Mechanical Response to Functional Loading Around the Threads of Retromolar Endosseous Implants Utilized for Orthodontic Anchorage: Coordinated Histomorphometric and Finite Element Analysis

Jie Chen, PhD*/Michael Esterle, MENG**/W. Eugene Roberts, DDS, PhD***

A 3-dimensional bone-implant finite element model was created. The objective was to further investigate the mechanical environment of cortical bone adjacent to the threads of a retromolar endosseous implant used for orthodontic anchorage to mesially translate mandibular molars in response to normal functional loading. This study emphasizes the stress invariants around and between the threads of the implant for future comparison to histomorphometric data from an ongoing clinical study. A strong stress pattern change was found immediately around the implant, which was reflected by a moderate change of stresses between the threads and a significant increase in stress at the tips of the threads.
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Key words: dental implant, finite element analysis, mechanical response

The remodeling of surgically devitalized bone at the implant-tissue interface is essential for achieving rigid osseous fixation ("osseointegration") of an implant. Previous research has documented the biology related to routine success in achieving rigid integration of endosseous implants.[1–7] Recent histomorphometric results have demonstrated a long-term sustained elevation of bone remodeling activity at the bone-implant interface in 4 species: humans, rabbits, dogs, and monkeys.[2] A direct effect of implantation is the change in mechanical environment around the implant. This change may relate to the mechanism of intense bone remodeling that appears to sustain osseointegration. Investigation of the mechanical environment related to the surface geometry of the implant is appropriate.

Roberts et al[5] reported a high remodeling rate that was originally estimated at about 30 percent per year but was recently shown to be about 10 times higher[2] for cortical bone in the threads of a 2-stage endosseous implant placed in the retromolar region of the mandible for orthodontic anchorage (Fig 1). In the first stage, an endosseous base was implanted into the mandible, and at the second stage, a transmucosal post was fixed to the base and an orthodontic force was applied to it. The implant was utilized as rigid anchorage to translate 2 molars 10 to 12 mm mesially into an atrophic edentulous ridge.[5] It was observed that the bone remodeling rate was high during the second stage of implantation. This observation has been confirmed by 5 clinical cases (results from 2 of the 5 cases were reported earlier[2] and reports of results from more cases are in preparation). Despite the clinical and biologic data, it is still not clear what changes occurred in the mechanical environment around the implant and whether the

*Associate Professor, Department of Mechanical Engineering, Purdue University at Indianapolis, Indianapolis, Indiana; and Department of Oral Facial Development, Indiana University, Indianapolis, Indiana.
**Engineer, Eli Lilly and Company, Indianapolis, Indiana.
***Professor, Department of Mechanical Engineering, Purdue University at Indianapolis, Indianapolis, Indiana; and Department of Oral Facial Development, Indiana University, Indianapolis, Indiana.

Reprint requests: Dr Jie Chen, Department of Mechanical Engineering, Indiana University-Purdue University at Indianapolis, 723 W. Michigan St., Indianapolis, IN 46202. Fax: (317) 274-9744. E-mail: jchen@engr.iupui.edu

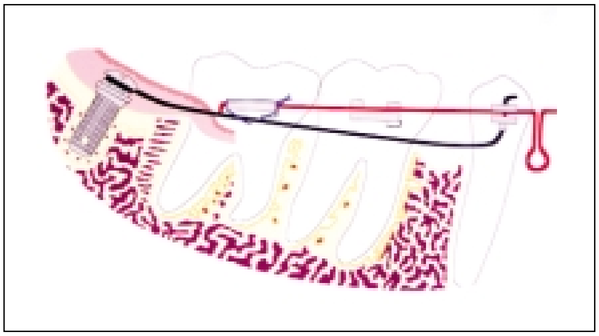


Fig 1a This drawing demonstrates the indirect anchorage mechanism in the sagittal plane. Note that the anchorage wire *(black)* is gingival to the archwire *(red)* that is used to close the space. The blue ligature tie from the third molar prevents extrusion during space closure.

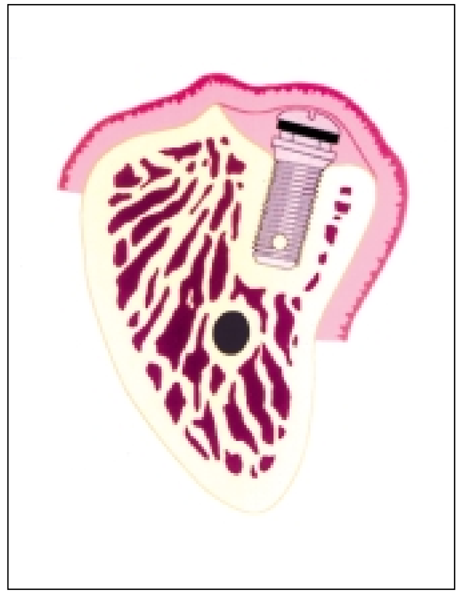


Fig 1b Frontal plane of a cross section through the implant with anchorage wire *(black)* attached is firmly anchored in cortical bone. Reprinted from Roberts et al[12] with permission from the Harvard Society for the Advancement of Orthodontics.

elevated remodeling rate is related to the change in the mechanical environment. Evidence from the 5 clinical cases provides a good experimental model for evaluating the mechanical parameters that initiate bone remodeling. From an orthodontic perspective, the critical question is whether rigid integration is maintained or altered when therapeutic loads are superimposed on function. A mechanical model can be helpful in answering the questions.

The finite element (FE) method has been used to investigate the mechanical environment in the human mandible.[8–11] Previously, unique FE models of the human mandible with and without an endosseous implant were created to simulate the clinical cases.[8,10] Stresses corresponding to different loading cases were studied. Those loading cases corresponded to an occlusal force applied to 4 different locations (ipsilateral premolar, contralateral premolar, incisor, and bilateral premolar). It was concluded that the bone stress distribution around an endosseous implant in the retromolar area is not affected by functional loadings (different loading cases). The mechanical stress changes adjacent to the implant are attributable mainly to implantation under functional loadings and are not substantially changed by orthodontic force. The stress elevation occurs mainly within 1 mm of the implant surface.[8] However, detailed stresses between and around the implant threads were not studied.

To further investigate the mechanical environment immediately adjacent to the implant surface, the elements around the implant need to be further refined. Commonly used interactive mesh refinement or rezoning methods may not be used for this study. These methods are normally used for models with uniform material property. It was not practical to use these methods in this study because different materials (cortical bone, cancellous bone, and implant) and complicated geometry (thread of implant, bone-implant interface) were presented around the implant. Therefore, a submodeling technique was developed to study the stresses around and between the implant threads resulting from functional loading on the mandible. The objective was to further reveal the mechanical environmental changes around the dental implant.

Methods

The submodeling technique consists of 2 steps: *(1)* using the existing global mandible model to determine the mechanical environment in the retromolar region, and *(2)* developing a 3-dimensional (3-D) local model, including detailed geometric structure of the implant threads and surrounding bony structure, to calculate the detailed stress distribution at the bone-implant interface. The local model used the displacement and stress field computed from the global model as its boundary conditions. By doing this, the effects of all constraints and the functional loadings on the mandible are transferred to the local model.

The mandible models previously published[8,10] were modified as the global model. Shown in Fig 2 is the FE model of the mandible with its exter-

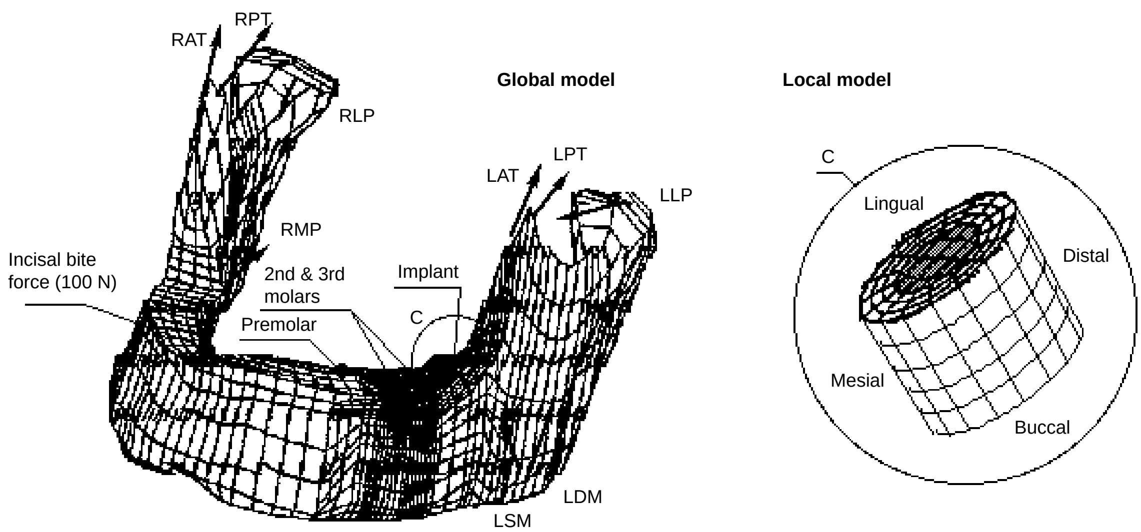


Fig 2 The global finite element model of the mandible with the retromolar endosseous implant and the muscle forces and boundary conditions.

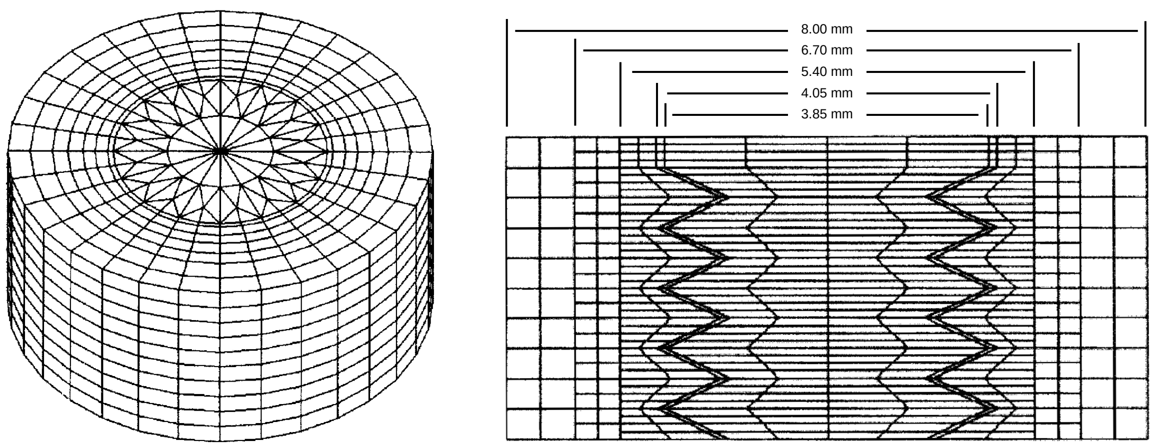


Fig 3 Schematic of the local 3-dimensional finite element model of the implant and the surrounding cortical bone.

nal forces. The local model consists of the implant and the surrounding bone. Only a portion of the implant, ie, the endosseous base, was included. The base was 7.90 mm long with an outside diameter of 3.85 mm and a 1-degree taper.[5] Coordinate transformation was conducted to place the local model in its correct location. A local model having the same geometry but no implant was also created for determination of the baseline stresses.

In the local model, the regions of cortical bone were meshed with 8-node hexahedral elements for agreement with the global model, and inner regions were meshed with 6-node wedge elements to adapt to the threads of the implant. The basic mesh used for the local model consisted of 8,649 nodes and 9,600 elements. The mesh and the model's dimensions are shown in Fig 3.

Locally homogeneous and isotropic material properties were assumed for the mandibular mod-

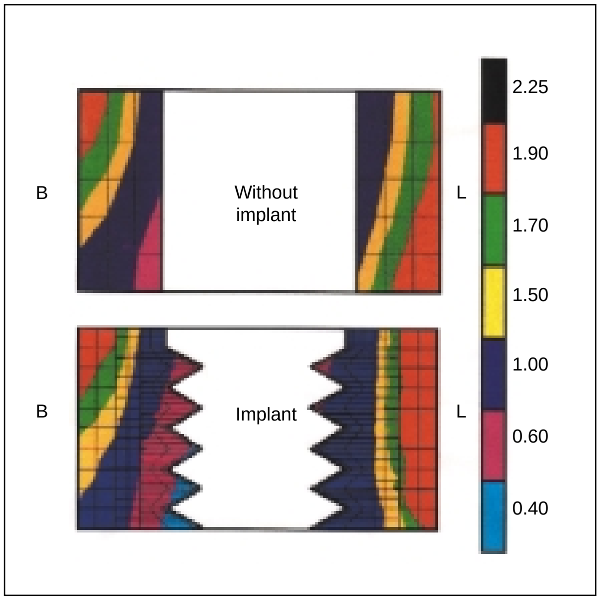


Fig 4 Von Mises stress distribution from the global *(top)* and the local *(bottom)* models in the buccolingual direction of the retromolar region without implantation.

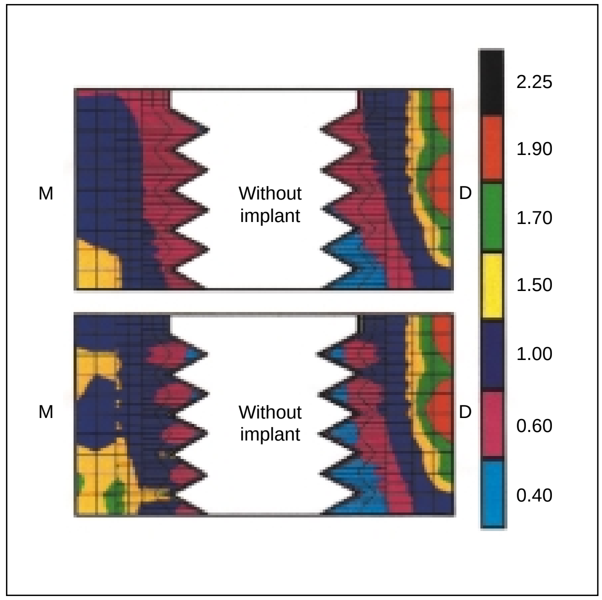


Fig 5 Von Mises stresses before *(top)* and after *(bottom)* implantation in the mesiodistal cross section.

els, since the remodeled bone at the surface of a threaded implant has no preferential orientation.[3] The bone and implant were assumed to have a perfect bond because, in the clinical cases modeled, the implants had been placed in patients for 2 to 4 years and a high degree of bone integration at the interface[5] was observed. The same material properties used in the global model[8] were used in the local model.

After the global model was run, the displacements and reactions of the nodes at the exterior boundary of the local model were computed. These data were applied to the local model as the boundary conditions. Because the stress pattern is independent of different occlusal conditions[8] and only relative changes of stress are of interest, an incisal biting of only 100 N was applied in this study.

PATRAN (PDA Engineering, Cosa Mesa, CA), a computer-aided engineering software for FE meshing, was used as the pre- and postprocessor. The stresses in the model were calculated using ABAQUS (Hibbit, Karlsson, and Sorensen, Providence, RI), a FE stress analysis software. The mechanical environments in the mandible with and without the implant were computed in terms of the mechanical parameters: principal, von Mises, and dilatational stresses. Finally, the variation of these parameters related to implantation was assessed.

Results

The local model was first validated by comparing stresses computed to those of the global model without implantation, so that the effects of boundary conditions and changes of element types on the models could be assessed. Good agreements in both stress pattern and magnitude from the local and global models were observed (Fig 4). The patterns of stress are nearly identical. The locations of the highest and lowest stresses and their values are the same for the 2 models, implying correctness of the boundary conditions applied to the local model. The stresses before and after implantation were then calculated. In this paper, only the relative stress changes in bone are of interest. Stress changes in 2 cross sections, buccolingual (B-L) and mesiodistal (M-D), are reported.

Von Mises Stress. The von Mises stress pattern changed significantly after implantation. Figure 5 shows the stresses around the retromolar region before and after implantation. The net changes of the stresses are shown in Fig 6. In both M-D and B-L, the stress at the tips of the threads increased 2 to 3 times, while the stresses between the threads and in the region 1 mm away from the bone-implant interface experienced negligible changes. The stress increased more symmetrically in B-L than in M-D. In the M-D, major changes occurred at top-distal and bottom-mesial areas (Fig 6).

Dilatational Stress. The change of dilatational stress was moderate compared to those of other stress components (Fig 7). The largest change occurred at the tips of the threads on the mesial side. Negligible changes were found between the threads and in the region 1 mm away from the bone-implant interface.

Maximum Compressive Stress. The maximum compressive stress rose significantly at the tips of the threads on the buccal and distal sides (Fig 8). The elevation was negative because the compressive stress component is expressed as a negative value. On the distal side, the stresses were 3 to 4 times higher than those before implantation. However, there were only small increases in the lingual and mesial sides. The stresses between the threads and in the region 1 mm away from the bone-implant interface showed negligible change.

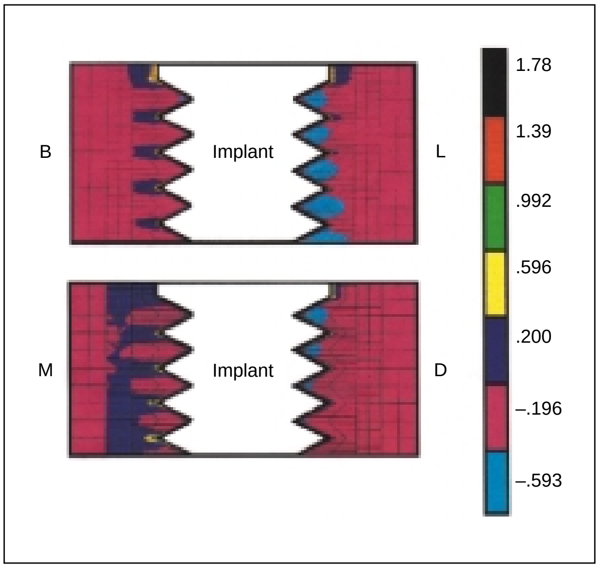


Fig 6 The change of von Mises stress before and after implantation in both mesiodistal (M-D) and buccolingual (B-L) cross sections.

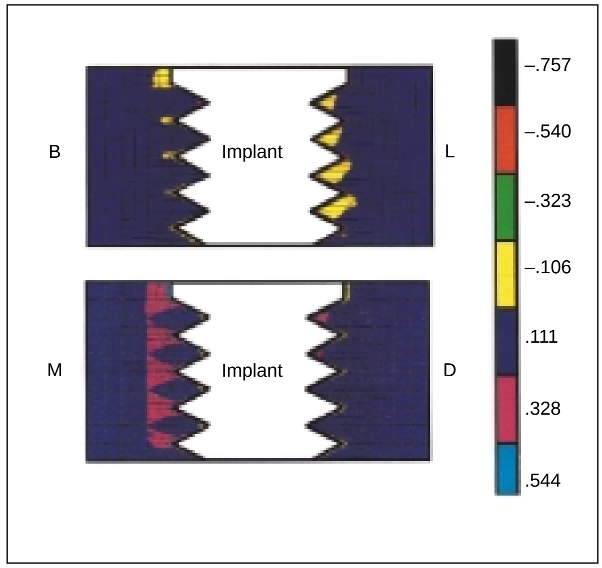


Fig 7 The change of dilatational stress before and after implantation in both mesiodistal (M-D) and buccolingual (B-L) cross sections.

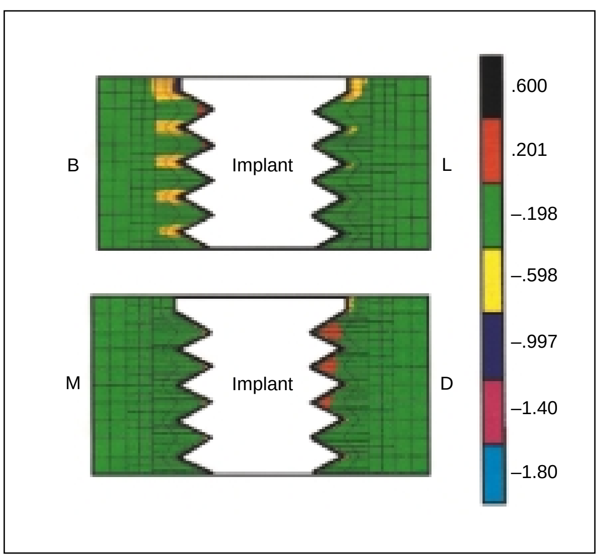


Fig 8 The change of maximum compressive stress before and after implantation in both mesiodistal (M-D) and buccolingual (B-L) cross sections.

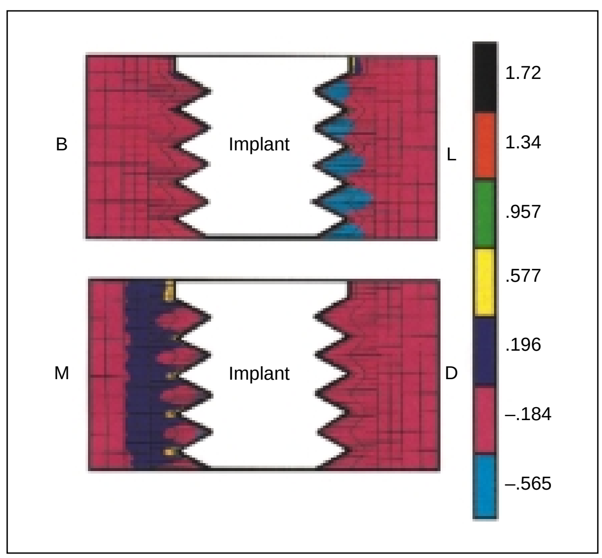


Fig 9 The change of maximum tensile stress before and after implantation in both mesiodistal (M-D) and buccolingual (B-L) cross sections.

Maximum Tensile Stress. In contrast to the maximum compressive stress case, the maximum tensile stress increased markedly at the tips of the threads on the lingual and mesial sides (Fig 9). On the mesial side, the stresses were 2 to 4 times higher than those before the implantation. Only small changes occurred on the distal and buccal sides. The stresses between the threads and away from the bone-implant interface were less affected.

Discussion

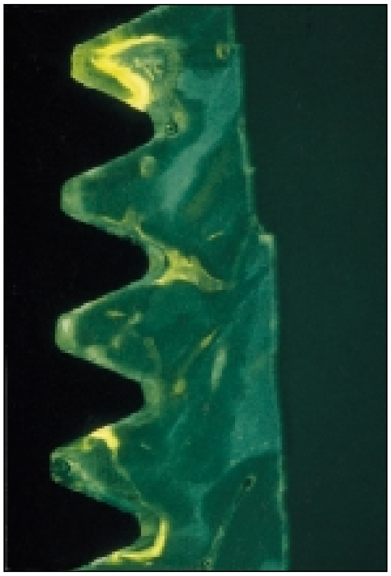
This study has provided a closer look at the stress changes found around implant threads in a clinic study[12,13] in which 5 clinical cases have shown intense remodeling activity at the bone-implant interface. It revealed the phenomenon of stress shielding between the threads and demonstrated stress distribution around the threads. However, this work is still a first approximation because of the assumptions made for the models—homogeneity of materials and perfect bonding between the bone and implant. Regarding the first assumption, the models did not include the heterogeneous aspects of the surrounding bone, such as osteons, Haversian canals, interstitial lamellae, porosity, etc, because their structures cannot be modeled. A more accurate model could be created if the distributions and material properties of these microstructures became available. Regarding the second assumption, more detailed models have been under development to study the effects of bonding on the stresses around the implant, because 100% integration may not be possible to achieve.

In this study, the changes in stress around implant threads were of interest because the stress could later be compared to bone histology at the bone-implant interface. A submodeling technique was developed and validated for the stress analysis. The effects of functional loading on the mechanical environment around the threads of a retromolar endosseous implant utilized for orthodontic anchorage were analyzed.

Functional loading on the human mandible is very complex. It is impractical to analyze every possible loading combination and to assess the corresponding stress levels. However, a previous study[8] showed that the stress pattern in the retromolar area is independent of different occlusal conditions; therefore, using one loading condition and studying only the relative changes in stresses is justified. The stress calculated from this study is within the physiologic range because it corresponds to a single point load. A combined functional loading may significantly increase the stress level. In this analysis, the percentage changes in the stresses have been emphasized, rather than their magnitudes. These results showed that stress changes were significant (2 to 4 times), which can be a good indicator of change in the mechanical environment around the implant. In this study, no attempt was made to quantify the stress levels around the implant, because this work is still a first approximation. The results computed from these FE models are representative, even though only one occluding situation was studied. This report concentrates on regions of high stress, where maximal stress changes occur. These characteristics are related only to the stress pattern.

The intense remodeling activity within 1 mm of the implant surface appears to be the stable, steady-state physiology of an integrated interface, because the same pattern was noted regardless of the loading and duration of implantation. The high remodeling rate occurred around the tips of the implant's threads, which were demonstrated in 5 cases using the same clinical procedure.[12] A typical fluorescence microscopy (Fig 10a) of a section in the frontal plane of an anchorage implant shows intense labeling near the interface of the implant. The prebiopsy labeling schedule was: –19d demeclocycline (150 mg 4 times daily for 1 day) and –12d tetracycline (250 mg 4 times daily for 2 days), and the implant was removed 10 days after the last label. A typical microradiographic image (Fig 10b) of the same section shows areas of relative radiolucency near the implant surface. The implant was used for orthodontic anchorage for 24 months and was removed 2 months after the anchorage wire was removed intraorally. This histologic picture is consistent with osseointegration being maintained by intense bone remodeling within 1 mm of the implant surface. There is a dramatic decrease in the rate of remodeling beyond 1 mm from the implant surface. The present FE study simulated the same clinical cases.[2,12] The zones of remodeling activity favor the areas of highest stress, as demonstrated by the finite element model. The present mechanical (FE) analysis showed a similar elevated stress pattern in the same regions. All 4 stress components showed significant stress elevations that occurred only at the tips of the threads. Only negligible changes were found between the threads and in the region 1 mm away from the bone-implant interface. These findings agree with the previous conclusion that the implantation effects are localized.[8,10]

The correspondence in the stress distribution compared to the region of high bone remodeling around retromolar implants is striking. The present studies of coordinated histologic and FE mod-



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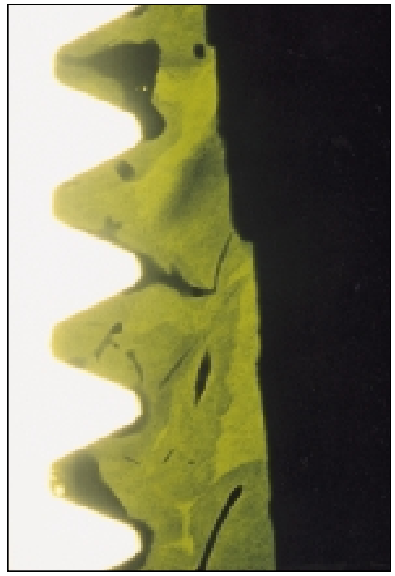

Fig 10b Microradiographic image of the same section shows areas of relative radiolucency near the implant surface. The implant was used for orthodontic anchorage for 24 months and was removed 2 months after the anchorage wire was removed intraorally. This histologic picture is consistent with osseointegration being maintained by intense bone remodeling within 1 mm of the implant surface. The zones of remodeling activity favor the areas of highest stress as demonstrated by the finite element model. Reprinted from Roberts et al[12] with permission from the Harvard Society for the Advancement of Orthodontics.

eling help explain the mechanism for achieving and maintaining implant rigidity despite continuous orthodontic loads. The high remodeling rate may be required to: *(1)* reduce the stresses, *(2)* repair the fatigue microdamage caused by large stress variations at the high stress areas,[14] and/or *(3)* physiologically adapt to the mismatch in the moduli of elasticity between the implant (10×) and adjacent bone.[7]

Intuitively, mismatch in the moduli of elasticity resulted from a lower modulus of the bone. High remodeling activity “softens” the bone,[15] which produces severe mismatch. This mechanism contradicts the common sense that bone adapts to its mechanical environment, if this is a static situation (no further remodeling in the bone). However, in the histomorphometric studies, the bone never reached a steady state after 2 to 4 years of implantation. In this dynamic process, the bone continuously undergoes remodeling in response to mechanical stimuli. This FE study revealed that mechanical environmental changes take place in the areas that high remodeling rates occur, which may provide the continuous stimuli to the remodeling activity. It is speculated that the elevated remodeling activity maintains the bone-implant integration. It appears that this may be a fundamental physiologic mechanism for maintaining relatively new, more compliant bone at the interface. This is a dynamic process that may never end because of the continuous modulus mismatch.

Retromolar implants, as presently defined, are not directly loaded by occlusion, yet their interfaces show the same remodeling gradient as implants that directly support occlusal function.[2] These results suggest that the intense remodeling of interfacial bone may not relate only to occlusal loading, but may be a more general mechanical response to the mismatch in the moduli of elasticity between titanium and cortical bone. This process appears to be a fundamental physiologic mechanism for maintaining relatively new, more compliant bone at the interface. An elevated remodeling rate may be correlated to an elevated stress. However, elevated remodeling activity softens the bone, which reduces the stress. Huja et al recently demonstrated there is a more compliant layer of bone within 1 mm of the implant interface.[15] This more compliant bone is apparently more forgiving of the mismatch in moduli, similar to the cushioning role of a periodontal ligament between a tooth and supporting bone.[16] It is understandable that this process will not reach an equilibrium because of its loading condition. The mandible in the area studied is not in occlusion, but is exposed to dynamic loadings that result in dynamic stresses at the interface.

The change in stress environment may be related to the bone remodeling mechanism. For example, the dilatational stress at the bone-implant interface was affected by implantation. Since the dilatational stress characterizes change in element volume, variation of this stress represents extracellular fluid redistribution, which may create electrical biopotential (streaming potential). This biopotential may be related to bone remodeling.[17] Other parameters may also be good indicators of bone activities. The location of the high stress elevation regions differs among the 4 stress components. The von Mises stress is elevated mainly on the mesial and distal sides, the maximum compressive stress change is localized on the buccal and distal sides, the maximum tensile stress increase is evident on the mesial and lingual sides, and the dilatational stress is primarily elevated on the mesial side. The results from this study show the detailed stress distributions around an implant. When the distribution of remodeling rates around an implant becomes available, the mechanical parameters that are dominant in initiating bone activities can be further elucidated. The present methodology, coordinated with analysis of remodeling around clinical specimens, may help clarify the long-term mechanism of osseointegration.

Summary

The results from this analysis are directly comparable to the histomorphometric data. As a result, the study is expected to elucidate the mechanism of the maintenance of rigid integration under functional loading. These studies may provide further understanding of the long-term mechanism of rigid osseous fixation (“osseointegration”).

Acknowledgment

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