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Research Article

Effect of Marginal Bone Resorption on Stress Distribution in Implants of Different Lengths: A Three-Dimensional Finite Element Analysis

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Abstract

Aim: Marginal bone resorption occurring around dental implants may cause biomechanical changes and lead to implant loss over time. It is not fully understood how this bone loss affects implants of different lengths and the stress on the surrounding bone.
Material and Method: Implant models with lengths of 6.6 mm and 13 mm were created at five different marginal bone resorption levels (0, 1, 2, 3 and 4 mm). All implants were 4.6 mm in diameter and were placed in idealized bone blocks with a crown representing the maxillary first molar. The models were analyzed under vertical and 30° oblique load of 100 newton (N). Von Mises stress in the implant body and maximum and minimum principal stress in cortical and cancellous bone were evaluated.
Results: The highest stress values were observed in 6.6 mm implants under oblique loading. While the von Mises stress was 97.4 megapascals (MPa) at 0 mm bone loss, it increased to 133.0 MPa at 4 mm bone loss. These values increased from 82 MPa to 99.1 MPa in 13 mm implants. The maximum principal stress in cortical bone increased from 13.7 MPa to 62.5 MPa in short implants and from 11.8 MPa to 36.0 MPa in long implants. Stress values were found to be higher in short implants at all resorption levels.
Conclusion: Implant length and level of bone loss affect stress distribution. Short implants and advanced resorption create more stress, while stress can be temporarily reduced by changing the load transmission geometry in the early stage.

Keywords: Finite element analysis, dental implants, bone resorption, alveolar bone loss

INTRODUCTION

Dental implants are a widely used treatment method today to restore the aesthetics and function of lost teeth, particularly in cases of single and partial tooth deficiencies, as they can be applied without damaging the neighboring teeth (1,2). The success of implant treatment is made possible by the osseointegration achieved between the titanium from which the implant is manufactured and the surrounding alveolar bone. Osseointegration is a stable form of connection in which the implant is directly united with the bone, without the presence of any intervening soft tissue. This connection is critically important for the long-term success of the implant and its ability to bear functional loads (3,4).

However, even if osseointegration has been achieved, marginal bone resorption around the implant may still occur over time. This bone resorption may develop due to a variety of biological and biomechanical factors, such as surgical trauma, implant position, occlusal overload, implant-abutment connection type, plaque accumulation, infection, presence of a microgap, and soft tissue phenotype (5-7).

Albrektsson et al. (1986) , based on the long-term follow-up results of Adell et al. (1981), proposed vertical bone loss as a criterion for evaluating implant success. Accordingly, in implants with successful osseointegration, a marginal bone loss of up to 1.5 mm during the first year and 0.2 mm in each subsequent year has been defined as the acceptable upper limit (8-10). However, when marginal bone loss progresses beyond these physiological limits, it causes the support tissue around the implant to decrease, negatively affecting the biomechanical load balance. Particularly in

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cases where bone loss reaches 1.5 mm or more, the stress concentrated at the implant–abutment interface may lead to structural deteriorations such as microcracks and the formation of microgaps, creating conditions favorable for bacterial leakage and thereby compromising the long-term success of the implant (11).

Long implants are considered biomechanically advantageous because they provide a larger bone implant surface area (12,13). However, in cases with insufficient bone height, the use of short implants has become increasingly common and is successfully implemented as an alternative to vertical bone augmentation (14,15). In contrast, when marginal bone loss occurs in short implants, it will result in more limited bone support compared to long implants, and stress accumulation in the bone and implant-neck region becomes more pronounced, especially under oblique forces. This predisposes the implant to complications such as implant fracture, abutment screw loosening, or progressive resorption of the surrounding bone. Therefore, preserving marginal bone support is of greater importance in short implants (16).

Finite element analysis (FEA) is an effective method that allows precise modeling of complex structures in the digital environment, thus analyzing the biomechanical behaviors of the implant, superstructure and surrounding bone that cannot be directly observed in the clinic. This method enables three-dimensional investigation and comparison of the mechanical effects caused by different implant designs and varying degrees of marginal bone loss (11,17,18).

The aim of this study is to evaluate the stress distributions in the bone and implant body of two implants with different lengths in the presence of different degrees of marginal bone resorption by using three-dimensional FEA. Our hypothesis is that, with increasing marginal bone loss, the stress intensity on both the surrounding bone and the implant structure will be higher in short implants compared to long implants.

MATERIAL AND METHOD

The stress distributions of two different NTA (Switzerland) implants with diameters of 4.6 mm, lengths of 6.6 mm and 13 mm in idealized bone models with different levels of marginal bone resorption were compared. A total of five different resorption levels were modeled: 0 mm (no resorption), 1 mm, 2 mm, 3 mm and 4 mm. These five bone conditions were modeled and evaluated separately for each implant length (Figure 1).

Idealized bone blocks were modeled as rectangular prismatic structures consisting of cortical (1 mm thickness) and cancellous layers. The dimensions of the block were defined as 27 mm height, 15 mm buccolingual width and 18 mm mesiodistal length. Implant geometries were created based on standard tessellation language (STL) files provided by the manufacturer and with permissions for use, and modeling was performed using Blender 4.2 (Amsterdam, Netherlands) and SolidWorks (Dassault Systèmes, France) software. Crown designs were created in accordance with the anatomical morphology of the maxillary first molar, and the implant-abutment-crown complex was modeled as a single-piece structure.

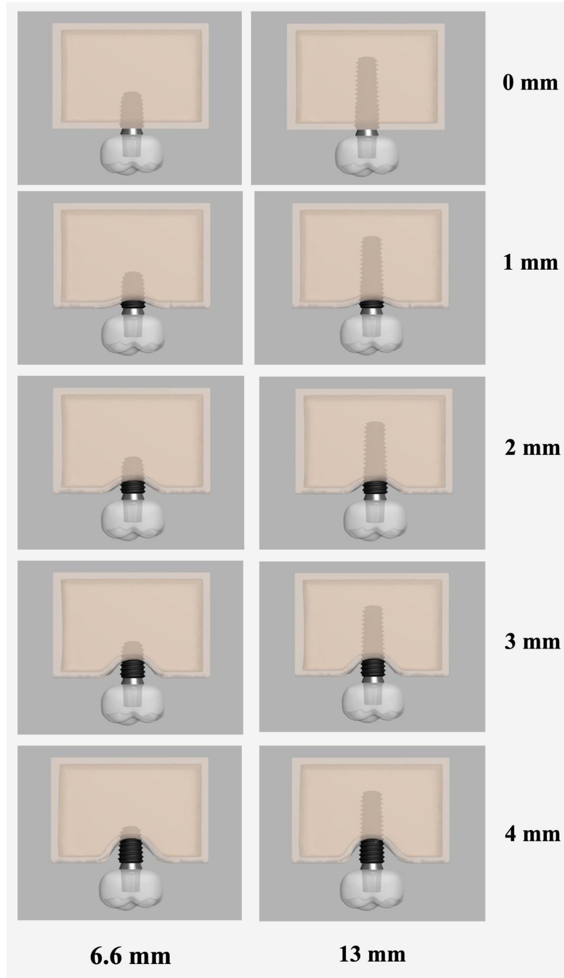

Figure 1. Finite element models of implants positioned in bone under varying levels of marginal bone resorption (0–4 mm) for 6.6 mm and 13 mm implant lengths

All structures are assumed to be isotropic, homogeneous and linearly elastic. The elastic modulus (Young's Modulus) and Poisson ratios of the materials used are defined by reference to the values in the literature (19-21) (Table 1).

Table 1. Mechanical Properties of the Materials Used

Material	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	13,700	0.30
Cancellous bone	1,370	0.30
Titanium	110,000	0.33
Porcelain	96,000	0.29

Meshing was performed using solid tetrahedral elements, with a denser mesh applied particularly in the implant–neck region. A fully osseointegrated condition (100% contact) was assumed between the implant and the surrounding bone, and these interfaces were defined as rigid. Fixed boundary conditions were applied to the bottom and lateral surfaces of the bone blocks. The number of elements and nodes for each implant length and marginal bone resorption level is presented in Table 2.

Table 2. Number of elements and nodes in each model according to implant length and marginal bone resorption depth

Implant length	Resorption level (mm)	Number of elements	Number of nodes
6.6 mm	0	450,484	109,945
	1	452,437	110,489
	2	452,405	110,323
	3	452,063	110,353
	4	453,914	110,683
13 mm	0	480,848	117,402
	1	484,533	118,178
	2	483,152	117,869
	3	484,334	118,164
	4	482,788	117,935

Two different loading scenarios were defined for each model. In the first case, a static vertical load of 100 newton (N) was applied perpendicular to the occlusal surface. In the second case, a force of 100 N was applied obliquely at an angle of 30° to the long axis of the implant. The loads were distributed homogeneously over the large contact area.

Analyses were performed using SIMULIA Abaqus (Dassault Systèmes, France) software. Maximum von Mises stress values were calculated in the implant body; maximum principal (tensile) and minimum principal (compression) stress distributions were analyzed separately in the cortical and cancellous bone regions.

This study was conducted entirely in a digital environment and does not contain any live data, patient images or personal health information. For these reasons, ethics committee approval is not required.

RESULTS

Von Mises Stress Values

Under vertical loading, the von Mises stress in the 6.6 mm implant was calculated as 25.60 megapascals (MPa) at 0 mm resorption, increasing to 26.90 MPa at 4 mm resorption, corresponding to a 5.1% increase. Under the same conditions, this value in the 13 mm implant increased from 19.60 MPa to 20.30 MPa, showing a 3.6% increase.

Under oblique loading, the von Mises stress in the 6.6 mm implant increased from 97.40 MPa at 0 mm resorption to 133.00 MPa at 4 mm resorption, corresponding to a 36.6% increase. In the 13 mm implant, under the same loading condition, the von Mises stress increased from 82.00 MPa to 99.10 MPa, representing a 20.9% increase (Table 3, Figure 2).

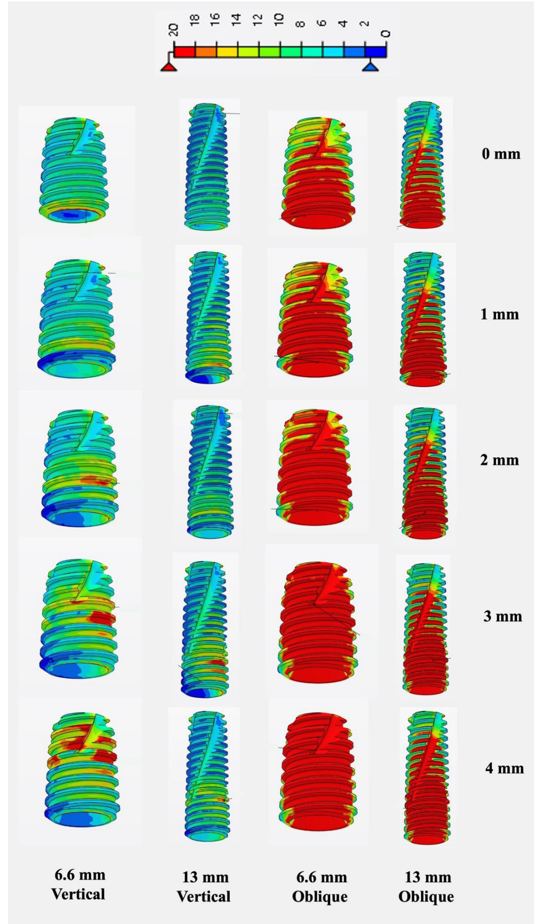

Figure 2. Von Mises stress distributions in the implants at varying levels of marginal bone resorption under vertical and oblique loading

Table 3. Maximum Von Mises Stresses (MPa) in the implant body according to resorption level

Loading direction	Implant length	Resorption (mm)	Von Mises Max (MPa)
Vertical	6.6 mm	0	25.6
		1	21.0
		2	22.5
		3	28.5
		4	26.9
	13 mm	0	19.6
		1	23.0
		2	19.5
		3	23.3
		4	20.3
Oblique	6.6 mm	0	97.4
		1	86.7
		2	87.4
		3	105.0
		4	133.0
	13 mm	0	82.0
		1	79.2
		2	80.3
		3	88.7
		4	99.1

Principal Stresses (Cortical Bone)

Under vertical loading, the maximum principal stresses in the cortical bone increased from 6.73 MPa to 16.10 MPa in the 6.6 mm implant, corresponding to a 139.2% increase. In the 13 mm implant, this value increased from 3.42 MPa to 5.84 MPa, representing a 70.8% increase.

Under oblique loading, the maximum principal stress in the cortical bone for the 6.6 mm implant rose from 13.70 MPa to 62.50 MPa, indicating a 356.2% increase. In the 13 mm implant, the same parameter increased from 11.80 MPa to 36.00 MPa, showing a 205.1% rise.

The minimum principal stresses also accumulated in the same cortical regions and increased with the depth of resorption. Under vertical loading, the minimum principal stress in the 6.6 mm implant increased from −11.80 MPa to −18.20 MPa, corresponding to a 54.2% increase; in the 13 mm implant, it rose from −6.66 MPa to −8.45 MPa, indicating a 26.9% increase.

Under oblique loading, the minimum principal stress in the cortical bone for the 6.6 mm implant increased from -11.8 MPa to -18.2 MPa, reflecting a 54.2% increase. In the 13 mm implant, this value rose from -6.6 MPa to -8.45 MPa, reflecting a 28% increase (Table 4, Figure 3).

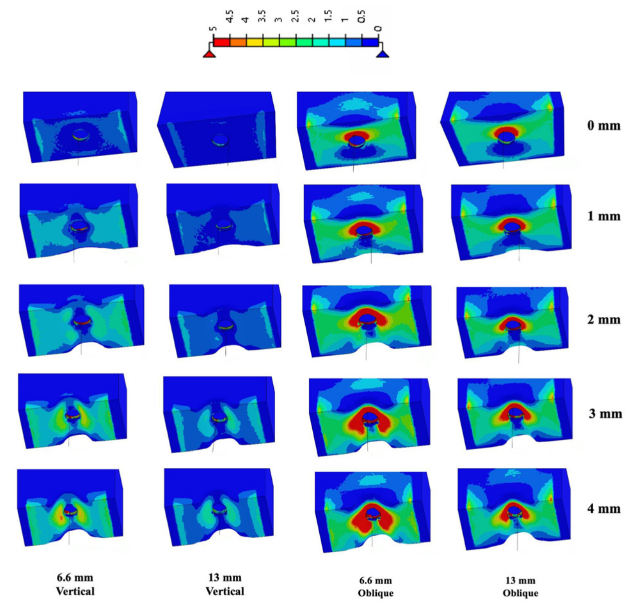

Figure 3. Maximum principal stress distributions in the cortical bone surrounding the implants at different levels of marginal bone resorption

Table 4. Maximum and minimum principal stress values (MPa) in cortical bone according to resorption level

Loading direction	Implant length	Resorption (mm)	Maximum principal		Minimum principal	
			Max (MPa)	Min (MPa)	Max (MPa)	Min (MPa)
Vertical	6.6 mm	0	6.73	-2.62	1.07	-11.8
		1	9.89	-2.49	1.15	-13.7
		2	9.72	-2.7	1.08	-17.9
		3	11.3	-3.64	1.42	-13.5
		4	16.1	-4.8	1.59	-18.2
	13 mm	0	3.42	-2.14	0.25	-6.66
		1	5.74	-2.3	0.47	-11.0
		2	4.93	-1.86	0.49	-8.65
		3	5.5	-1.96	0.7	-8.61
		4	5.84	-1.8	0.65	-8.45
Oblique	6.6 mm	0	13.7	-6.37	1.07	-11.8
		1	21.0	-9.01	1.15	-13.7
		2	25.0	-11.1	1.08	-17.9
		3	47.2	-14.6	1.42	-13.5
		4	62.5	-19.6	1.59	-18.2
	13 mm	0	11.8	-4.49	0.25	-6.66
		1	16.7	-6.12	0.47	-11.0
		2	20.1	-8.05	0.49	-8.65
		3	26.7	-7.98	0.7	-8.61
		4	36.0	-10.2	0.65	-8.45

Principal Stresses (Cancellous Bone)

In cancellous bone, the maximum principal stresses reached higher values under oblique loading conditions. In the 6.6 mm implant, this stress increased from 3.70 MPa to 5.23 MPa, corresponding to a 41.4% increase; in the 13 mm implant, it increased from 1.87 MPa to 3.09 MPa, indicating a 65.2% increase.

The minimum principal stresses were measured at lower levels but still showed a marked increase under oblique loading. In the 6.6 mm implant, the stress increased from −2.95 MPa to −5.51 MPa, reflecting an 86.8% rise; in the 13 mm implant, it rose from −1.62 MPa to −2.02 MPa, showing a 24.7% increase (Table 5, Figures 4, 5).

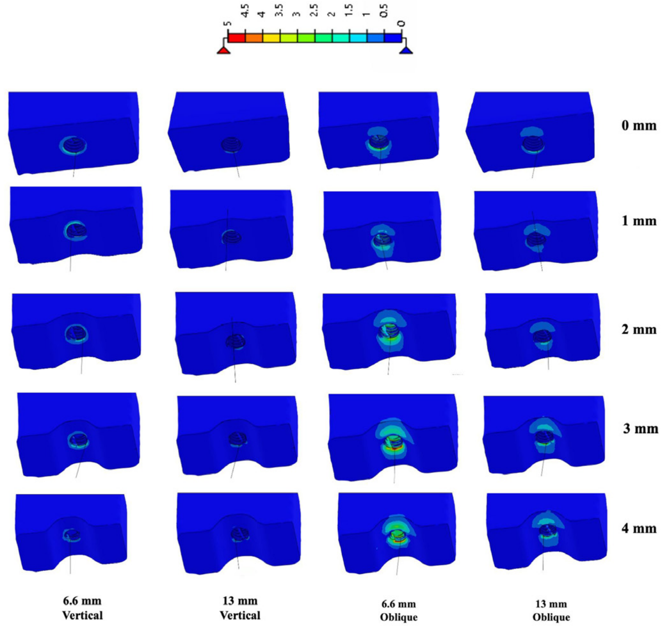

Figure 4. Maximum principal stress distributions in the cancellous bone surrounding the implants at different levels of marginal bone resorption

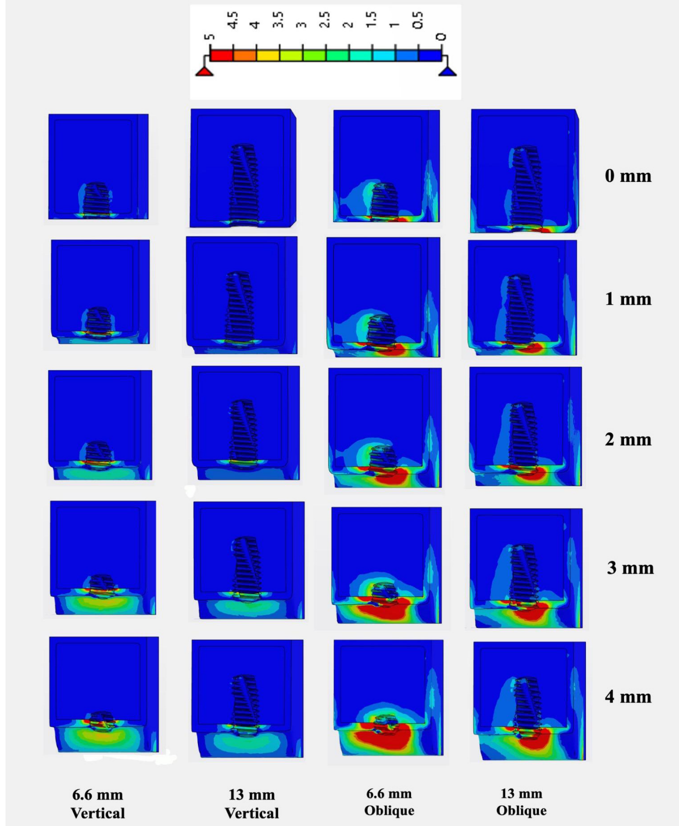

Figure 5. Maximum principal stress distributions in cortical and cancellous bone at various levels of marginal bone resorption (sectional view)

Table 5. Maximum and Minimum Principal Stress Values (MPa) in Cancellous Bone According to Resorption Level

Loading direction	Implant length	Resorption (mm)	Maximum principal		Minimum principal	
			Max (MPa)	Min (MPa)	Max (MPa)	Min (MPa)
Vertical	6.6 mm	0	1.85	-0.52	0.56	-2.02
		1	2.04	-0.56	0.59	-2.07
		2	1.33	0.53	0.32	-2.11
		3	2.21	-0.53	0.47	-2.19
		4	1.34	-0.51	0.15	-2.07
	13 mm	0	0.83	-0.53	0.24	-1.75
		1	0.94	-0.55	0.27	-1.83
		2	0.9	-0.44	0.11	-1.58
		3	1.44	-0.47	0.34	-1.65
		4	1.29	-0.51	0.19	-1.72
Oblique	6.6 mm	0	3.7	-0.32	0.97	-2.95
		1	3.02	-0.37	0.16	-3.33
		2	3.47	-0.44	0.65	-3.85
		3	6.57	-0.29	1.24	-4.74
		4	5.23	-0.37	0.18	-5.51
	13 mm	0	1.87	-0.47	0.42	-1.62
		1	1.17	-0.47	0.1	-1.91
		2	1.36	-0.38	0.11	-1.87
		3	4.26	-0.37	0.86	-2.02
		4	3.09	-0.29	0.22	-2.02

DISCUSSION

In this study, the stress distributions of dental implants with two different lengths (6.6 mm and 13 mm) at five different marginal bone resorption levels (0, 1, 2, 3 and 4 mm) were evaluated by three-dimensional FEA. The findings showed that implant length and resorption amount had significant effects on both the von Mises stresses in the implant body and the principal stress distributions in cortical and cancellous bone.

At each resorption level, the stress values occurred in the 6.6 mm long short implant were found to be higher compared to the 13 mm long implant; also, the stress increase rate observed with increasing bone resorption was more pronounced in short implants. While the von Mises stress in the 6.6 mm implant under oblique loading was 97.4 MPa at 0 mm resorption, this value increased to 133.0 MPa at 4 mm bone resorption (36.6% increase). Under the same condition, the stress in the 13 mm implant increased by 20.9%, from 82 MPa to 99.1 MPa. The maximum principal stress increase in the cortical bone also showed a similar trend; This value increased from 13.7 MPa to 62.5 MPa (356.2%) for the 6.6 mm implant and from 11.8 MPa to 36.0 MPa (205.1%) for the 13 mm implant.

Similarly, in the FEA study conducted by Romeed et al. (2013), where they modeled marginal bone resorption at different levels on a 13 mm long implant, it was shown that the abutment screw was the region where the highest stress was concentrated and that the maximum stress was observed at the screw/implant connection, especially when the bone support was at the level of 10 mm, but that the stresses on the abutment screw decreased significantly, especially under oblique and vertical loading, when the bone support increased to 11.5 mm (22). Again, in the FEA study conducted by Lin et al. (2022), it was reported that the von Mises stress increased significantly in the implant screw and abutment connection regions as the marginal bone loss exceeded 1.5 mm. Especially in the external hexagon connection system, when the bone loss progressed from 3 mm to 5 mm, the stress on the screw increased by more than 25% and this stress exceeded the yield limit of the Ti–6Al–4V alloy, creating a potential risk of screw loosening or fracture (11).

Kitamura et al. (2005), in their study evaluating the effects of marginal bone loss on stress distribution, showed that the maximum von Mises stress observed in cortical bone, especially under oblique loading, increased with bone resorption depth in 1.3 mm and 2.6 mm bone loss scenarios (23). In the study, the maximum stress measured in cortical bone in the case of 2.6 mm horizontal resorption increased approximately 5 times compared to the model without bone loss. In addition, it was emphasized that the stress in cortical bone against oblique loads was 2 to 4 times higher than under axial loading. This finding of Kitamura et al. is also consistent with the findings of our study; in fact, the maximum principal stress in cortical bone at the level of 0 mm bone resorption in a 6.6 mm implant was measured as 6.73 MPa in vertical loading, while it was 13.7 MPa in oblique loading and increased approximately 2 times. In the same implant, in the case of 4 mm resorption, the stress, which was 16.1 MPa in vertical loading, increased approximately 3.9 times to 62.5 MPa in oblique loading. Similarly, Akça and Çehreli (2006) showed that the displacement and elastic stress equivalent in the trabecular bone in contact with the implant neck increased significantly in simulations of progressive bone loss and oblique load (24).

In our study, contrary to expectations, a decrease in von Mises stress values was observed in the implant body during the early stages of marginal bone resorption (1 and 2 mm) in both short and long implant models. Under oblique loading, the von Mises stress in the 6.6 mm implant decreased from 97.4 MPa in the absence of resorption to 86.7 MPa and 87.4 MPa at 1 mm and 2 mm resorption levels, respectively. Similarly, in the 13 mm implant, no significant change in stress values was observed at these early resorption levels. This situation may result from the more angular connection of the cortical bone to the implant as resorption progresses in the early stages. Such angular contact may cause the cortical bone to wrap around the implant surface over a longer vertical distance. In addition, when the cortical bone approaches the implant body at an angle, the load transmission occurs on a longer cortical bone since the cortical bone surface will be the hypotenuse of the triangular area formed. This geometry may prevent stress concentration in a specific region and exert a stress-reducing effect on the implant. Another possibility is that the resorption line corresponds to different cross-sections of the implant's thread geometry. For instance, resorption at the 2 mm level may coincide with a narrower segment of the implant, leading to a more localized stress concentration; whereas at the 3 mm level, bone support aligning with a wider thread geometry may allow for more effective load distribution. Indeed, the observation in our study that stress under vertical loading at 4 mm resorption is lower than at 3 mm supports this possibility. Ultimately, such geometric differences may explain the non-linear behavior of stress values measured at different resorption levels.

Inglam et al. (2010) also reported in their FEA study on maxillary grafted sinus that similar strain energy density (SED) values were observed in cortical, cancellous and grafted bone regions in the case of 1.3 mm bone loss, indicating that the load was shared equally between the bone tissues. It was also reported that SED values in cortical bone at this level were lower than in models without bone loss (21). Although this study did not directly examine the stress distribution in the implant body, this balance in load sharing indicates that the stress occurring in the implant body in the early period may be limited.

There are some limitations to this study. First of all, the models we used in the FEA were created with idealized homogeneous and isotropic material properties and cannot fully reflect the biological, morphological and mechanical properties of real bone tissue. Cortical bone thickness was kept constant in all models, however, changes in cortical bone thickness may occur with resorption, which may affect stress distribution. In addition, all analyses were performed under static loading and dynamic forces formed during chewing could not be evaluated. For these reasons, caution should be exercised when correlating the study results with clinical applications.

CONCLUSION

The findings showed that implant length, marginal bone resorption level and loading direction significantly affect the stress distribution in the implant and surrounding bone tissues. Especially in the short implant preference and in the 3 and 4 mm bone resorption scenarios, the stress values were found to be higher. In contrast, in the 1 and 2 mm bone resorption, a temporary decrease was observed in the von Mises stress values in the implant body. In addition, it was observed that the loads applied in the oblique direction created higher stress in both the implant and the bone compared to the vertical loading. In conclusion, not only the existing bone height but also the possible bone loss levels should be taken into account in implant planning.

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Ethical approval: *This study was conducted entirely in a digital environment and does not contain any live data, patient images or personal health information. For these reasons, ethics committee approval is not required.*

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