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Influence of diameter in the stress distribution of extra-short dental implants under axial and oblique load: a finite element analysis

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Aim: This study evaluated the influence of a wide diameter on extra-short dental implant stress distribution as a retainer for single implant-supported crowns in the atrophic mandible posterior region under axial and oblique load. **Methods:** Four 3D digital casts of an atrophic mandible, with a single implant-retained crown with a 3:1 crown-to-implant ratio, were created for finite element analysis. The implant diameter used was either 4 mm (regular) or 6 mm (wide), both with 5 mm length. A 200 N axial or 30º oblique load was applied to the mandibular right first molar occlusal surface. The equivalent von Mises stress was recorded for the abutment and implant, minimum principal stress, and maximum shear stress for cortical and cancellous bone. **Results:** Oblique load increased the stress in all components when compared to axial load. Wide diameter implants showed a decrease of von Mises stress around 40% in both load directions at the implant, and an increase of at least 3.6% at the abutment. Wide diameter implants exhibited better results for cancellous bone in both angulations. However, in the cortical bone, the minimum principal stress was at least 66% greater for wide than regular diameter implants, and the maximum shear stress was more than 100% greater. **Conclusion:** Extra-short dental implants with wide diameter result in better biomechanical behavior for the implant, but the implications of a potential risk of overloading the cortical bone and bone loss over time, mainly under oblique load, should be investigated.

Keywords: Jaw, edentulous, partially. Dental implants. Dental prosthesis, implant-supported. Finite element analysis.

Introduction

Implant-supported rehabilitation of the mandibular posterior region is challenging when severe mandibular bone resorption is present. The poor bone availability above the mandibular canal difficult the insertion of regular length implants[1,2]. There are different treatments for this clinical situation, including short dental implants (SDI), >6 to <10 mm in length, extra-short dental implants (ESDI), ≤6 mm in length[3], or surgeries for vertical bone augmentation[2,4]. A recent systematic review showed at 1-year follow-up that SDIs have less morbidity, rehabilitation cost, and better survival rate (97%) than regular implants (92.6%) installed in a grafted bone area[5]. Besides, in this same study, the proportion of patients with biological and mechanical complications was lower for SDIs, with an incidence of 6%, while 39% of complications were reported for regular implants in grafted areas[5]. Meanwhile, over a 5-year follow-up period, it was shown that there was no statistically significant difference in implant survival and success rates between SDIs and regular implants in the grafted area[4]. Also, ESDIs compared to regular implants have similar survival rates, 96.2%, and 99%, respectively, as well as the technical complications incidence, 14.14%, and 18.36%, respectively, after 3-years of follow-up[6].

In addition, a study that evaluated the long-term effectiveness of ESDI reported a survival rate of 94.1% at a five-year follow-up[1]. This slightly lower survival rate, when compared to regular implants, can be explained by its unfavorable biomechanics[7], due to an increased crown-to-implant ratio (C:I) that creates a more significant vertical lever arm and a disadvantageous stress distribution[2]. These implants have a smaller bone/implant contact surface, which leads to increased stresses at the bone and prosthetic components[8]. Therefore, SDI and ESDI generally have a wide diameter (WD) compensating the limitation in high, increasing the surface and its bulk, which improves the stress dissipation[9], leading to better biomechanical behavior[10].

The treatment plan also requires checking the patients' occlusion and the antagonistic type affecting the implant success[10]. In a physiological occlusion predominantly occur axial loads (AL), in the mandibular posterior region, transmitted by the long implant axis to the bone, resulting in an adequate stress dissipation[11,12]. However, when a non-physiological occlusion is present, the resultant occlusal force is an oblique load (OL), creating an unbalanced stress distribution[8]. Therefore, when the high C:I anchored by ESDI is used, the incidence of OL increases the bending moment of the vertical lever arm, causing a non-homogeneous force dissipation, leading to poor prognosis, which may contribute to peri-implant bone loss[8,12]. Clinical and in vitro studies showed that the increased C:I only negatively influences the stress distribution when an OL is present[8,13].

Previous systematic reviews focused on C:I evaluation have shown no significant differences in biological complications and peri-implant health results[14,15], being 2.36:1 the higher C:I evaluated[15]. Meanwhile, a recent four-year retrospective clinical trial concluded that the higher the C:I ratio (0.47 to 3.01), the less the marginal bone loss[16]. However, the biomechanical behavior of a challenging scenario where a 3:1 C:I crown supported by an ESDI, with 5 mm in length, at the severe reabsorbed mandibular posterior region, in the presence of OL, has not yet been investigated. That is critical since it can make the long-term success of this type of rehabilitation uncertain.

Besides, the benefits of using WD in ESDI have not reached a consensus in the literature since clinical and laboratory studies have not found differences in survival rates when assessing different diameters and lengths[2,17]. This fact contradicts the prerogative of better biomechanics due to its larger contact surface[10]. Therefore, there is a need for further studies to evaluate the rehabilitation mechanical behavior[12] before future prospective clinical studies. Thus, by using finite element analysis (FEA), the present study evaluated the influence of WD on the stress distribution of ESDI as support for single implant-supported crowns in the posterior region of the atrophic mandible, with a 3:1 C:I ratio, under AL or OL. For then, to verify if the WD is relevant enough to justify the insertion of an implant that will wear out more bone. The tested null hypothesis stated that WD would have no difference from the RD regarding the stress distribution.

Materials and Methods

Through the computer-aided design (CAD) software (SolidWorks; Dassault-Systemes SolidWorks Corp; Waltham, Massachusetts, USA) were created the 3D virtual models of a single crown, cement layer, cortical and cancellous bone. Also, CAD models of a universal abutment (4.5 x 2 x 6 mm) and two morse-taper implants of 4 x 5 mm (28.274 mm^3, bone/implant contact surface: 101.39 mm^2) and 6 x 5 mm (75.75 mm^3, bone/implant contact surface: 155.36 mm^2) were assessed virtually, and were left 2 mm submerged into the bone, which were obtained by the manufacturer (S.I.N Implant System, São Paulo, SP, Brazil). Two study factors were evaluated: I) implant diameter: 4 mm (RD: regular diameter, being this the control group) or 6 mm (WD) (Fig. 1); II) load angulation: AL or OL (30° off-axis) being applied at the mesiobuccal cusp (Fig. 2)[18]. The bone model had a 12.94 mm height and 16.11 mm of thickness, and a 2 mm layer of cortical bone surrounding the cancellous bone (Fig. 1)[19]. The crown of a mandibular right first molar, 13 mm in height with a 3:1 C:I[15] (Fig. 1), was virtually cemented on the abutment (70-μm layer), and four groups were created: RDAL (regular diameter implant under AL); WDAL (wide diameter implant under AL); RDOL (regular diameter implant under OL); WDOL (wide diameter implant under OL). The FEA models validation[20] was performed by past literature for the location of force application and bone layers dimensions and by past in vivo study for crown and C:I.

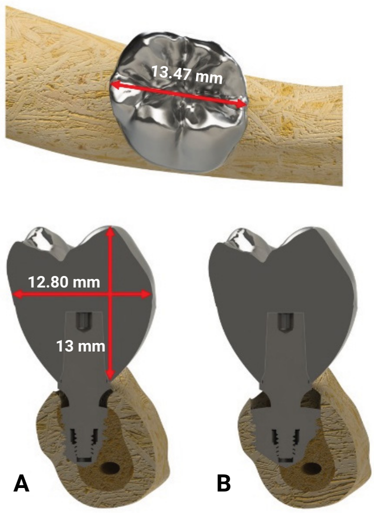

Figure 1. Sagittal view: (A) regular implant diameter, 4mm; (B) wide implant diameter, 6 mm. Dimensions of bone and crown (red) used are equal in all groups.

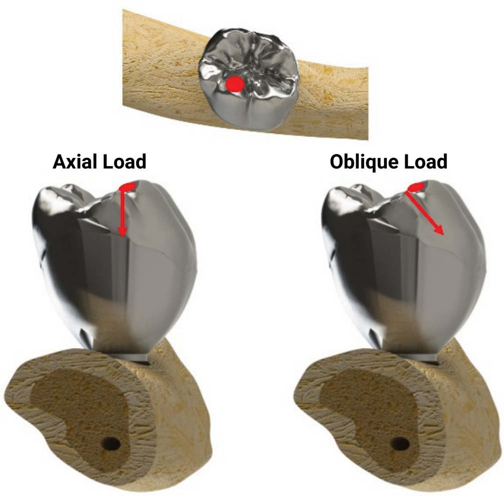

Figure 2. Load angulation applied at the mesiobuccal cusp for different groups, axial load and 30º oblique load.

After assembly, the virtual models were exported to finite element software (ANSYS Workbench 15.0; ANSYS Inc; Canonsburg, Pennsylvania, USA) for a mathematical solution. A tetrahedral mesh was generated with an element size of 0.6 mm after convergence analysis with 5% tolerance. The Young modulus (GPa) and Poisson ratio (δ) of each material were set in the software according to table 1. The number of elements and nodes of each element is described on table 2. All components were considered homogenous, isotropic, and linearly elastic. Also, the contact conditions between implant/abutment were assumed as no separation, and the contacts crown/abutment and implant/bone were assumed as bonded.

Table 1. Mechanical properties of materials.

Material	Young Modulus (GPa)	Poisson ratio (d)
Titanium Grade IV[21,22]	110	0.33
Co-Cr alloy[23]	220	0.3
Cortical bone[24]	13.7	0.3
Cancellous bone[24]	1.370	0.3
Resin cement[25]	18.3	0.33

Table 2. Numbers of nodes and elements of each component.

Components	Nodes	Elements
Crown	16769	9940
Abutment	11121	6327
Cement layer	7862	3966
Cortical bone (RD)	30221	17527
Cortical bone (WD)	30757	17910
Cancellous bone (RD)	28762	17244
Cancellous bone (WD)	30325	18004
Implant (RD)	106384	61350
Implant (WD)	142268	82199

RD, regular diameter groups; WD, wide diameter groups.

Then, the models were fixed in two lateral portions of the bone segment and were submitted to a 200N load on the occlusal surface of the mandibular right first molar (Fig. 2)[8]. The equivalent von Mises stress (σ_{vM}) was used for the implant and the abutment[8,10]. Minimum principal stress (σ_{min}), and maximum shear stress (τ_{max})[8,26], were used for both cortical and cancellous bone. A qualitative analysis was performed for the implants, abutment, and bone, using the colors of the resulting FEA images. The colors varied from warmer (red) to cooler (blue) tones, with the peak stress represented by the warmest tone.

Results

Results for the FEA assessment are presented in table 3. Regardless of diameter, there was a significant increase in stress in all components, over 200%, under OL compared to AL results. Also, the stress was greater on the abutment and cortical bone and less on the cancellous bone and implant for WD groups. A substantial increase in stress was observed in cortical bone for WD groups compared to RD groups, being higher 66.3% for σ_{min} and 99.8% for τ_{max} under AL and higher 125.7% for σ_{min} and 201.7% for τ_{max} under OL (Table 3). For the AL groups, the peak stress concentration was in the area in contact with the apical region of the implant, being the maximum values found at σ_{min} of 72.34 MPa (WDAL) (Fig. 3) and τ_{max} of 42.02 MPa (WDAL) (Fig. 4). Meanwhile, in the OL groups, the highest stress concentration was in the cervical third of the bone, and the maximum values were at σ_{min} 266.7 MPa (WDOL) (Fig. 3) and τ_{max} 130.88 MPa (WDOL) (Fig. 4).

The analysis of σ_{min} and τ_{max} showed decrease stress in the cancellous bone for WD groups, about 44.9% for σ_{min} and 55.9% for τ_{max} under AL and 73.2% for σ_{min} and

71.9% for τ_{max} under OL (Table 3). Also, the images showed a peak stress concentration in the cervical third of the bone in all groups, and the minimum value of the σ_{min} was 9.79 MPa (WDAL) and of the τ_{max} 7.32 MPa (WDAL) (Fig. 5 and Fig. 6). Besides, the σVm evaluation images showed that in all groups, the peak stress area was at the abutment collar level (Fig.7) and in the corresponding region of the implant (Fig. 8). The analysis demonstrated that with the WD, a low increase occurred in the abutment stress of 3.6% under AL (WDAL: 202.94 MPa) and 12.7% under OL (WDOL: 1157.4 MPa) (Table 3). However, a decrease in the implant of 38.7% was observed under AL (WDAL: 185.98 MPa) and 38.2% under OL (WDOL: 873 MPa) (Table 3).

Table 3. Von-Mises criteria (MPa) for implants and abutment, minimum principal stress and shear stress for cortical and cancellous bone (MPa), and the differences between the groups and direction of the load.

	Axial load			**Oblique load of 30º**			**Axial load x Oblique load of 30º**	
	RDAL	**WDAL**	**% stress**	**RDOL**	**WDOL**	**% stress**	**% RDAL/ RDOL**	**% WDAL/ WDOL**
Abutment (σ_{vM})	200.97	202.94	*3.6%	1026.9	1157.4	*12.7%	*511.0%	*570.3%
Implant (σ_{vM})	303.48	185.98	#38.7%	1414.4	873.4	#38.2%	*466.1%	*469.6%
Cortical bone (τ_{max})	21.02	42.02	*99.8%	43.37	130.88	*201.7%	*206.3%	*311.5%
Cortical bone (σ_{min})	43.53	72.34	*66.3%	118.19	266.7	*125.7%	*271.5%	*368.7%
Cancellous bone (τ_{max})	16.62	7.324	#55.9%	73.5	20.66	#71.9%	*442.2%	*282.1%
Cancellous bone (σ_{min})	17.78	9.795	#44.9%	94.19	25.23	#73.2%	*529.8%	*257.6%

RDAL, regular diameter implant under axial load; WDAL, wide diameter implant under axial load; RDOL, regular diameter implant under oblique load; WDOL, wide diameter implant under oblique load; *, increased stress; #, stress decreased.

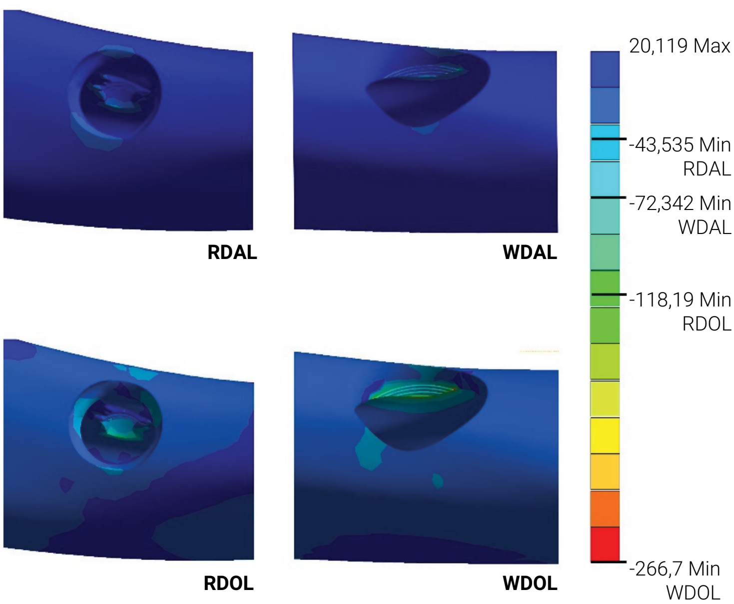

Figure 3. Minimum principal stress peak concentration for cortical bone (MPa) for all groups. Blue to red color represents stress values from higher to lower, respectively.

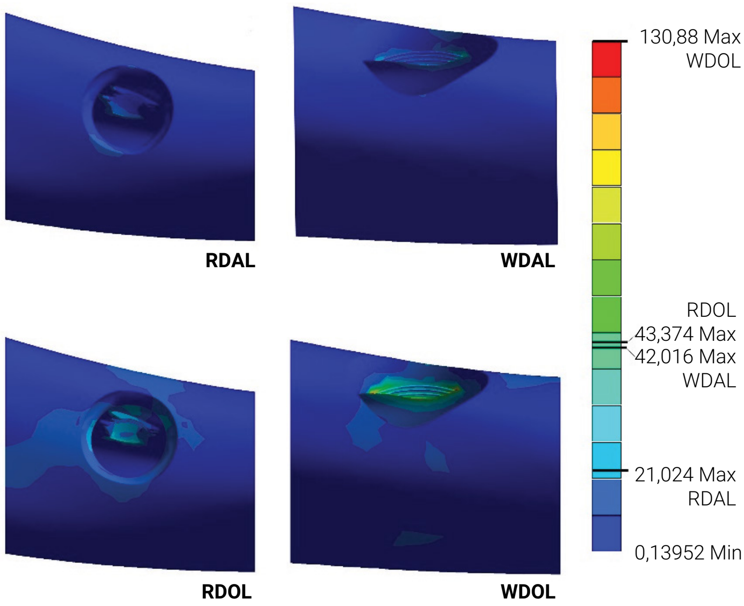

Figure 4. Maximum shear stress peak concentration for cortical bone (MPa) for all groups. Blue to red color represents stress values from lower to higher, respectively.

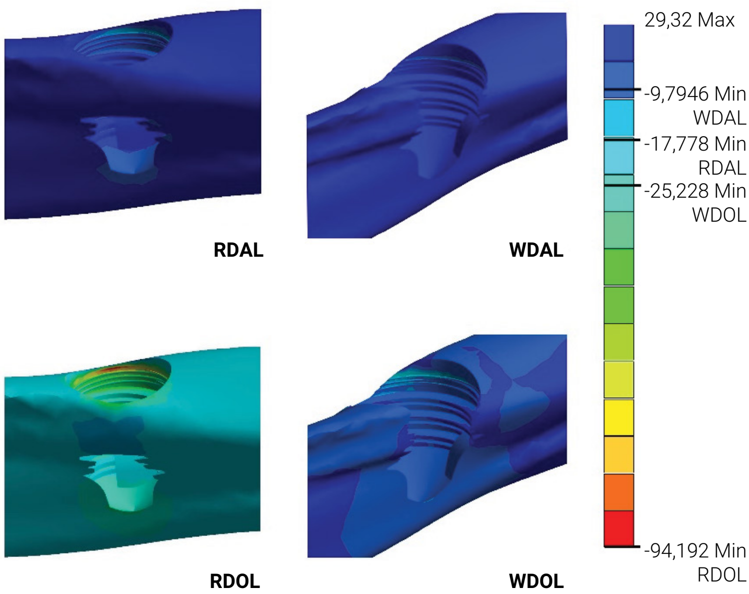

Figure 5. Minimum principal stress peak concentration for cancellous bone (MPa). Blue to red color represents stress values from higher to lower, respectively.

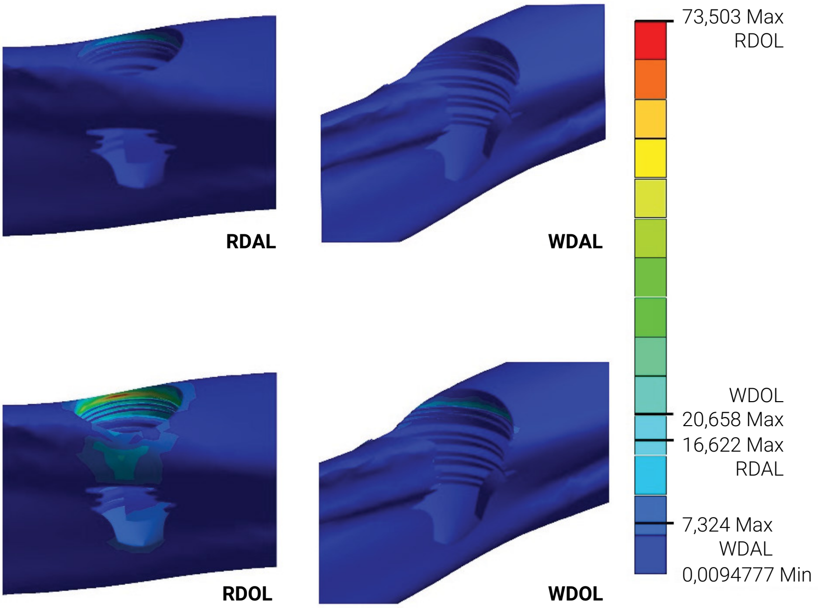

Figure 6. Maximum shear stress peak concentration for cancellous bone (MPa). Blue to red color represents stress values from lower to higher, respectively.

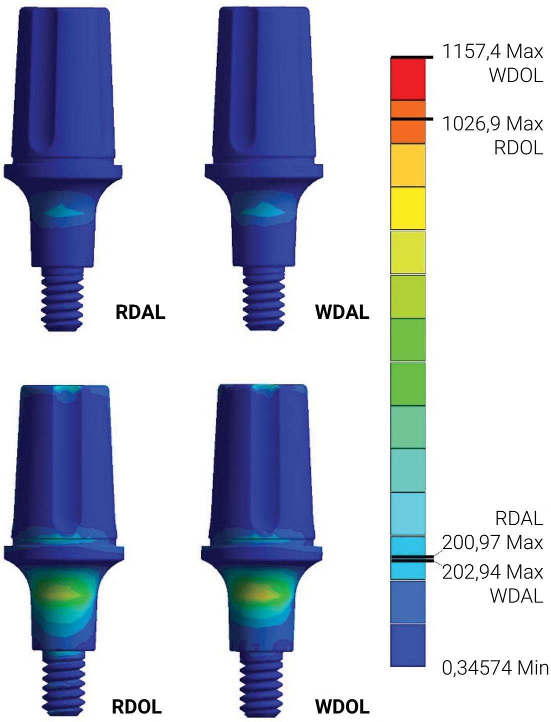

Figure 7. Von-Mises stress peak concentration (MPa) in abutment. Blue to red color represents stress values from lower to higher, respectively.

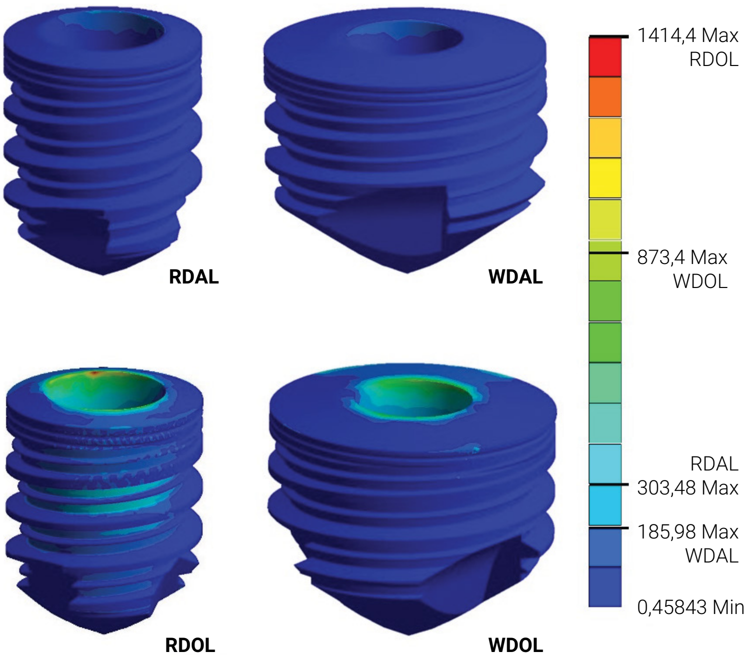

Figure 8. Von-Mises stress peak concentration (MPa) in implant. Blue to red color represents stress values from lower to higher, respectively.

Discussion

There is no consensus in the literature about the benefits of using WD in ESDI in the treatment of severe mandibular bone resorption in the posterior region[12]. Also, recent studies showed that a high C:I ratio only increases the stress concentration when OL is present[8,27], being traumatic occlusion the primary cause of biomechanical complications[8,13,27]. Thus, by FEA, the present study evaluated the influence of WD on ESDIs stress distribution as support for single implant-supported crowns in the posterior region of the atrophic mandible, under AL and OL. The hypothesis that WD would have no difference from the RD regarding the stress distribution, had to be rejected. It was observed that WD in ESDI, under both load directions, showed a decrease of stress at the implant and the cancellous bone (WDAL: τmax=7.324 MPa, σmin=9.795; WDOL: τmax=20.66 MPa, σmin=25.23 MPa), a relevant increase in the cortical bone, and a possible slight increase in the abutment. Besides, when submitted to OL, there was an increase in stress in all components and groups by more than 200%, corroborating with previous studies[8,13,27].

In this study, the stress distribution on the peri-implant bone was different when a WD was used. A relevant increase (up to 66%) in the stress can be observed in the cortical bone when τ_{max} and σ_{min} were evaluated independently of load angulation. This is important since some studies have reported, without a consensus, a critical threshold of compressive (ranging from 50 MPa to 170 MPa) and tensile stress (ranging from 34.72 MPa to 100 MPa) of the bone[28-31], and in the WDAL, RDOL, and

WDOL these values were overtaken. What shows the need for more studies and other methods of evaluation of bone impact when WD is used. Also, the figures in WD groups shows a stress peak in the cervical third of the bone of at least 311.5% under OL higher than the findings of the AL groups, which could be explained by the use of the WD implant providing a 34.73% higher bone/implant contact and wear on the cortical bone. These results corroborate with Elias et al.[27], which evaluated the influence of the prosthetic crown height in SDI and found a higher stress concentration in the OL groups.

Meanwhile, in the WD groups, a decrease in the stress was observed in the cancellous bone, bringing the MPa values found within the limits of compressive and tensile stress at WDOL[28-31]. This may be related to its Young modulus, since its value is lower than that of the cortical bone. The greater the Young modulus the stiffer the material, the greater the stress accumulation[10], and more resistance to deformation[32]. In the present study, when the WD implant was evaluated the contact between the implant and cortical bone was increased, leading to higher stress on the cortical bone and a reduction on the cancellous bone, which can explain the results[10]. This enhanced contact with the cortical bone may negatively influence the bone remodeling around the implants since the cortical bone is less vascularized than the cancellous bone, which leads to interference of blood supply that directly affects the bone resorption response[33]. According to the results of this study, this would only be a problem in the presence of oblique load. Considering that in the posterior region the pattern of forces is axial, perhaps it would not be a clinical problem, as long as the patient has a favorable occlusal pattern.

The consequences of higher stress concentration on the cortical bone associated with its decrease on the cancellous bone remain uncertain since low-stress values around the implant resulting in a bone loss due to disuse atrophy, while high-stress cause microfracture at the bone resulting either in bone loss or fatigue failure of the implant[32,33]. Also, since WD in ESDI increases the stress at the implant/cortical bone interface, being MPa values over the compressive and tensile limits of the bone[28-31], it represents a potential biological risk for marginal bone loss that might be even higher under OL. Besides, the mechanical loading conditions regulate the morphology of the bone[34], and it is still unknown how much bone/implant contact is necessary for the success of ESDIs[27].

The results of von Mises stress showed, in all groups, a higher stress concentration at the surface of the abutment collar level and at the implant platform where it touches the abutment collar. In both loads, the WD showed an increase of 12.7% in stress at the abutment and a reduction of at least 38.2% in the implant. Despite this percentage difference, the color pattern exhibits a great similarity in the stress distribution in general for the abutment, and under axial load for the implant. This substantial stress reduction at WD implants might be explained by its structure 62% bulkier than RD implants. Since the stress increased over 400% at implant and abutment at the OL groups, clinically, would increase the risk of the implant, and abutment failure once was exceeded the limits of tensile yield strength 0.2% (483 MPa) and ultimate tensile strength (550 MPa) of the titanium grade IV[35]. Suggesting that should be avoided the use of ESDI when it is impossible to eliminate OL during mandibular excursive movements, for example, in a parafunction scenario.

Another important point to be highlighted is that a WD implant might reduce the bone mechanical resistance, since the remaining bone around it is reduced when compared to a RD implant. There is a literature gap regarding the effects generated by an overload on the cortical bone, when a mandibular implant-retained crown is evaluated under different load directions. Also, the maximum stress values of FEA studies strongly depend on the size of the mesh used. So, even with this study results being encouraging, showing that the WD ESDI can be a reliable option as shown in the AL groups, it also shows the necessity to perform further studies on this behalf.

Clinically the masticatory forces are not acting in just one way, and it is impossible to isolate the force direction. So, it is essential to perform in silico studies, which allow the researcher to evaluate and study every direction of occlusal forces like was performed in this study. Besides, the present study is a numerical theoretical analysis, and its results should be validated with an in vitro study assessing implant failure mode in the same conditions of this study. In addition, other simulations could be performed to estimate possible statistical differences, for example, by using different prostheses, abutments, and materials with different elastic modulus since they could reach a different result because of its dampers chewing loads[10]. Finally, a reliable way to effectively assess the influence on the bone would be performing randomized controlled trials. These studies must include patients with severe bone atrophy in the posterior region of the mandible with different types of occlusal patterns and a minimum of 1 mm cortical bone wall to surround the implant.

Therefore, extra-short implants with wide diameter result in better biomechanical behavior for the implant, but the implications of a potential risk of overloading the cortical bone and bone loss over time, mainly under oblique load, should be investigated.

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Data availability

Datasets related to this article will be available upon request to the corresponding author.

Conflicts of interest

None.

Author Contribution

Vanessa Felipe Vargas-Moreno: Design of the work; Acquisition and interpretation of data for the work; Drafting the work; Revising it critically for important intellectual contente; Final approval of the version to be published; Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Rafael Soares Gomes: Drafting the work; Interpretation of data for the work; Revising it critically for important intellectual contente; Final approval of the version to be published.

Michele Costa de Oliveira Ribeiro: Drafting the work; Interpretation of data for the work; Revising it critically for important intellectual contente; Final approval of the version to be published.

Mariana Itaborai Moreira Freitas: Drafting the work; Revising it critically for important intellectual contente; Final approval of the version to be published.

Altair Antoninha Del Bel Cury: Drafting the work; Revising it critically for important intellectual contente; Final approval of the version to be published.

Raissa Micaella Marcello-Machado: Design of the work; Drafting the work; Revising it critically for important intellectual contente; Final approval of the version to be published; Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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