A Finite Element Analysis of Stress Distribution in Bone Tissue Surrounding Uncoupled or Splinted Dental Implants

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ABSTRACT

Background: Several studies on one-stage surgery in the treatment of the edentulous maxilla with implant-supported fixed prostheses have reported problems with removable provisional prostheses, which can load the implants in an uncontrollable manner during healing, and jeopardize healing. Immediate splinting of the implants with a fixed provisional prosthesis has been proposed to protect the bone-implant interface.

Purpose: This study used the finite element method (FEM) to simulate stresses induced in bone tissue surrounding uncoupled and splinted implants in the maxilla because of bite force loading, and to determine whether the differences in these stress levels are related to differences in observed bone losses associated with the two healing methods.

Materials and Methods: Stress levels in the maxilla were studied using the FEM program TRINITAS (Institute of Technology, Linköping University, Linköping, Sweden) in which all phases – preprocessing/modeling, equation solving, and postprocessing/evaluation – were simulated.

Results: Stress levels in bone tissue surrounding splinted implants were markedly lower than stress levels surrounding uncoupled implants by a factor of nearly 9.

Conclusion: From a mechanical viewpoint, FEM simulation supports the hypothesis that splinting reduces damage evolution in bone tissue, which agrees with clinical observations.

KEY WORDS: dental implants, finite element method, immediate loading, maxilla, splinting

When dental implants are placed in the maxilla with one-stage surgery according to conventional treatment protocol, a healing period of 3 to 4 months without loading is recommended to promote mucosal healing and osseointegration.[1–4] Recent studies on treatment of the edentulous or partially edentulous maxilla have reported problems with patients' transitional removable prostheses, which can load implants in an uncontrollable manner during healing – placing rotational, horizontal, and shear forces on the implants – and jeopardize the healing process. Crater-shaped bone defects observed around implants are suspected to be a result of such adverse loading.[5,6]

According to the index of Lekholm and Zarb,[7] the jawbone can be divided into four different classes of bone quality where class 4 represents the poorest quality with a high proportion of trabecular bone. In the maxilla, the dominant bone type is trabecular bone, and the thin layer of cortical bone can make it difficult to achieve primary implant stability, which is a prerequisite for successful osseointegration. Several studies report lower implant success rates in the maxilla than in the mandible, which often has a higher proportion of cortical bone.[8] Other authors are of the opinion that the high proportion of trabecular bone in the maxilla makes bone tissue more sensitive to optimal healing conditions.[9]

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It has been proposed that immediate splinting with a fixed provisional prosthesis after surgery in the maxilla might protect the bone-implant interface from adverse loading and improve healing conditions.[5] Results of recent studies on immediate or early loading with such prostheses were promising, with less crestal bone loss than in studies that used conventional treatment protocols.[10,11] One explanation of this encouraging outcome is that, when loaded, splinted implants act together as a group instead of as single units.[12] Based on these findings, the hypothesis of this study is that stress values in bone tissue are lower around splinted than around uncoupled implants, and that implant stability and healing are better with splinted than uncoupled implants.

The finite element method (FEM)[13,14] is often used in biomechanical studies to analyze complex processes and loading situations in an efficient way. FEM has also been used in implant dentistry to predict the biomechanical effect of clinical factors on implant success.[15]

The aim of this study was to use FEM to examine stresses in bone tissue surrounding uncoupled and splinted implants that are induced by a bite force loading the maxilla, and to determine whether the differences in these stress levels can be related to clinically observed differences in bone loss associated with the two methods.

MATERIALS AND METHODS

In this study, stress levels in the maxilla caused by bite force loading were studied using the FEM program TRINITAS (Institute of Technology, Linköping University, Linköping, Sweden).[16] The implants were modeled as cylinders – diameter is 4.1 mm and length is 12 mm – and soft tissue was excluded (Figures 1 and 2). Part of the maxilla, with fixed boundaries, was included. The element mesh used in the FEM model consisted of about 900 solid brick elements with a higher-order displacement assumption and slight refinement of the mesh in the bone tissue region close to the implants. As a control, a convergence study on mesh size was carried out. A factor 2 mesh refinement in each direction (eight times as many elements as in the model presented here) produced only negligible changes in stress levels.

In the uncoupled model, three conventional loading situations on the left side of the maxilla were investigated: only implant L1 was loaded, only implant L2 was loaded, and only implant L3 was loaded. In each situation, only the implant that was to be subjected to loading was connected to the prosthesis. Stresses around all three implants were studied in each loading situation. The implants on the right side were presumed to behave in a similar manner (see Figure 1). In the splinted model, all six implants were simultaneously connected to the prosthesis (see Figure 2).

In both models, bite force was set to 300 N[17] and applied directly above the implant being tested. The direction of the forces applied to implants L1 and L2 had a slope of 10° diagonally from the rear, while implant L3 was subjected to a vertical load of 90°. Von Mises equivalent stress was measured in the bone tissue and calcu-

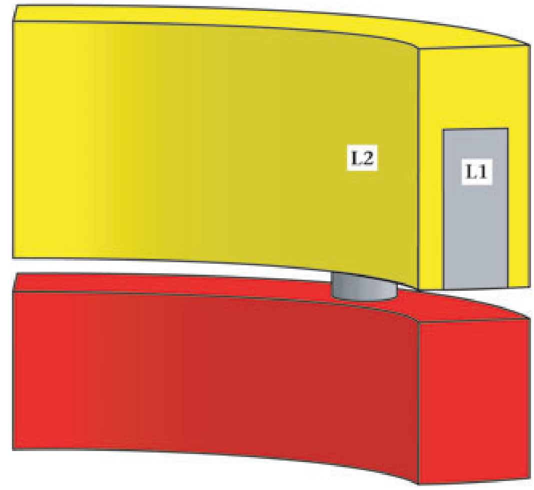

Figure 1 Finite element model showing three of six implants in the maxilla. In this illustration, implants L1 and L3 are uncoupled while implant L2 is coupled. Maxillary bone (yellow), implants (gray), and prosthesis (red).

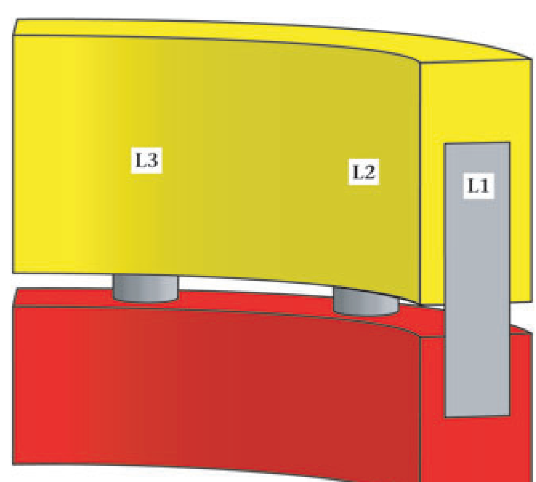

Figure 2 Finite element model showing three (L1, L2, and L3) of six splinted implants in the maxilla. Maxillary bone (yellow), implants (gray), and prosthesis (red).

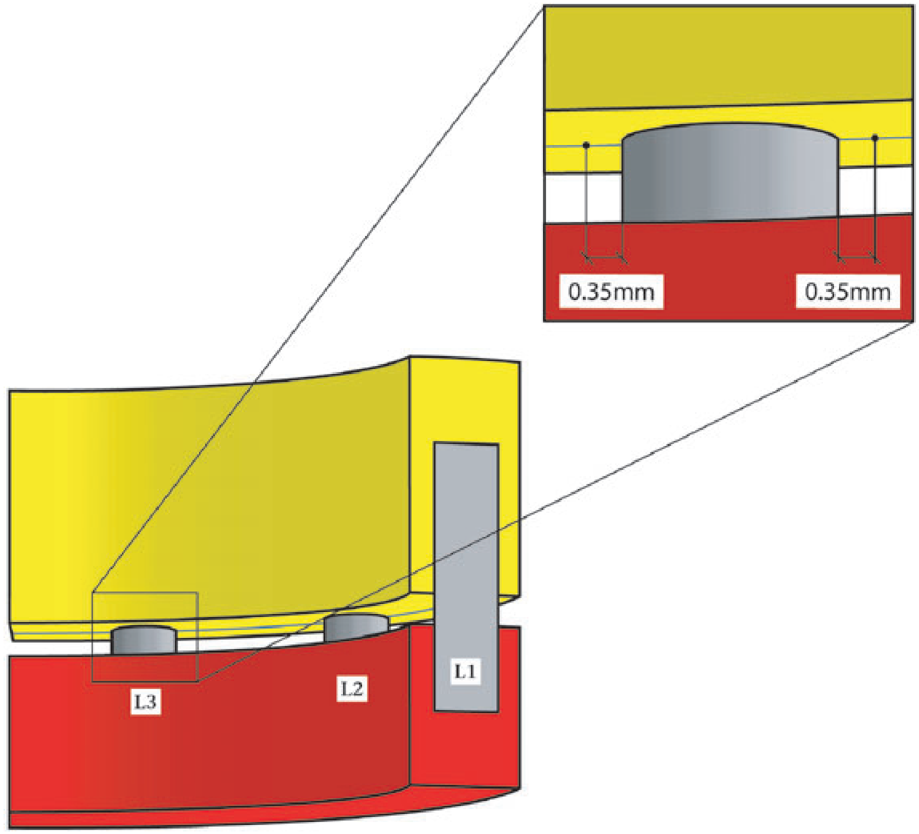

Figure 3 The evaluation points, 0.35 mm on either side of the implant (L3).

lated as the mean of the stresses measured at the midpoints of the mesial and distal elements closest to the implants; the evaluation points were 0.35 mm outside the implants (Figure 3). Two Young's modulus (E) values of maxillary bone were used to simulate different qualities (densities) of trabecular bone. Table 1 lists the material properties of the implants and trabecular bone used in the FEM model.

RESULTS

Tables 2 and 3 present the equivalent stresses in the vicinity of the implants on the left side of the maxilla for each method (splinted or uncoupled), bone density ($E = 560$ MPa, see Table 2; $E = 273$ MPa, see Table 3), and loading situation (loading of L1, L2, or L3). When all six implants were splinted and L1 was loaded, stresses in the bone tissue around L1 and L2 were reduced by a factor of more than 7 (5.7 and 7.2, respectively) compared to the uncoupled method (see Table 2). But the reduction in stress around implant L3 was far less, because the slope of the applied force was vertical (90°) compared to 10° from the rear on L1 and L2.

Table 3 shows stress values around implants in trabecular bone of a lower density than the bone in Table 2.

TABLE 1 Material Properties Used in the Finite Element Model (E = Young's Modulus)

	E	Poisson's Ratio	Reference Number
Trabecular bone I	560 MPa	0.3	20
Trabecular bone II	273 MPa	0.3	21
Titanium	114 GPa	0.3	Institut Straumann, Basel, Switzerland
Acrylate	2.4 GPa	0.4	27

TABLE 2 Equivalent Stresses (MPa) in Bone Tissue Surrounding Implants L1, L2, and L3 for a Young's Modulus of 560 MPa (Trabecular Bone I) when L1, L2, and L3 are Loaded Individually and the Implants are Splinted Together or Uncoupled in These Three Loading Situations

	L1	L2	L3
Loading on implant L1			
Splinted	1.17	0.40	1.38
Uncoupled	6.65	2.89	0.74
Factor (uncoupled/splinted)	5.68	7.23	0.54
Loading on implant L2			
Splinted	0.39	1.35	1.93
Uncoupled	2.70	6.14	2.71
Factor (uncoupled/splinted)	6.92	4.55	1.40
Loading on implant L3			
Splinted	0.19	0.20	2.99
Uncoupled	0.10	0.50	3.25
Factor (uncoupled/splinted)	0.53	2.50	1.09

The trend observed in Table 2 is more pronounced in Table 3. Specifically, in the splinted method discussed earlier when L1 is loaded, stress in the bone tissue surrounding L1 and L2 is reduced by a factor of nearly 9 (7.0 and 8.8, respectively). Figure 4 illustrates the distribution of stress levels in implant L1, the surrounding bone tissue, and the prosthesis when L1 is uncoupled or splinted (model described in Table 3). Red represents the region of highest stress (100 MPa).

TABLE 3 Equivalent Stresses (MPa) in Bone Tissue Surrounding Implants L1, L2, and L3 for a Young's Modulus of 273 MPa (Trabecular Bone II) when L1, L2, and L3 are Loaded Individually and the Implants are Splinted Together or Uncoupled in These Three Loading Situations

	L1	L2	L3
Loading on implant L1			
Splinted	0.92	0.33	1.26
Uncoupled	6.45	2.90	0.74
Factor (uncoupled/splinted)	7.01	8.79	0.59
Loading on implant L2			
Splinted	0.32	1.10	1.76
Uncoupled	2.71	5.95	2.72
Factor (uncoupled/splinted)	8.47	5.41	1.55
Loading on implant L3			
Splinted	0.19	0.25	2.82
Uncoupled	0.10	0.50	3.16
Factor (uncoupled/splinted)	0.53	2.00	1.12

DISCUSSION

This study found that splinting dental implants strongly reduces stress levels in the surrounding bone tissue, especially when the implants were exposed to an angled force.

Concerning material description, the present study is in clear contrast to most other dental FEM studies that have focused on osseointegrated implants in healed bone tissue. Information in the literature about the precise material properties of maxillary trabecular bone is scarce. Trabecular bone is the dominant type of bone in the maxilla, especially in the posterior regions where the surrounding compact bone often has a thickness less than 1 mm.[18] In our model, the maxilla was designed to be of homogenous trabecular bone and to be isotropic and linearly elastic.[19] We used the same *E* proposed by Zhang and colleagues[20] in their FE modeling of the facial skeleton. When the *E* of the bone tissue was lowered to simulate less dense bone, stress reduction was even more pronounced. But it is important to point out that these are in vitro results; they are qualitative in nature and their clinical significance may be limited.

Although the proportion of trabecular bone is generally higher in the maxilla than in the mandible, bone density varies and is generally lower in the posterior parts.[9] Furthermore, properties of unhealed bone surrounding the implants are difficult to predict. So, a second group of simulations was carried out to simulate bone with lower density. A comparable *E*, slightly less than 50% of the value in the first model, was used in the second model. This value was actually proposed by Carter[21] for the posterior mandible, but was considered comparable to values for unhealed bone because trabecular structures of unhealed bone and bone in the posterior part of the maxilla are similar, and because one of the primary biomechanical functions of trabecular bone is to withstand compressive loading.[9] The prosthesis in the simulation was made of polymethylmethacrylate and is a pattern we used for one of the patients in a previous study on immediate loading of dental implants.[11] Within the limitations of the model – the implants were modeled as cylinders and soft tissue was excluded – this qualitative study aimed to illustrate force distribution in the maxilla when implants are splinted and when implants are uncoupled.

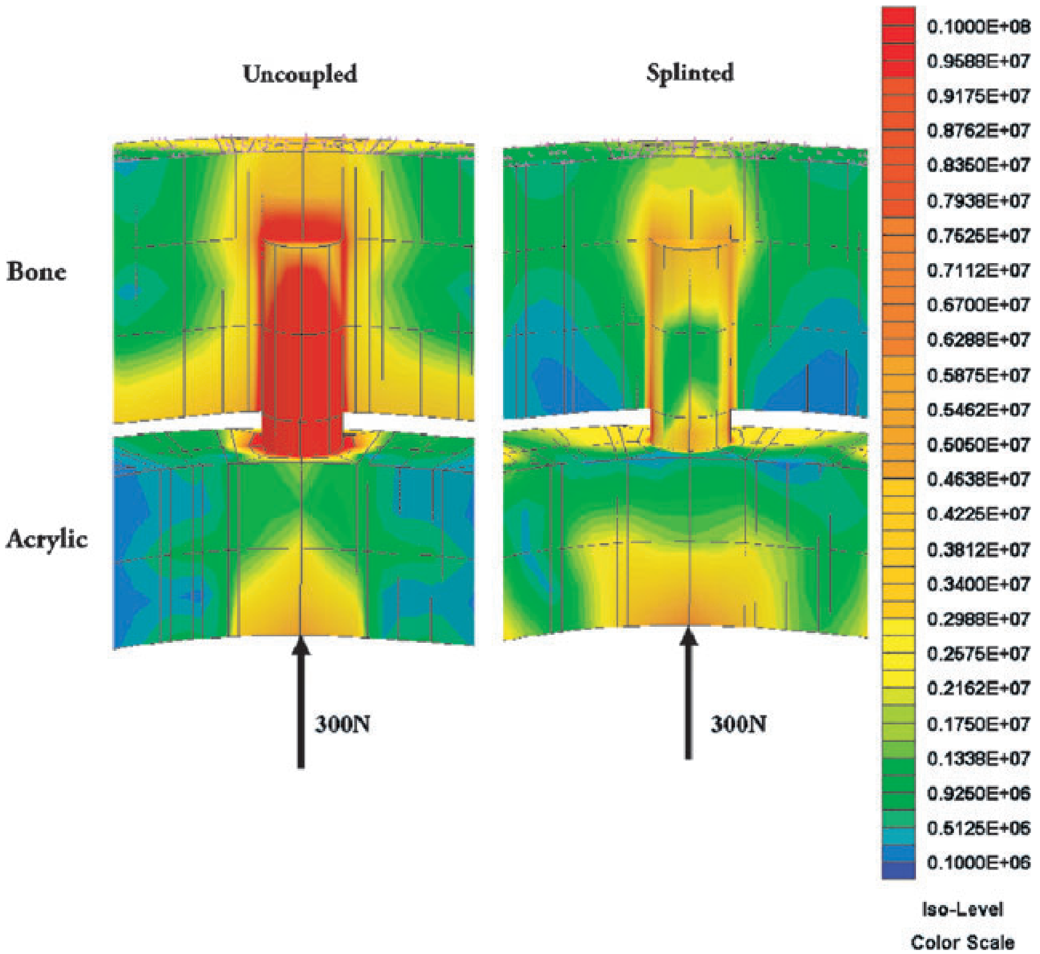

Figure 4 Distribution of stress levels (Pa) in the prosthesis, in implant L1, and in surrounding bone tissue (Table 3) when L1 is loaded with a force of 300 N at a 10° slope diagonally from the rear and is uncoupled or splinted. Red represents the region of highest stress (100 MPa).

FE simulations used to study the stress distribution in implants and surrounding bone tissue have mainly been modeled on the human mandible.[15] Lai and colleagues[22] found in their study on stress distribution around a single osseointegrated implant that high stresses in bone are always located around the neck of the implant. Günter and colleagues[23] carried out a FEM analysis of two dental implants splinted with a bar in the mandible and found that splinting lowered the highest stress at maximum occlusive force by 704% compared with uncoupled implants. A stress reduction of almost 60% during chewing was observed. Another study compared load on solitary implants with load on four implants connected with a bar in the intraforaminal region of the mandible and found that the most extreme forces were always located around the neck of the implants.[24] The authors observed a reduction in the magnitude of the principal extreme stresses that occurred with the connected implants compared to the solitary implants. The results of the present study are mainly in agreement with the findings of these studies.

In an in vivo experimental animal study, crater-shaped defects were found in the bone tissue surrounding uncoupled implants because of adverse dynamic loading.[25] As in that study, findings in other clinical studies – of crater-shaped bone defects surrounding implants – are believed to be caused by adverse loading; but in those studies, the defects were thought to be initiated by removable prostheses.[5,26] If the assumption that bone material, like inorganic material, exhibits a stress-dependent damage/fatigue behavior upon repeated loadings and culminates in bone loss is correct, the present study indicates that such bone loss is less pronounced with splinted than with uncoupled implants. This has also been found clinically.[10,11]

Use of the FEM in the present study has been valuable in gaining understanding about the prerequisite for immediate loading of dental implants. In future studies, FEM could also be of interest to use in analyses of whether implant splinting can compensate for poor implant stability in the bone tissue and in estimates of the optimal number of implants needed to support a maxillary prosthesis.

CONCLUSION

Bone tissue surrounding splinted implants was found to exhibit a pronounced reduction in stress compared to bone tissue surrounding uncoupled implants. From a purely mechanical viewpoint, splinting is likely to positively affect healing after surgery.

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