Analysis of the distribution of stress and deformation in single implant-supported prosthetic units in implants of different diameters

Análise da distribuição das tensões e deformações em reabilitações implanto-suportadas unitárias com implantes de diferentes diâmetros

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Resumo

Introdução: Quando os níveis de tensão e compressão gerados no sistema osso-implante excederem a capacidade óssea ocorre uma fadiga mecânica, resultando em colapso e perda da osseointegração. **Objetivo**: Analisar o comportamento biomecânico em próteses unitárias implanto-suportadas com implantes de diferentes diâmetros na região posterior de mandíbula. **Material e método**: Foram criados três modelos de elementos finitos de implantes cone-Morse de mesmo comprimento, variando-se o diâmetro: 3,3 mm, 4,1 mm e 4,8 mm. A localização do implante foi a região de primeiro molar inferior, com componente e coroa protética sobrejacentes. A mandíbula foi composta por osso cortical e medular. Foi criada malha refinada de 0,5 mm nas interfaces criticas a serem analisadas. O carregamento dos modelos foi realizado nos pontos de contatos oclusais, com uma carga oclusal de 400 N. **Resultado**: Tensão e deformação máximas ocorreram nas regiões cervicais dos implantes em todos os grupos, tanto na análise dos implantes e componentes quanto na análise do osso cortical. Quanto maior foi o diâmetro, menores foram tensão e deformação encontradas no implante. O grupo 3,3 mm apresentou a maior deformação em osso cortical periimplantar, tendo o grupo 4,1 mm a menor deformação, significantemente menor em relação ao grupo 4,8 mm. **Conclusão**: Apesar de o implante de maior diâmetro (4,8 mm) ter apresentado os menores valores de tensão e deformação, o grupo do implante de diâmetro intermediário (4,1 mm) mostrou menor taxa de deformação em osso cortical periimplantar. Portanto conclui-se que o implante de plataforma 4,1 mm apresentou-se mais efetivo biomecanicamente para manutenção óssea periimplantar.

Descritores: Biomecânica; implante dental; análise por elementos finitos.

Abstract

Introduction: When stress and strain levels in the bone-implant system exceed It's capacity, a mechanical fatigue occurs, resulting in collapse and loss of osseointegration. **Objective**: Analyze biomechanical behavior in single implant-supported prosthesis with implants of different diameters in the posterior mandible. **Material and method**: Three different finite element models of Cone-Morse implants with the same height were created, varying the diameter (3.3 mm, 4.1 mm and 4.8 mm). The mandibular first molar area was the location of the implant, with It´s component and overlying prosthetic crown. The jawbone was composed of cortical and cancellous bone. Refined mesh of 0.5 mm was created in the critical interfaces to be analyzed. The loading of the models was performed at the point of occlusal contact with an occlusal load of 400 N. **Result**: Maximum stress and strain occurred in the cervical regions of the implants in all groups, either in the implants or in components as well as in the analysis of cortical bone. The greater the diameter, the lower the stress and strain found in the implant. The 3.3 mm group had the highest strain in peri-implant cortical bone, and the 4.1 mm group had the smallest deformation, significantly lower than in the 4.8 mm group. **Conclusion**: Although the biggest implant diameter (4.8 mm) appears to have lower values of stress and strain, the group of intermediate implant diameter (4.1 mm) showed less deformation rate in the cortical peri-implant bone. Therefore it is concluded that the 4.1 mm implant platform presented a more biomechanically effective peri-implant bone maintenance.

Descriptors: Biomechanic; dental implant; finite element analysis.

INTRODUCTION

Despite the high clinical success rate observed in the treatment with osseointegrated dental implants, they might fail. Occlusal overload stands out as one of the possible causes of delayed failure. Implant designs and inadequate prosthetic construction are among the risk factors for complications, interfering directly in peri-implant tissues[1].

The understanding of the dynamic of peri-implant tissues plays a fundamental role in clinical challenges. The level of scientific evidence has been low, due to the diversity of the results found. Facing an occlusal overload, the effect may be only of bone loss or total loss of osseointegration in implants already osseointegrated. However, in both situations, the peri-implant osseous tissue presents a high rate of remodeling is submitted to occlusal overload[2]. The loss of an implant may be justified by the excess of occlusal load leading to fatigue on the implant[3]. However, cause-effect studies on occlusal overload and damage to the implant are rare, with a low level of evidence and no indication of consequent peri-implant osseous loss, except in cases of inflammation. Obviously, micro-movements between the implant and the bone compromise osseointegration. Nevertheless, in cases of efficient force transfer between these structures, the load may even stimulate peri-implant osseous neoformation and osseointegration[4].

In an experimental study with Beagle dogs, implants were installed in the maxilla using a standard protocol. The test group consisted of applying gradual and progressive static force on the implant posts, using an orthodontic device, for the first three weeks following the implant. Next, the implants and the peri-implant osseous tissue were removed and analyzed. The histomorphometric analysis showed a greater osseo-implant contact area when compared with the control group. Both the peri-implant osseous density and the reabsorption of the osseous crest showed no difference in relation to the control group. The authors concluded that the application of progressive and controlled orthodontic force was beneficial, leading to an increase in the osseo-implant contact area in dog maxilla[5].

The mechanical issue plays a fundamental role in the survival rate of implants. Regarding natural teeth, the periodontal ligament provides the central nervous system with protective proprioceptive information in cases of parafunctional activities. On the other hand, the lack of this ligament in implants becomes a predisposing factor for occlusal overload, leading to mechanical fatigue and consequent peri-implant osseous loss[6].

To understand the patterns of stress and compression dissipation correctly, in the peri-implant region and its relationship to the physiopathology of osseous resorption, the finite element method has been broadly recommended[7,8]. Occlusal overload may, still, be simulated for the detection of failure due to mechanical issues in Implantology, as this methodology is easily standardized and reproduced[8]. Previous studies using this method have shown that the great concentration of tension/compression occurs in peri-implant osseous crest[9].

Several researchers have tried to minimize peri-implant osseous loss at the expense of the increase of the osseo-implant contact area reducing, therefore, the tension in the area of the peri-implant osseous crest. Thus, several studies focused on testing the increase of the diameter and/or length of the implant or alterations in the macrogeometry thereof[10,11]. Previous studies have shown that the diameter of an implant has significant effects on the generation of tension/deformation of the peri-implant osseous tissue[12,13]. Several authors have suggested that an increase in the diameter favors the biomechanical issue for peri-implant osseous maintenance[14-16]. However, there are other studies that disagree with this[11,17-19].

The aim of the present study was to analyze the biomechanical behavior, after application of the load to implant-supported prosthetic units, in implants having different diameters in the posterior region of the mandible, using the finite element method.

MATERIAL AND METHOD

Three tridimensional CAD models were created to be analyzed by the finite element method. Each model was composed of a hemimandible and a prosthetic implant-component-crown unit of ceramic in the region of the first lower molar. The mandible was differentiated in two layers: cortical and medular. Three cone-morse implants, all 10 mm in length; and 3.3 mm, 4.1 mm and 4.8 mm in diameter were modeled together with their respective prosthetic posts of 2 mm height for the cemented prosthesis. Crowns of pure zirconium were modeled over these, having the same dimensions, with the help of the Solidworks 2013 3D (Solidworks, Waltham MA, United States) program.

Subsequently, the models were exported to the finite element mathematical analysis program, AnsysWorkbench, version 13.0 (SwansonAnalysis Inc., Houston, PA, USA). Each model was composed of 235,000 tetrahedral nodes and 130,000 elements. Convergence analyses were performed at 5% to create models with more accurate meshes.

Cortical and medular osseous tissue were considered anisotropic, homogeneous and linearly elastic. Models of the mandible were made using cone beam computed tomography from the radiology database of the College of Dentistry at the Federal University of Juíz de Fora (UFJF). The references used for both the implants and the components were made of pure titanium with modulus of elasticity of 104 GPa and Poisson ratio of 0.34. For the simulation of gingival tissue, the modulus of elasticity used was 19.06 Mpa and 0.33 was used for the Poisson ratio. For zirconium, the modulus of elasticity was 210 Gpa and the Poisson ratio was 0.31. For the cortical bone, the modulus of elasticity was 12,600 MPa and the Poisson ratio was 0.30. For the medullary bone, the modulus of elasticity was 1,150 MPa and the Poisson ratio was 0.001[20,21].

The interfaces between cortical and medullary bone and between the implant and each one of the osseous layers were considered in perfect contact, which corresponds to ideal osseointegration. The loading of the models was performed at the occlusal contact points. For the 1st lower molar, the contact occurs on the sliding and grinding surfaces of the buccal cuspids, and on the grinding surfaces of the lingual cuspids. The occlusal loading was characterized by a load of 400N, divided into five application points, with 80N in each region of the molars. The implants were evaluated according to

von Mises and deformation criteria, while the osseous tissues were analyzed according to stress, compression and deformation criteria.

RESULT

The distribution and intensity of stress and deformation were examined individually in each model. It was observed that the patterns found both in the implants and in the components, as well as in the mandibular bone, were not uniform; and, the maximum values of tension were different in each experimental model.

Analysis of Stress and Deformation of Implants and Components

The maximum stress concentration occurred in the cervical threads of the implants, next to the cortical bone, in all situations analyzed. In the abutments analyzed, the stress was concentrated in the cervical portion, in the area of the connection with the platform of the implant (Figure 1).

Quantitatively, the greatest stress in implants was found in the 3.3 mm group. However, the 4.1 mm group showed maximum stress very close to this. The 4.8 mm group showed the least stress on the implant. In regard to the prosthetic components, the greatest stress and deformation occurred in the 4.1mm group, with the 3.3 mm group showing the least stress and deformation in relation to the 4.8 mm group (Figure 2). The greatest implant deformation occurred in the 3.3 mm group; however, the deformation in the 4.1 mm group was also similar to this group. There was practically no deformation in the 4.8 mm group. The greatest deformation among the components occurred in the 4.1 mm group. The 4.8 mm group showed greater deformation in the component in relation to the 3.3 mm group.
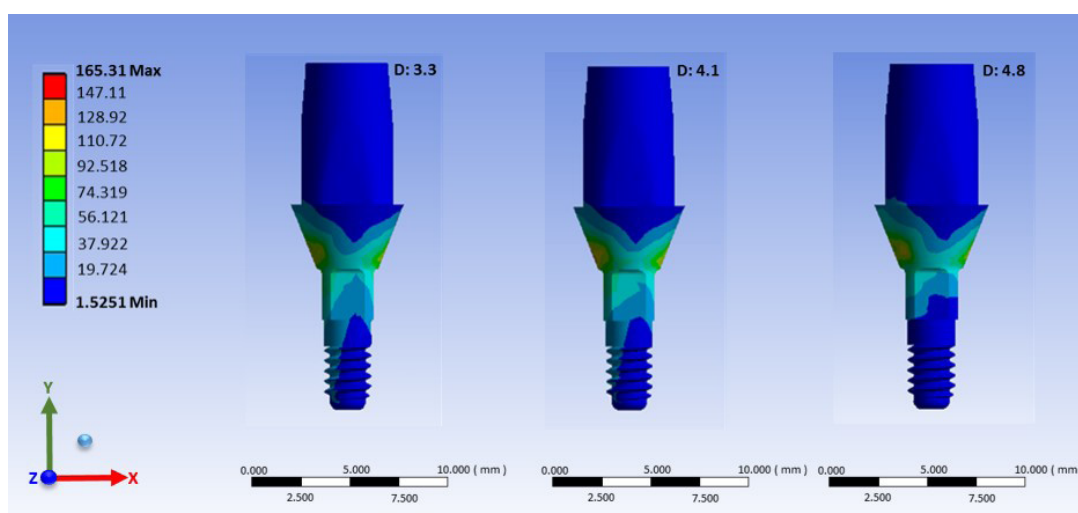

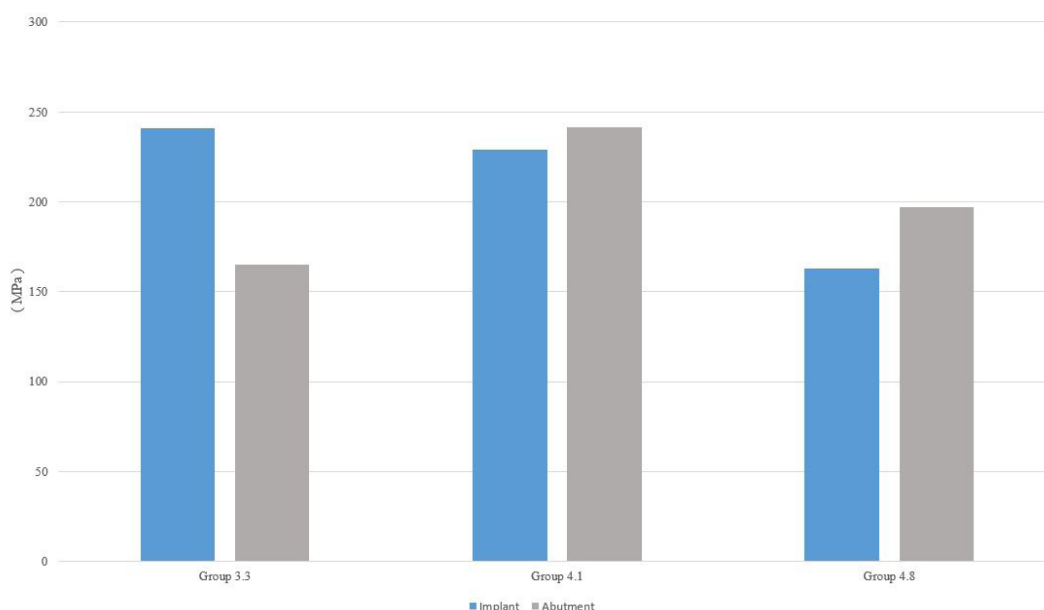**Figure 1.** Stress distribution map on prosthetic abutment.

Figure 2. von Mises equivalent stress in implants and abutments.

Stress, Compression and Deformation Analysis in Cortical and Medular Bone

The distribution map of maximum stress in the cortical bone in all experimental groups showed a similar pattern. The greatest concentration was in the cortical bone around the more cervical spirals of the implants (Figure 3).

When comparing the compression and deformation variables quantitatively, the 3.3 m group showed the highest values. This indicates a significantly greater stress level in the cortical bone, in relation to the others. Consequently, this was the group that underwent the greatest deformation. The 4.1 mm group, despite having shown a higher rate of shearing in relation to the 4.8 mm group, showed less compression and similar tension, resulting in a significantly lower rate of deformation in relation to the 4.8 mm group (Figure 4).

In the medullary bone, the maximum values of compression and deformation were close, among the groups analyzed. However, the rate of deformation of medullary bone in the 3.3 mm and 4.1 mm groups was insignificant when compared to the 4.8 mm group.

DISCUSSION

Occlusal overload as well as the inappropriate distribution of chewing forces on the osseo-implant system may contribute to accelerated osseous resorption and loss of the implant[3]. This suggests that additional investigations should be made in biomechanical studies, as to the distribution and magnitude of stress and deformation that occur in the osseo-implant system. In the present study, three different groups were studied numerically, when submitted to the simulation of chewing load, in centric occlusion, varying the diameter of the implants in order to evaluate comparatively. To validate the numeric models, a comparison was made with the data in the literature. The levels of stress and deformation found in the present study conform with those found in other finite element analyses[19,21,22]. However, some assumptions were adopted in this study: the bone-implant interface was completely in contact, as in a perfect osseo-integration; the cortical and medullary bones were assumed to be linearly elastic – situations that, clinically, are not always true. However, for purposes of comparison, the study is extremely useful.
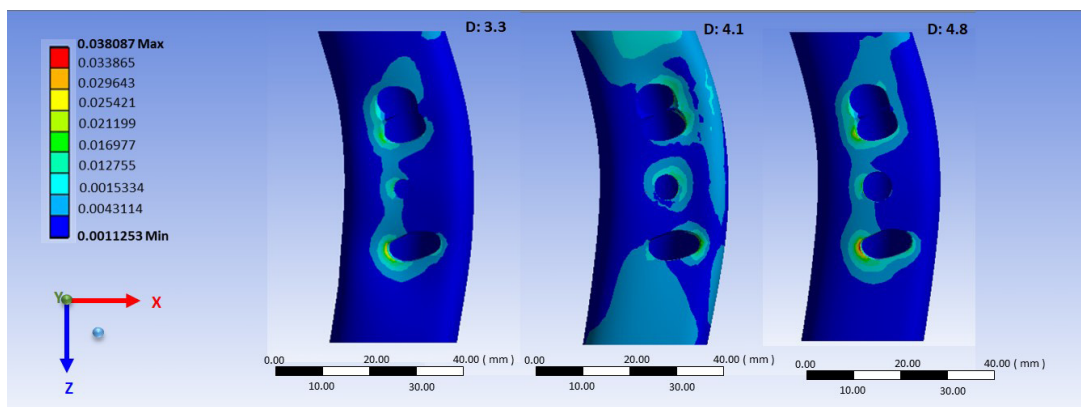

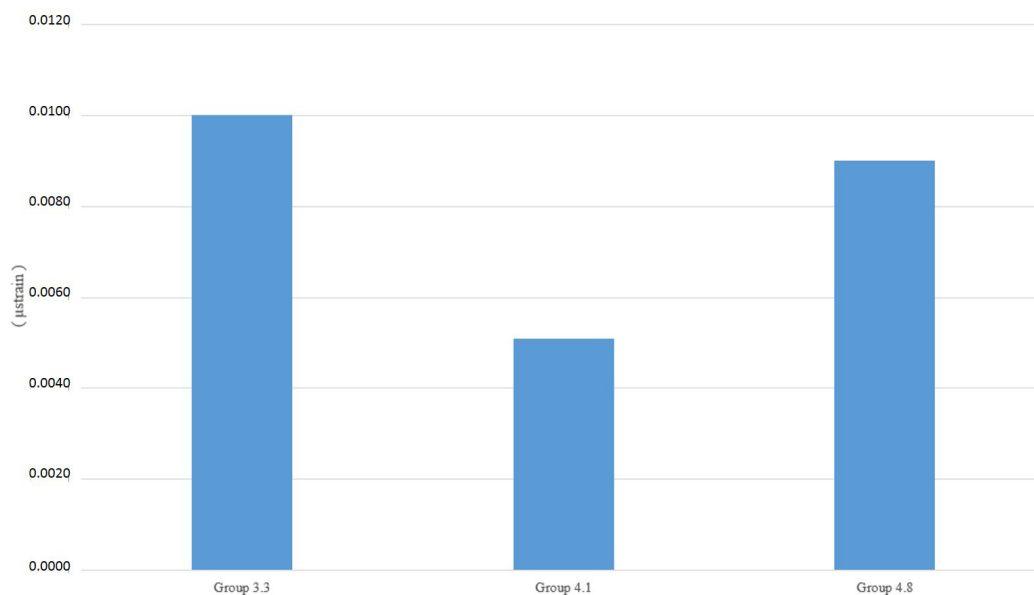**Figure 3.** Stress distribution map on cortical bone.

Figure 4. Strain rates in cortical bone.

The results of the present study showed that a larger diameter implant helps to reduce the maximum values of tension and deformation both in the bone and in the implant. Therefore, it should be the better choice in clinical situations. These results align with previous studies in the literature[12]. The correlation between the present biomechanical study, which shows unfavorable biomechanical conditions in group 3.3 and the clinical evidence previously reported suggest that, to increase the longevity and minimize the stress in peri-implant cortical bone in these narrow implants, it is recommended that a prosthetic crown be made with reduced buccal-lingual size, reducing occlusal interference[14]. The quantitative reduction of the stress and deformation in larger diameter implants occurs as a result of the increased bone-implant interface. Also, the maximum stress is concentrated mainly in the cortical bone, near the implant collar, when a simulation of chewing load is applied. This localized stress corresponds perfectly to the clinical observation of marginal peri-implant bone loss and occurs, invariably, in all implant diameters[19,21].

In the present study, despite the 3.3 mm implants having been proven inferior to those of larger diameter, both the stress and deformation, when clinically indicated, prevent bone grafting procedures in the posterior mandible and/or allow implant placement in reduced mesio-distal space. Therefore, careful recommendation and technique must be used. Therefore, success rate is high, as shown in several studies[12-14]. The use of 3.3 mm implants has also been highly satisfactory in relation to prosthetic units, with no clinical difference when compared to 4.1 mm diameter prosthetic implants in the posterior region of the mandible[14-17]. In the present study, the 4.1 mm diameter implant group showed the lowest rate of deformation in the cortical bone, half that of the 3.3 mm group, although this difference did not reflect distinct results as to the survival of the implants in these various clinical studies[14-17].

However, this success cannot be considered exclusively by survival, since several intrinsic and extrinsic factors impact on the stability of the marginal bone. As intrinsic factors, surrounding osseous quality and quantity, also adjacent soft tissues, should be considered, since the size of the osseous alveolar crest and the distance between the tooth and the implant is of critical importance for their maintenance[15,17,18]. The extrinsic factors involve the design of the implants, the size of the implant-abutment interface, the depth and angle or the intermediate abutments and, mainly, parafunctional habits such as bruxism[15]. Therefore, there is still no consensus or absolute contra-indication for the use of implants with reduced diameter in posterior areas, as shown by some authors in a literature review that shows no difference in the survival of implants with reduced diameter when compared to implants of a regular diameter[17]. According to the same study, the success rate of these implants seems to be reduced only when associated with short implants, i.e., less than 7 mm.

According to a previous study[20], an increase in the angle of force on the implant quantitatively increases the stress and deformation of the cortical bone adjacent to the cervical region of the implant. The oblique force is the condition that imposes the biggest overloaded in the osseo-implant system and should be avoided whenever possible. However, no correlation with any controlled clinical study has been made to date, due to the difficulty in reproducing only axial or oblique forces. In the present study, the simulation was performed applying simultaneous force on five points of the cuspid surfaces on the crown of the implant-component set. Thus, the evaluation became more precise upon simulation of a normal chewing cycle.

Implants with different diameters were tested for the distribution of both stress and deformation on the adjacent cortical bone using the finite element method, varying the angle of application of force[21]. The widest implant was the least sensitive to variations of angle of applied force. However, this study used forces applied directly on the implant platforms without using a prosthetic component or overlying crown. In the present study, the evaluation of stress and deformation on cortical bone was made after the application of load on the prosthetic crown, with the intermediate diameter (4.1 mm) implant group having shown the least stress and deformation, followed by the widest implant group (4.8 mm).

Due to the complexity of the osseo-implant system, a wide range of factors may influence the biomechanical aspects. Therefore, detailed investigation of these factors becomes necessary, including: the shape of the implant, prosthetic abutment and crown[10]; a qualitative and quantitative evaluation of available bone[10,12]; as well as occlusal conditions[10,17,18]. In addition, finite element models, constructed from tomographic images, may simulate clinical situations more precisely. Studies involving implants of different diameters in the posterior mandible should be conducted with animals in order to make a comparison with the results found in the present study.

CONCLUSION

Despite the larger diameter implant (4.8 mm) having presented the lowest values of stress and deformation, the implant group with the intermediate diameter (4.1 mm) showed the lower deformation rate in peri-implant cortical bone, being more biomechanically effective for bone peri-implant maintenance.

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CONFLICTS OF INTERESTS

The authors declare no conflicts of interest.

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