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Stress to the Bone around Orthodontic Implants in the Mandibular Molar Region: A Finite Element Evaluation

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ABSTRACT

Mini-screw implants have been commonly used for orthodontic anchorage. However, the behavior of implants may vary according to their location, inclination, loading position and loading direction. The objective of this study was to apply finite element to analyze stress distribution around mini-implants inserted into the buccal cortical bone, in the inferior molar region, when a force of 3 N was applied, varying implant inclination and loading direction, also simulating immediate loading and osseointegration conditions. We carried out a three-dimensional analysis of a human cadaveric mandible and of a 9 mm length, 1.5 mm diameter titanium implant. The implant model was introduced into the buccal cortical bone, between the first and second mandibular molars. Finite-element analysis of the implant-bone structure was carried out applying a constant force of 3 N at varying angles (15, 30, 45, 60, 75, and 90 degrees), and in five different positions along the bone surface axis (perpendicularly, vertically at ± 10 degrees, and horizontally at ± 20 degrees). Out of all combinations tested, stress affected only the cortical bone, not being intense enough to cause cortical bone resorption. Stress distribution varied slightly (8.55 to 38.74 Mpa) due to implant inclination and loading direction. Immediate loading generated greater tensions (12.70 to 38.74 Mpa) when compared to osseointegration (8.55 to 21.44 Mpa). A force of 3 N did not result in a tension that could cause cortical bone resorption. Immediate loading resulted in greater tensions to the bone, regardless of implant inclination and loading direction.

Keywords: dental implants, finite element analysis, Orthodontics.

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Estresse ao Osso em Torno de Implantes Ortodônticos na Região de Molares Inferiores: uma Avaliação por Elementos Finitos

RESUMO

Mini-implantes têm sido utilizados para ancoragem ortodôntica e seu comportamento pode variar de acordo com a sua localização e inclinação, com a posição e a direção da carga aplicada. Este estudo analisou a distribuição de tensões ao osso em torno de mini-implantes inseridos no osso cortical na região de molares inferiores, quando uma carga de 3 N é aplicada, variando a inclinação do implante e a direção da força, assim como situações de carga imediata e osseointegração. Uma mandíbula humana e um implante de titânio com 9 mm de comprimento e 1,5mm de diâmetro foram modelados, com o implante introduzido na face vestibular entre o primeiro e o segundo molares. Este modelo foi analisado pelo método de elementos finitos aplicando força constante de 3N com angulações de 15, 30, 45, 60 e 75 graus, com o implante perpendicular ao osso e com inclinação vertical de 10 graus e horizontal de 20 graus. Em todas as combinações testadas a tensão afetou apenas o osso cortical, porém não apresentou intensidade suficiente para resultar em reabsorção óssea. Sua distribuição variou (8,55 a 38,74 Mpa) em função da inclinação do implante e da direção da carga. A situação de carga imediata gerou maiores tensões (12,70 a 38.74 Mpa) quando comparada à osseointegração (8,55 a 21,44 Mpa). Conclui-se que uma força de 3N não resulta em tensão que possa causar reabsorção da cortical óssea e que a carga imediata produz maior tensão ao osso, independentemente da inclinação do implante e da direção da força.

Palavras-chave: implantes dentários, análise por elementos finitos, Ortodontia.

INTRODUCTION

The use of dental implants is an excellent alternative to conventional orthodontic anchorage methods, especially in cases of a small amount or poor quality of dental elements, in the impossibility of using extraoral anchorage, or in the case of uncooperative patients (1-3). In the past few years, the design of orthodontic implants has improved; consequently, they have become smaller and easier to use. The advantages of mini-screw implants are their low cost, uncomplicated insertion and removal, and great versatility. Mini-screw implants allow for insertion at several sites, which is an advantage in terms of orthodontic planning (4,5). The criteria for assessment of successful implantation of mini-screws are no signs of inflammation, absence of clinical mobility, and ability to support anchorage during orthodontic treatment (6,7).

Mini-screw implants have been used as anchorage in several orthodontic movements, such as intrusion, extrusion, rotation, mesial and distal bodily movements, and uprighting movement. In most studies, the force applied is between 0.3 and 2.5 N, similar to the force applied normally in orthodontics when such movements are performed (1). A small force (0.1 to 0.2 N per tooth) is recommended for intrusion of anterior teeth, but a greater force (1.5 to 2 N per tooth) is necessary for intrusion of posterior teeth (5).

Finite element analysis (FEA) is a numerical analysis method employed in mechanical engineering, in which the structure being investigated is determined by a given number of elements. The mechanical behavior of each element is described by different equations, which are, in their turn, solved by computational software. FEA can be used

to evaluate implant design, without the risks and costs associated with clinical assays (8). Moreover, experimental studies have confirmed that despite the simplifications of linear analysis with FEA, the method is reliable and efficient, and can be applied in investigations in implantodontics (9-12). FEA also allows collecting data on the distribution of measured tensions, which, in its turn, allows for identifying critical points. This numerical analysis, combined with clinical evaluation, can bring significant advancements in the understanding of different conditions that affect the oral cavity (13).

However, little has been done in the sense of employing mechanical analyses to qualify and quantify the tension status of implants. Therefore, there is a vast field of scientific investigation, which may yield a more robust knowledge base on tensions and orthodontic implants. The aim of this study was to apply FEA to analyze stress distribution around mini-implants inserted into the buccal cortical bone, in the inferior molar region, when a force of 3 N was applied, varying implant inclination and loading direction.

METHODOLOGY

Modeling

This study was approved by the institutional Research Ethics Committee. An edentulous human dry mandible was digitized through a tridimensional scanner (Atos Standard, Gom mbH, Braunschweig, Germany) and its surface was solidified (SolidWorks 2005, SolidWorks Co., Concord, MA, EUA). The distribution between the cortical and medullary bones of different regions was established using dimensions obtained from computed tomography scan data of adult individuals. The mesh generated for the initial global model had 37,356 threads and 20,338 elements. This analysis employed three types of elements: 10-Node Quadratic Tetrahedron, Quadratic Triangular Contact and Quadratic Triangular Target.

According to Roychowdhury et al (14), the modeling of the whole mandible does not affect results, since significant stress effects occur only near the site of loading. Our pilot study, a global assessment of the computational model, corroborated this finding. As a result, the model was split into a local model so as to refine the mesh into 21,362 threads and 12,487 elements, distributed according to Table 1.

TABLE 1 – Mesh composition of the local model.

Material	Nodes	Elements
Cortical bone	14087	7958
Trabecular bone	5134	3348
Implant	2141	1181

The implant had 9 mm in length, and 1.5 mm in diameter (Conexão, São Paulo, Brazil). It was made of pure titanium, with no surface treatment. The implant model was inserted into the buccal cortical bone between the first and second mandibular molars on the left side. The implant simulated traction and/or intrusion of a molar tooth on that same side. The model had 1.7 mm of cortical bone, and 9.7 mm of trabecular bone. Thus, the implant was inserted 1.7 mm into the cortical bone and 4 mm into the trabecular bone; it did not reach the lingual cortical bone. The difference in length (3.3 mm) corresponds to the implant pillar located externally in relation to the bone.

Materials Properties

The mechanical characteristics of the human mandible were obtained from different authors (12-15), according to Table 2. Due to a lack of more accurate models, the cortical bone, the trabecular bone, and titanium were considered to have an isotropic, homogeneous, and linearly elastic behavior. Although different bone qualities result in different biomechanical behaviors (16), we adopted a standard bone structure with two types of bone (cortical and medullary) (17,18).

TABLE 2 – Mechanical properties of materials used in the analysis.

Material	Young's modulus	Poisson's ratio	References
Cortical bone	15000 MPa	0.33	Akpınar et al. (15)
Trabecular bone	1500 MPa	0.3	Akpınar et al. (15)
Implant	110000 MPa	0.3	Baiamonte et al. (12)

Finite Element Analysis

A finite element analysis of the implant-bone structure was carried out using Ansys 9.0 system (Ansys Inc., Houston, PA, USA), by the Group of Applied Mechanics, Universidade Federal do Rio Grande do Sul, Brazil. The analysis determined the areas of stress on the bone tissue around the implant. Von Mises equivalent stress values were used to assess critical areas of the implant-bone structure, and to allow for comparison with other studies.

Load

Figure 1 shows a three-dimensional illustration of the bone structure and inserted implant. The bone deformation was evaluated after application of different loading directions (15, 30, 45, 60, 75, and 90 degrees), and a constant load of 3 N (300 g). The load was applied according to five positions of the implant axis, in relation to the bone

surface: perpendicular to the axis; at 10 degrees from the vertical axis, either cervical or apical inclination; and at 20 degrees from the horizontal axis, either mesial or distal inclination.

Two situations of implant-bone contact were simulated. In total osseointegration, or late loading, there is direct and continuous contact at the implant-bone interface (no relative mobility between the surfaces of the material) (12,15). In immediate loading, mobility at the implant-bone interface may occur (11,19,20).

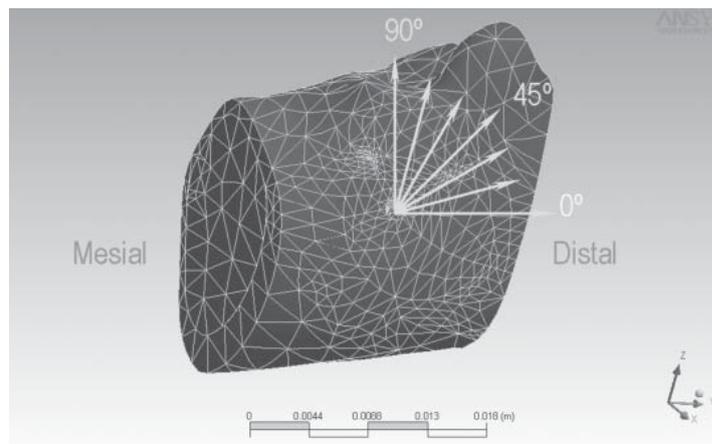


FIGURE 1 – Local model representing the angle of load application.

RESULTS

Table 3 shows the Von Mises equivalent stress values that resulted from the application of 3N load on all combinations analyzed in this study. The distribution of stress on the bone was seen on buccal surface, axial and bucco-lingual cross-sections. The variation in the area under stress was minimal, both in relation to the implant inclination and loading direction. The greater equivalent stress was confined to the cortical bone and, in the present study, was not intense enough to cause cortical bone resorption (103.37 ± 20.9 Mpa) (21).

TABLE 3 – Von Mises equivalent stress (Mpa) resulting from 3N load.

Loading directions	15°	30°	45°	60°	75°	90°
<i>Perpendicular</i>						
Osseointegration	21.440	17.230	15.890	16.160	17.220	18.620
Immediate loading	38.740	24.820	26.030	25.360	25.520	23.480
<i>10° - cervical</i>						
Osseointegration	8.983	9.436	9.591	9.864	9.506	8.551
Immediate loading	12.700	14.200	14.750	14.330	14.200	13.670
<i>10° - apical</i>						
Osseointegration	8.858	8.963	8.859	9.375	9.301	8.645
Immediate loading	15.760	16.340	17.160	19.140	20.840	21.600
<i>20° - mesial</i>						
Osseointegration	9.890	10.160	10.930	11.050	10.490	10.120
Immediate loading	25.290	25.280	25.310	31.550	26.500	24.950
<i>20° - distal</i>						
Osseointegration	14.550	14.830	14.270	13.720	12.510	10.640
Immediate loading	21.930	24.600	26.760	28.090	26.660	21.320

The comparison of equivalent stress as a function of loading direction is represented in Figures 2 to 6, according to the implant position (perpendicular or inclined). The simulation of immediate loading resulted constantly in higher tension values than the simulation of osseointegration. The greater tensions (>30 MPa) were observed when an implant inserted perpendicularly to the buccal surface of the mandible is submitted to a load at a 15 degree angle (Figure 2), and when an implant inserted at 20 degrees from the vertical axis (mesially) is submitted to a load at a 60 degree angle (Figure 5). Both cases simulate immediate loading.

Smaller equivalent stress is observed when the implant is inserted with apical, cervical, or mesial inclination in osseointegration. In situations of immediate loading, the more favorable results were observed in implants with cervical or apical inclination.

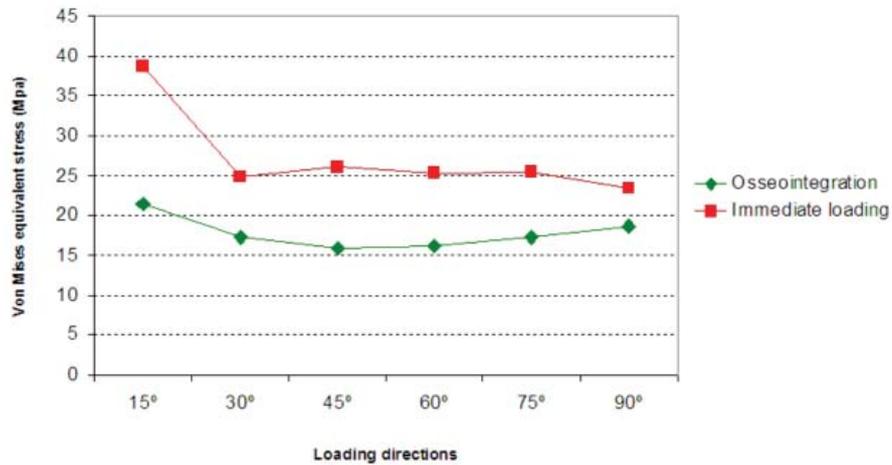


FIGURE 2 – Comparison of Von Mises equivalent stress (Mpa) resulting from a 3N load at different angles, on the implant inserted perpendicularly to the buccal surface of the mandible. Simulation of immediate load and osseointegration.

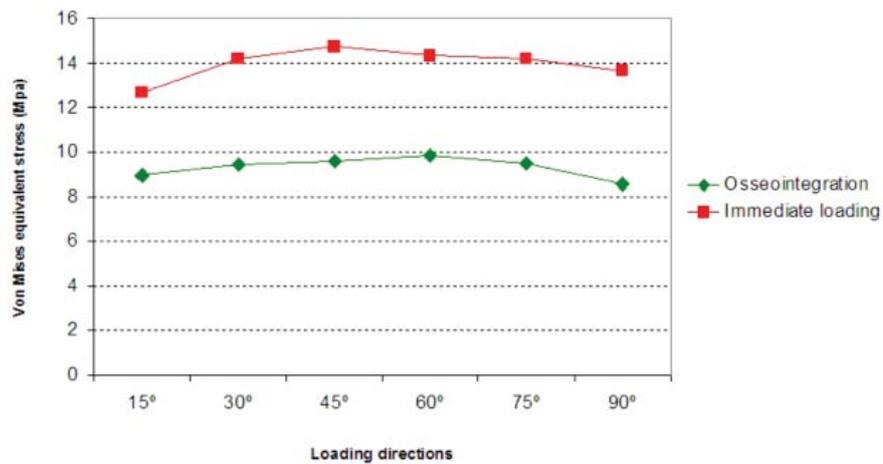


FIGURE 3 – Comparison of Von Mises equivalent stress (Mpa) resulting from a 3N load at different angles, on the implant inserted at a 10-degree angle (cervically). Simulation of immediate load and osseointegration.

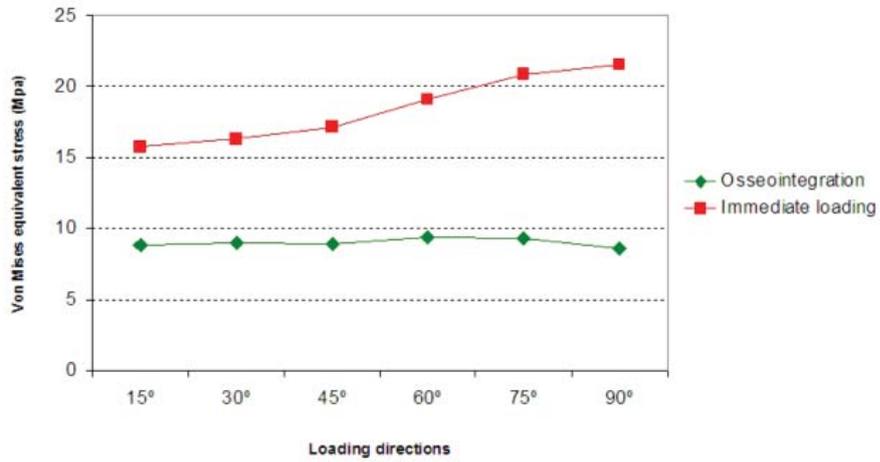


FIGURE 4 – Comparison of Von Mises equivalent stress (Mpa) resulting from a 3N load at different angles, on the implant inserted at a -10-degree angle (apically). Simulation of immediate load and osseointegration.

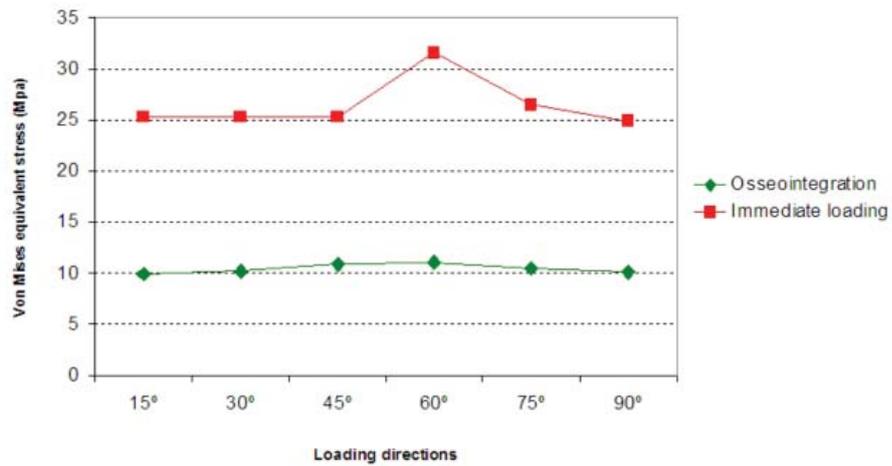


FIGURE 5 – Comparison of Von Mises equivalent stress (Mpa) resulting from a 3N load at different angles, on the implant inserted at a 20-degree angle (mesially). Simulation of immediate load and osseointegration.

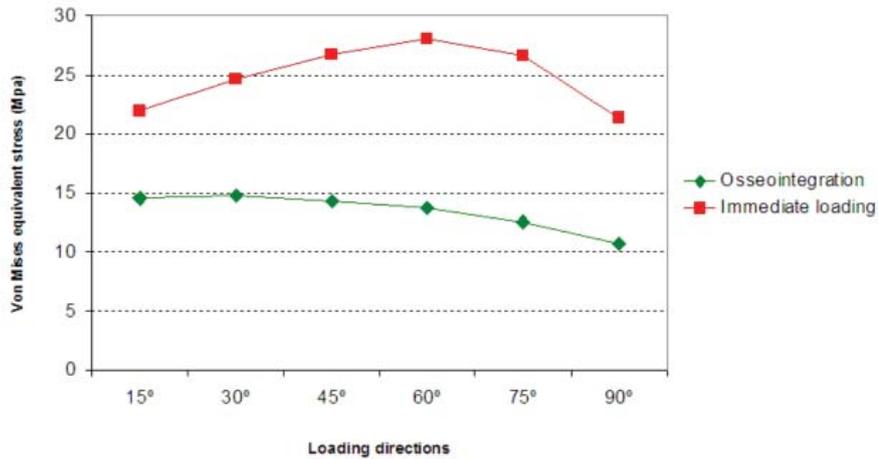


FIGURE 6 – Comparison of Von Mises equivalent stress (Mpa) resulting from a 3N load at different angles, on the implant inserted at a -20-degree angle (distally). Simulation of immediate load and osseointegration.

DISCUSSION

Orthodontic implants with reduced length and diameter, as those applied in the present study, withstand orthodontic stress provided that an appropriate design and implant-bone interface exist. The tensions must be distributed onto the adjacent bone tissue physiologically, so as to avoid surgical trauma or iatrogenic resorption (1). Implant size must also be compatible with the amount of bone tissue available at the implant site.

Considering that the implant analyzed is used only as orthodontic anchorage, and given the several clinical situations that could have been simulated, we chose to insert the implant at the site corresponding to the buccal cortical bone between the first and second mandibular molars. The orthodontic movements to be analyzed were mesial shift of the third mandibular molars, and intrusion of the first and second mandibular molars.

Umemori et al (22) also chose the region between the first and second mandibular molars to introduce a skeletal anchorage system of mini-plates on the buccal cortical bone, for open-bite correction, and obtained satisfactory results. For this site, the use of small implants is recommended, in view of the uncomplicated insertion and removal of mini-implants, in addition to their great versatility and of the site being in close proximity to the inferior alveolar nerve and to the roots of adjacent teeth.

The possibility of intrusion of posterior teeth in orthodontic practice offers great treatment benefits. According to Park et al (5) mini-implants may provide anchorage for intruding mandibular molars approximately 0.5 to 1 mm per month, without damaging the dental pulp or inducing root resorption. As a result, mini-implants can avoid the

need for crown reduction, endodontic treatment, or even the extraction of an extruded opposing tooth.

Cheng et al (6) analyzed 140 mini-implants in terms of orthodontic anchorage, and did not find statistically significant differences between the lengths of implants (5 to 15 mm). According to the authors, extrusive forces on mini-implants should be avoided since they may induce mobility and, consequently, implant failure. In this study, we did not carry out a separate analysis of extrusive forces. However, it is possible that these forces occur when the implant is inclined in the same direction as the applied load.

The different inclinations of the mini-implant in relation to bone surface determine a small variation in the area under stress, according to Gedrange et al (8). Horizontal loading shifted the deformation from the trabecular to the cortical bone. Considering that excessive load is generated around inclined implants, resulting in microfractures in the bone, which, in turn, result in mobility and eventual implant failure. Watanabe et al (23) observed more pronounced implant tension at a 45 degree angle. The maximum horizontal angle for the model analyzed was 20 degrees, due to anatomical limitations caused by the mandibular surface and contact with the implant.

All loading direction simulations in this study showed greater tension on the cortical bone adjacent to the neck of the orthodontic implant. This finding is corroborated by other studies that used radiographic examinations, experimental clinical investigations, and numerical analysis of different conventional implant designs (11, 15). The concentration of tension on the crest of the implant may induce pathological bone resorption, and it is influenced by the thickness of the cortical bone (24). This may lead to failure of osseointegration, being comparable to clinical bone resorption observed around implants (25).

CONCLUSION

The application of a load of 3N did not generate enough tension to cause cortical bone resorption. Moreover, immediate load generated greater tensions, regardless of implant inclination and of loading direction.

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