Stress analysis of different configurations of 3 implants to support a fixed prosthesis in an edentulous jaw

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Abstract: This study's aims was to evaluate the stress distribution in a mandibular implant-supported prosthesis and peri-implant bone considering implant quantity, diameter and position using linear 3-D finite element analysis. Models of an anterior jaw comprised 4 groups according to implant quantity, diameter, and position: control group C, 5 regular implants; R, 3 regular implants; W, 3 wide implants; and DTR, 3 regular implants with the distal ones tilted 30° distally. The cantilever was loaded with an axial load of 50 N. Data was evaluated using von Mises stress on implants and maximum principal stress and microstrain on the bone. The W group showed the lowest value of maximum principal stress in peri-implant bone of the loaded side (4.64 MPa) when compared to C (5.27 MPa), DTR (5.94 MPa), and R (11.12 MPa). Lower stress values in the loaded implants were observed in the experimental groups when compared to the C group. However, the unloaded implants presented opposite results. All the screws of the W group presented lower stress values when compared to the C group. However, the R and DTR groups presented an increase in stress values with the exception of the loaded screw. A reduction in the number of implants associated with wider implants reduced the stress in the bone and prosthetic components.

Descriptors: Dental Implants; Jaw, Edentulous; Finite Element Analysis.

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Introduction

Fixed implant-supported prostheses have shown clinical success and proven functional benefits for use in the edentulous mandible.[1,2] Changes in the original protocol have been proposed to simplify and optimize the rehabilitation of edentulous patients, increasing access to treatment.[3-9] Branemark *et al.*[3] initially proposed the use of 3 wide implants to support a fixed implant-supported prosthesis in the edentulous mandible, obtaining a success rate of 98% over 3 years of follow-up. However, this rehabilitation did not achieve similar results compared to conventional implant-support rehabilitations with immediate loading.[3,8,10] Consequently, this therapy is not often prescribed. The unfavorable results were attributed to the angulation of the implants during the surgical procedure and the difficulty in obtaining a passive fit with the prefabricated metallic frameworks.[8,9]

Based on the Novum protocol, Branemark[3] developed a new proposal for a complete fixed mandibular implant-supported prosthesis. This option aimed to provide a less expensive fixed implant-supported prosthesis and a simplified surgical procedure, which could be applied to a broader range of edentulous patients. This new concept of prosthetic rehabilitation consists of a complete fixed mandibular prosthesis supported by 3 implants splinted with a manufactured metal framework, subjected to immediate loading. Implants are placed between the mental foramina. Two distal implants are placed next to the foramina, and a single central implant is placed at the midline.[9] The use of 3 regular implants in this configuration has shown promising clinical results, with success rates above 96%.[8,9] However, data on the limitations and long-term complications of these rehabilitations are still insufficient.[8,9]

Increasing the implant diameter and tilting the distal implants have been proposed to improve the biomechanical behavior by increasing the contact surface area and reducing the average cantilever length of the prosthesis.[5-7,11,12] However, it is unclear how the number, diameter, and arrangement of the implants impact the biomechanical behavior of fixed implant-supported complete dentures. Given the absence of experimental studies that support the clinical use of this configuration, the aim of this study was to use linear three-dimensional (3D) finite element (FE) analysis to evaluate the stress distribution in the peri-implant bone and prosthetic components with different implant configurations. The hypothesis was that the stress distribution in a fixed implant-supported prosthesis is influenced by the number, diameter, and arrangement of implants.

Methodology

A 3D modeling software (SolidWorks 2010, SolidWorks Corp., Concord, USA) was used to build a model of a severely resorbed jaw, with external hex titanium implants (10.0 mm length) between the mental foramens and a fixed implant-supported prosthesis seated on the implants by UCLA abutments and a titanium metal bar (5.0 mm diameter). Models were divided into 4 groups according to the number, diameter, and arrangement of the implants. The control group had 5 regular implants, arranged in parallel; the regular implants group had 3 regular implants, arranged in parallel; the distally tilted regular implants (DTRI) group had 3 regular implants, with the distal implants tilted 30 degrees; and the wide implants group had 5 wide implants, arranged in parallel. Regular and wide implants measured 3.75 and 5.0 mm in diameter, respectively. The bar was the same for all groups. The cantilever extension was 15 mm for the control, regular implants, and wide implants groups. The DTRI group had a shorter cantilever extension due to inclination of the distal implants.

Table 1 - Material properties adopted in this study.

	Young modulus (MPa)	Poisson's ratio
Cancellous bone	1,370	0.3
Cortical bone	13,700	0.3
Ti cp	11,000	0.28
Titanium alloy	11,000	0.33

FE models were obtained by importing the model into a mechanical simulation software package (ANSYS Workbench 11, Ansys Inc., Canonsburg, USA). All materials used in this study were considered to be isotropic, homogeneous, and linearly elastic. The elastic properties used (Table 1) were taken from the literature.[13-16]

Convergence tests, with 6% confidence levels, were performed to guarantee that the results were not influenced by the FE mesh. The implant thread was removed to reduce the number of elements. The elements used in the mesh were tetrahedral with 10 nodes. The final mesh presented an element size of 0.5 mm. The number of elements and nodes generated in the FE models varied within the groups:

- control: 454,375 and 754,763;
- regular implants: 297,236 and 502,513;
- DTRI: 307,877 and 517,612;
- wide implants: 299,260 and 505,617, respectively).

Arrangements of the investigated models are presented in Figure 1.

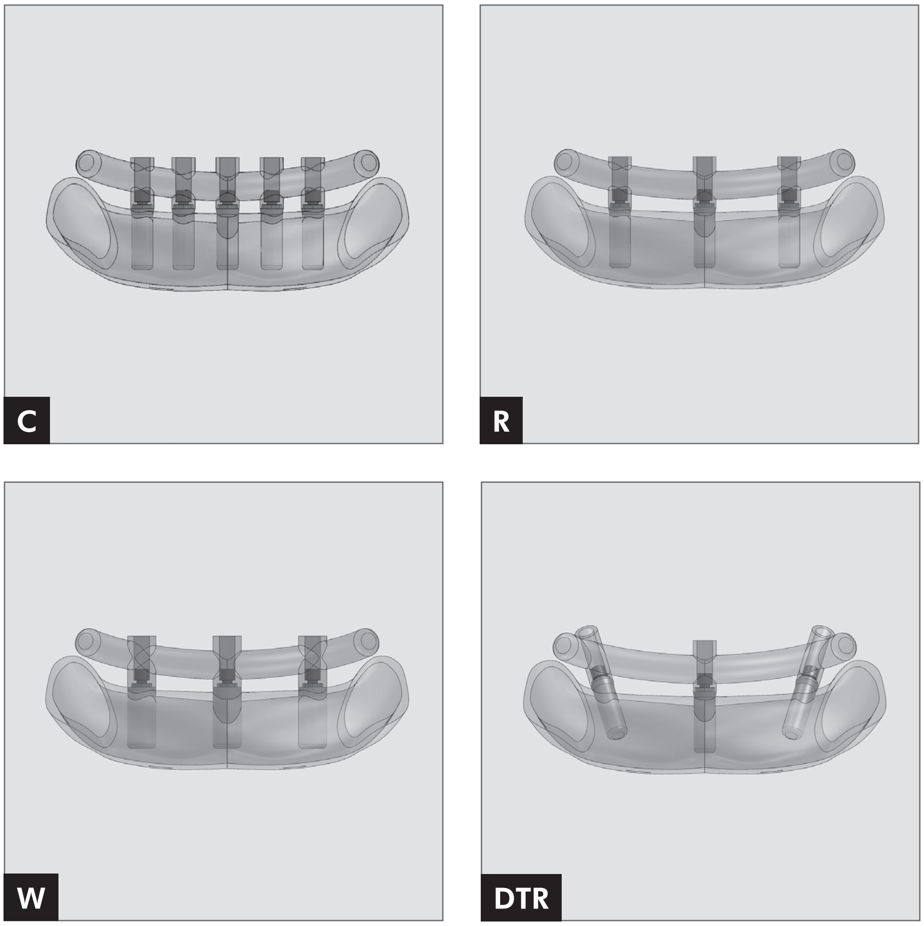

Figure 1 - Three-dimensional model configurations.

Table 2 - Maximum principal stresses (MPa), microstrain values, and percentage of variance in relation to the C group in the peri-implant bone.

Group	Left distal implant		Medial Implant		Right distal implant (loaded)	
	Maximum principal stresses	Microstrain	Maximum principal stresses	Microstrain	Maximum principal stresses	Microstrain
C	3.445	221.33	3.53	222.70	5.27	952.34
R	4.02 (+16.6%)	251.34 (+13.5%)	7.57 (+114.2%)	501.55 (+125.2%)	11.12 (+111.0%)	928.64 (–2.4%)
W	3.38 (–1.6%)	215.16 (–2.7%)	3.48 (–1.5%)	245.67 (+10.3%)	4.64 (–11.8%)	931.49 (–2.1%)
DTR	3.20 (6.9%)	227.56 (+2.8%)	6.70 (+89.5%)	466.54 (+109.4%)	5.94 (+12.7%)	889.79 (–6.5%)

Constraint conditions for the displacement were applied to the mandible base. Loads were applied unilaterally in the right cantilever (50 N). Data for von Mises stresses for implants, screws, and frameworks, and the maximum principal stresses (MPS) and microstrain for peri-implant bone were analyzed, reproduced numerically, color-coded, and compared among the groups.

Results

The MPS and microstrain values on the peri-implant bone are described in Table 2. The wide implants group showed the highest decrease in MPS (–11.8%) in the peri-implant bone of the loaded implant compared to the control group. The regular implants group presented the highest increase in the medial implant (114.2%). The control group presented the highest stress value in the right distal implant (loaded; 62.41 MPa), whereas the regular implants group presented a slight decrease (–0.5%) and the DTRI (–27.2%) and wide implants (–41.2%) groups had larger reductions in stress values.

In all analyzed models, stresses were concentrated in the cortical bone near the implant platform. The highest stress values were observed adjacent to the load application. The stress values decreased progressively as the components were located further from the load (Table 3 and Figure 2).

As shown in Table 4, the wide implants group presented a reduction in the stress values in all screws compared to the control group. However, both arrangements (parallel and tilted implants) with 3 implants of regular diameter presented an increase in stress values, except for the right distal screw (loaded) in the DTRI group.

The stress distribution in the framework is presented in Table 5. The DTRI group presented the lowest and the regular implants group the highest value of stress.

Discussion

The hypothesis of this study was partially confirmed. Reducing the number of implants from 5

Table 3 - von Mises stresses (MPa) and percentage of variance in relation to the C group in the implants.

	Left distal implant	Medial implant	Right distal implant (loaded)
C	5.16	11.27	62.41
R	9.00 (+74.3%)	23.17 (+105.5%)	62.07 (–0.5%)
W	5.94 (+15.0%)	14.53 (+28.8%)	36.66 (–41.2%)
DTR	8.89 (+72.3%)	18.14 (+60.9%)	45.42 (–27.2%)

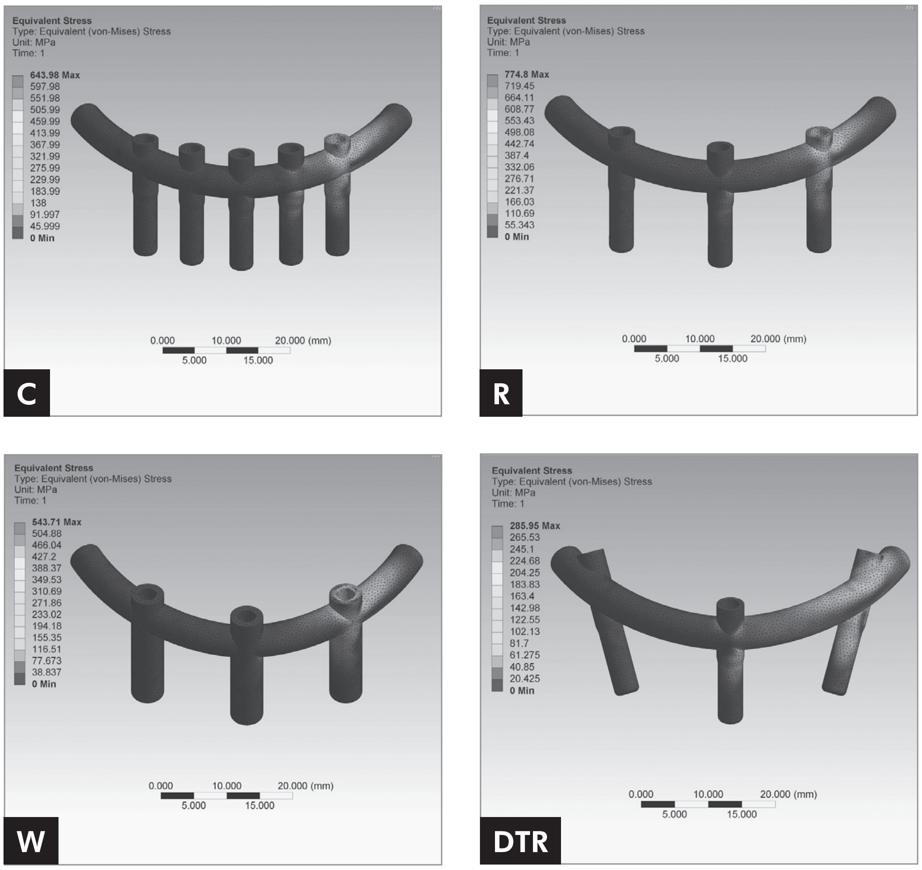

Figure 2 - Stress distribution in the prosthetic components on the different groups.

Table 4 - von Mises (MPa) stresses and percentage of variance in relation to the C group in the distal and medial screws.

	Left distal screw	Medial screw	Right distal screw (loaded)
C	1.91	5.81	19.136
R	2.84 (+48.4%)	11.45 (+97.1%)	21.69 (+13.3%)
W	1.17 (–38.6%)	4.97 (–14.3%)	15.04 (–21.3%)
DTR	2.74 (+43.1%)	9.55 (+64.4%)	18.30 (–4.3%)

(control group) to 3 (regular implants group) increased the stress in the peri-implant bone, implants (except the loaded implant), screws, and framework. However, the stress values were reduced for the wide implants group, which had fewer implants of greater diameter compared to the control group. These results corroborate the findings proposed by the Novum concept.[17] Thus, although high clinical success rates have been obtained for mandibular implant-supported rehabilitations using 3 implants, the use of regular implants in this setting can possibly overload the components, resulting in higher rates of screw loosening, which leads to a greater need for more follow-up appointments.

The possibility of reducing the number of implants was based on the distribution of load between them. According to Duyck *et al.*,[18] the distal and central implants receive the greatest loads, regardless of the number of implants between them or the total number of implants. Such findings suggest that it is not necessary to use a large number of implants to support a mandibular fixed implant-supported prosthesis.[9] In the present study, the regular implants group showed the highest stress values in the peri-implant bone. The stress in the peri-implant bone was higher as it approached the region of load application, whereas the unloaded distal implant presented the lowest stress values for all groups.

When the DTRI group was compared to the regular implants group, the tilted implants were even more important in decreasing stress on the loaded region. These findings confirm previous evaluations of mandibular fixed rehabilitations supported by 4 implants. Those previous studies found a stress reduction when the distal implants were tilted about 30°–45°, due to a reduction in the lever arm and largest cortical bone area for stress distribution.[4,6,7,12] Nevertheless, the DTRI group presented higher levels of stresses in the peri-implant area of the loaded side when compared to the control and wide implants groups. In the screws and framework, components next to the loaded region presented higher stress values than the distant ones. The regular implants group showed the highest values for both screws and framework. The DTRI group presented increased stress values in the unloaded screws (medial and left distal), but the loaded screws had decreased stress values compared to the control group. The reduction in the number of implants could be a risk factor facilitating screw loosening or fracture.[18] A decrease in the number of implants with maintenance of the implant diameter led to a relevant increase in stress in the prosthetic components. Similar studies evaluating the quantity and arrangement of implants did not evaluate prosthetic components.[7,12] Thus, there are few data to allow comparisons.

Table 5 - von Mises (MPa) stresses and percentage of variance in relation to the C group in the framework.

	Framework
C	128.80
R	154.96 (+20.3%)
W	108.74 (–15.5%)
DTR	57.19 (–55.6%)

The unloaded implants and screws of the DTRI group showed increased stress values compared to the control group, perhaps due to the reduction in the number of the implants and the dissipation of stress in the entire system. Although high stress concentrations could lead to long-term fatigue failure,[8,9] the increased stress values were still lower than those observed in the regular implants group.

The increase in diameter is more relevant to increasing the peri-implant bone surface than the implant length. Larger peri-implant bone surface areas provide greater dissipation of stresses when a prosthesis is loaded. In some cases, this situation can compensate for a reduced number of implants in prosthodontic rehabilitations.[19-21] Similarly, in this study, a reduction in the number of implants associated with an increase in the implant diameter did not influence the stress and strain values in the peri-implant bone compared to the control group.

The wide implants group presented higher stress values in the unloaded implants compared to the control group. However, these stresses are probably supported by the implants due to their increased diameter and, as a result, the fatigue resistance is likely increased compared to regular implants.[22] A comparison of the stress values of the wide implants group with the other groups with 3 implants showed more relevant results, indicating a better stress distribution.

These findings agree with the initial concerns reported in the development of the Novum system®, which advocated a reduction in the number and an increase in the diameter of implants.[3] The results also reinforce the hypothesis that failures observed in the Novum system® were possibly caused by inadequate implant positioning during the surgical procedures, due to the difficulty in obtaining a passive fit with prefabricated metallic frameworks.[8] The use of wide implants in the anterior region of the mandible is a limitation on the prescription of this technique, due to the reduced bone quantity in this region. Also, the presence of type I cortical bone requires a change in the bone milling protocol and increases the risk of tissue necrosis.

In all arrangements with 3 implants, the microstrain values were below levels considered harmful to bone.[23] The load applied in this test simulated a conventional denture as antagonist. If the load applied were to be increased, as is the case with opposing natural dentition or implant rehabilitations, then the stress values and strains would be more harmful to the system, possibly compromising the longevity of the therapy. Some studies have shown that the use of 3 implants in an edentulous mandible to support a fixed prosthesis is viable, and that the stresses generated during function are not sufficient to damage the osseointegration. However, these stresses can still be detrimental to the long-term success of the rehabilitation.[8,9]

Although UCLA abutments were used in the present study, micro-units are the most commonly used abutments in clinical application. However, micro-units are more expensive than UCLA abutments. Because the authors sought to evaluate the biomechanics of various implant distributions, UCLA abutments were used to minimize the costs. Use of FE analysis helps to overcome some traditional experimental methodological limitations, by offering information about the biomechanics of a given situation.[13-16] However, FE analysis presents some limitations due to simplifications made in the analysis. The assumption of homogeneous, isotropic, and linearly elastic properties for the bone is common in the literature,[13-16] but could affect the reliability of the results. Another limitation was the removal of the implant threads. Although a previous study observed that the threads influence the biomechanical behavior,[24] their removal was useful for reducing the number of elements and nodes of the FE model. These aspects are limiting factors when the FE analysis comprises a large model with many components.

In this study, conventional rehabilitation with 5 implants did not present the best results for the prosthetic components and peri-implant bone. The use of 3 wide implants showed the lowest stress values for components and peri-implant bone, with the exception of the framework. Further studies using implant threads, nonlinear conditions, and different methodologies, such as experimental studies and clinical trials, should be performed to verify the effects of such arrangements on the longevity of this type of rehabilitation.

Conclusion

The arrangement of 3 regular implants presented the highest stress values in all evaluated regions. The use of 3 wide implants presented lower stress values compared to the standard 5-implant technique.

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