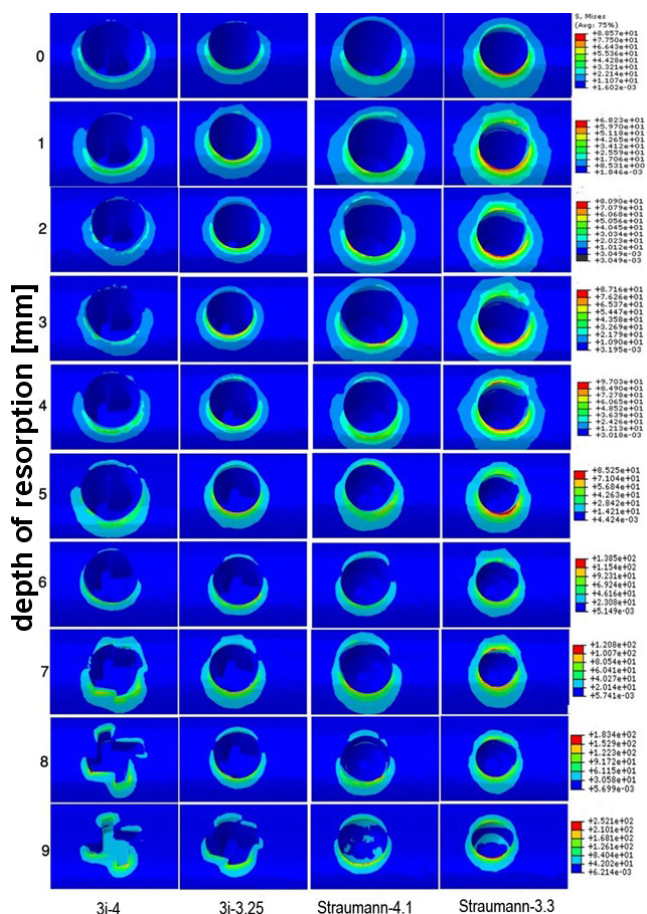


Fig. 1. Von Mises stress distribution in the cortical bone

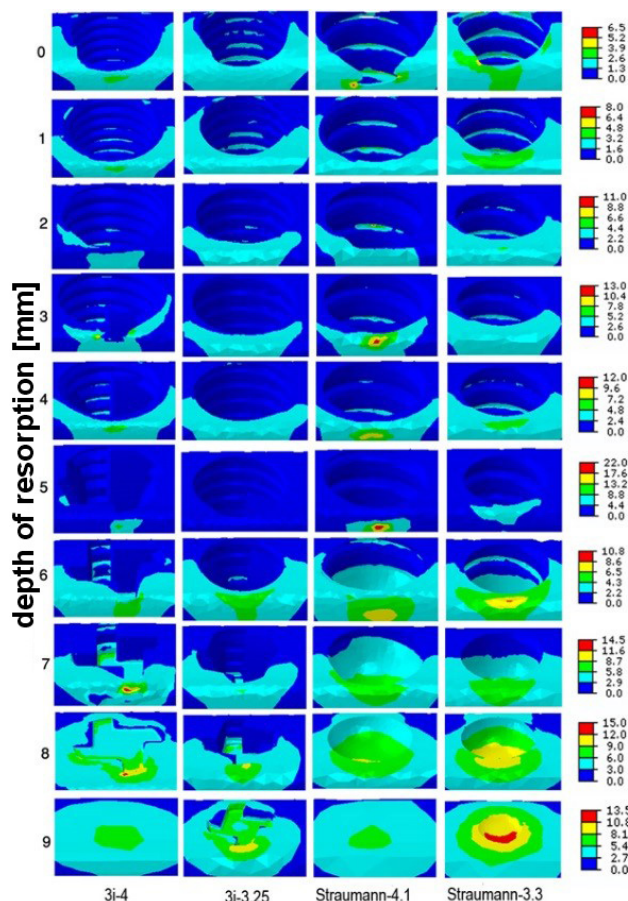


Fig. 2. Von Mises stress distribution in the cancellous bone

respectively, from left to right. The data for the models with 1–9 mm of bone resorption is presented in the subsequent rows.

A high level of stress was noted in the cortical and cancellous bone surrounding the implant neck, and the highest values were found lingually in all models (Fig. 1,2). The comparison of the amount of stress at different depths of resorption showed that the amount of stress increased with an increase in depth of resorption in all models, but there was no significant change in the amount of stress in the first several millimeters of resorption. The amount of stress in the models with the highest depth of resorption increased by up to 3 times the value for the lowest depth of resorption.

Although the 3i implants had a smaller diameter than the Straumann implants, the 3i implants showed lower stress with a relatively even distribution pattern (Fig. 1,2 – columns 1 and 2 compared to columns 3 and 4).

Maximum von Mises stress

Figure 3 shows the maximum von Mises stress in the models with the same fixture length in bone: the shorter model with a greater diameter without any resorption compared to the longer model with a smaller diameter with 2 mm of bone resorption and so on, so they had

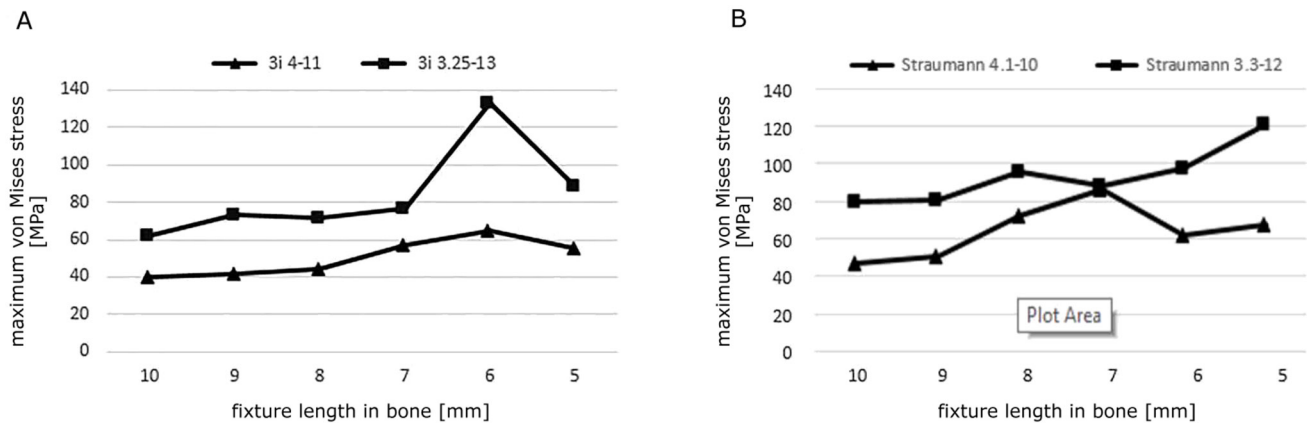


Fig. 3. Maximum von Mises stress in the cortical bone
A – 3i implant models; B – Straumann implant models.

the same fixture length in bone (Fig. 4); for example, the 3i implant with a diameter of 4 mm without bone resorption compared to the 3i implant with a diameter of 3.25 mm and 2 mm of bone resorption, or the 3i implant with a diameter of 4 mm and 1 mm of bone resorption compared to the 3i implant with a diameter of 3.25 mm and 3 mm of bone resorption.

The comparison of all models with the same fixture length in bone revealed that the implants with a greater diameter created lower stress in bone than the implants with a smaller diameter. The implants with a greater diameter in all depths of resorption (with different fixture lengths in bone) created lower stress in bone than the implants with a smaller diameter and no bone resorption (Fig. 3).

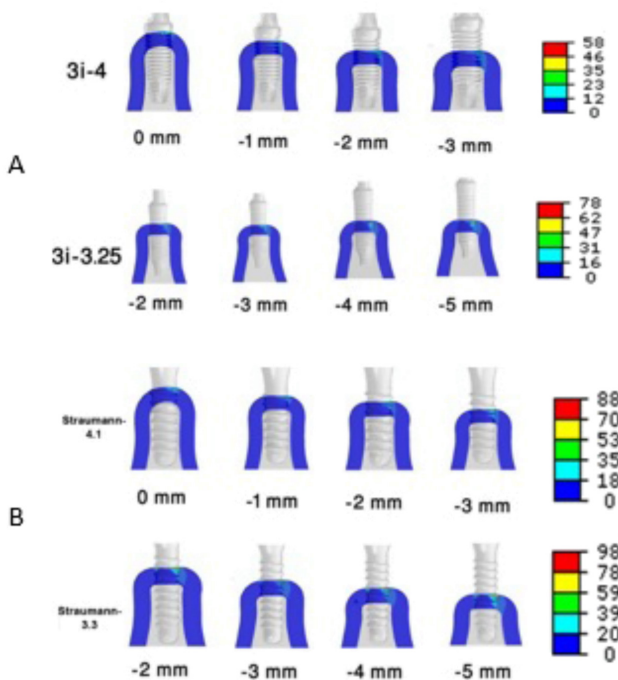


Fig. 4. Von Mises stress distribution in the cortical bone
A – 3i implant models; B – Straumann implant models.

Figure 4 shows that the implants with a greater diameter caused lower stress in bone.

The smaller diameter models with some depths of resorption had almost the same implant-to-bone contact area as the greater diameter implants with no or lower depth of resorption. However, a higher level of stress was observed in the former models.

Discussion

The stress distribution pattern is completely different around dental implants and natural teeth due to the absence of the periodontal ligament around dental implants. Dental implants may be more susceptible to occlusal overloading, which is often regarded as one of the potential causes of peri-implantitis when inflammation is present.¹⁴ In our study, the highest stress values were found mainly in the crestal bone around the implant neck and in the lingual side in all models, because the force was applied at a buccolingual angle. This was in agreement with the results of other finite element study,¹⁵ and also corroborated the clinical observation that marginal bone loss often occurs around the implant neck.¹⁶ The level of stress in the cortical bone was much higher than that in the cancellous bone, mainly reflecting the difference in Young's modulus, as mentioned in other studies.^{17,18}

Several finite element studies have reported a reduction in the crestal bone strain by increasing the implant diameter.^{8,13,19–21} Also, it has been stated that the implant diameter is more important than its length in improving the stress distribution pattern.^{19,22} Greater diameter implants have a larger bone-to-implant contact area, higher resistance to fracture and higher initial stability, and create less stress in bone.^{8,23} However, in the clinical setting, the use of wide implants is limited by the thickness of the residual alveolar ridge. Yu et al. suggested that the implant diameter should be at least half the ridge width; however, narrower alveolar ridges can increase bone stress in narrow

bone walls along the implant and may result in rapid bone resorption, which decreases the crown–root ratio and further aggravates the stress accumulation in the crestal bone.²⁴

A prospective cohort study reported that narrow diameter implants (2.75–3.25 mm) could be successfully used as alternatives to bone augmentation in the posterior mandible, but their follow-up time was about 1 year, and they suggested that narrow diameter implants should be splinted with a bridge instead of using a single molar crown.²⁵

Several clinical reports have shown that the long-term success of narrow diameter implants is less frequent than that of standard diameter implants.^{23,26,27} A recent prospective study evaluated narrow diameter implants with a 5-year follow-up clinically and radiographically, and explained that the use of 2-piece narrow 3.0 mm dental implants was useful in the case of stable marginal bone levels, but suggested their appropriateness for the restoration of upper lateral or lower incisors.²⁸

In another finite element study, the effects of the implant diameter, length and taper on the crestal bone strain around implants were evaluated in the premolar region of the mandible.¹³ The results showed a 3.5-fold reduction in the crestal bone strain by increasing the implant diameter. The authors suggested that narrow, short implants should be avoided, especially in low-density bone.¹³

Our findings support the preference for the insertion of larger diameter implants, in agreement with the study of Ohyama et al.²⁹

In our study, modeling gradual crestal bone resorption, simulating the clinical situation and altering the crown–implant ratio increased the level of stress in bone, which was in accordance with the findings of Qian et al.¹⁶ The results of the present study also supported the findings of other research, reporting no significant difference in the level of stress at 1 mm of crestal bone resorption; however, higher levels of stress were noted following bone resorption of 2 mm or more.³⁰

Considering the inherent limitations of FEA, the findings of this study indicate the reduction of bone height and insertion of a shorter implant with a greater diameter in preference to no bone reduction and the placement of longer implants with smaller diameters, with regard to the optimal stress and strain distribution in bone. Apparently, this is feasible only if allowed by the topography of the alveolar ridge, and this is true both at the time of insertion and over time following gradual bone resorption, which was simulated in this study.

Conclusions


An implant with a maximal possible diameter, considering the alveolar ridge topography, would be ideal. The effect of the implant height was not as profound as that of the implant diameter.

The stress increase following the first several millimeters of resorption was insignificant. There was an increase in the level of stress as the crown–implant ratio changed over time following crestal bone resorption.

Based on the obtained results, it may be recommended to reduce the bone height at the time of the implant insertion and use a wider implant rather than to insert a longer implant with a smaller diameter.

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