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Influence of different crown lengths on shorter implants with different lengths, diameters and designs at atrophic posterior mandible: A finite element analysis

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Abstract

Aim: The aim of the study was to compare the stresses caused of different crown heights on short implants with different lengths, diameters, and designs under axial and oblique loads on the cortical bone and implant system using finite element analysis.

Methodology: In the atrophic posterior mandible, four different implants of different sizes and designs were placed in the first molar region. Metal supported porcelain crowns with three different heights (10 mm, 12.5 mm, and 15 mm) were designed on the computer. A total of 12 study models were created. Axial and oblique loads were applied, and Von Mises values in the implant and abutment; maximum and minimum principal stress values in the cortical bone were evaluated by the finite element analysis method.

Results: Compared to axial load, significantly higher stress values were found at the implant and cortical bone in obliquely loaded models. As the length and diameter of the implant increased, the stress on the cortical bone decreased. Compared to the threaded implant, the plateau design implant caused less stress on the bone under vertical loads, while causing more stress on the oblique. Unlike the literature, it was observed that the stresses on the implant were higher in the larger diameter implant compared to the narrower.

Conclusion: As a result of the stress values obtained within the limits of the analysis, when the lengths of the crowns restored on short implants were compared, it was determined that the axial forces were at an acceptable level under all conditions.

Keywords: Short implants, implant restorations, implantology, axial load, oblique load, finite element analysis

Introduction

Long-term edentulous and advanced periodontal diseases result in significant bone loss. Resorption occurs more rapidly in the posterior regions of the maxilla and mandible than in the anterior regions. Therefore, the implants to be applied to these regions and the surgical procedures to be performed are of critical importance. Advanced surgical procedures such as sinus elevation, inferior alveolar nerve transposition-lateralization, and bone augmentation are required to place longer implants in atrophic crests. These advanced surgical procedures are high-priced and have high complication risks, and they also prolong the treatment period. Short implants have been developed due to the need for less invasive options for patients with inadequate bone height, insufficient distance to important anatomical structures, limited field of view and difficult access, and surgical contraindications (1, 2).

There are various views about the term short implants in the literature. Implants with a diameter of 3.75 mm or larger and a length of 8 mm or less were defined as short implants, and those shorter than 6 mm were defined as ultra-short implants (3).

Various alternative in vitro techniques, such as experimental, analytical, computational models, digital photoelasticity, strain gauges, and finite element analysis (FEA), have been employed to assess the biomechanical characteristics of dental implants (4). Finite Element Method (FEM) utilizes virtual models to simulate and evaluate the gradual resistance and distribution of stress in complex components (5). The use of three-dimensional analysis enables the creation of models that accurately represent real-life scenarios and possess complex geometry, resulting in more reliable outcomes. FEM studies utilize this approach to analyze mechanical difficulties by breaking down the element-problem into several smaller and more manageable pieces, creating a mesh of elements. The problem is then solved using mathematical functions (6, 7). Therefore, it is useful for modeling and assessing the biomechanical characteristics of bone, implants, and the interfaces of prosthetic components. This would be unachievable to examine by experimental analysis conducted in a controlled in vitro or in vivo environment (6-8).

The aim of the study was to evaluate the effects of crown heights on ultrashort implants with different lengths, diameters, and designs using finite element analysis.

Materials and Methods

Equipments

For editing and making the 3D mesh structure more homogeneous, creating a 3D solid model, and finite element stress analysis, computer equipped with Intel Xeon ® R CPU 3.30 GHz processor, 500 GB Hard drive, 14 GB RAM, and the Windows 7 Ultimate Version SP 1 operating system, 3D scanner Activity 880 optical scanner (Smart Optics Sensortechnik GmbH, Bochum, Germany), A 3D modeling software Rhinoceros 4.0 (McNeel, Seattle, WA, USA), analysis programs which named VRMesh Studio (Virtual Grid Inc., Bellevue City, WA, USA), and Algor Fempro (ALGOR Inc., Pittsburgh, PA, USA) were used.

After the models were created geometrically with VRMesh software, they were transferred to Algor Fempro (Algor Inc.) software in STL format for analysis. After making it compatible with the Algor software, the properties of the materials were introduced to the software. Young modulus and Poisson ratio, which show the elastic properties of the materials used in the study, are listed below (Table 1).

Table 1. Elastic properties of the materials used in the study (5, 7, 9)

Materials	Young Modulus (MPa)	Poisson Ratio
Cortical Bone (7)	13700	0.30
Grade 4 Titanium (5)	110000	0.33
Grade 5 Titanium	114000	0.33
Co-Cr Framework	218000	0.33
Feldspathic Porcelain	82800	0.35

Modelling

In order to model the bone tissue, images of the patient's cone-beam computed tomography (Iluma CBCT, 3M Imtec, OK, USA) were used. The radiographs were transferred to the 3D-Doctor software, and the bone tissue was separated by looking at the Hounsfield values with the "Interactive Segmentation" method. After the decomposition process, a 3D model was obtained using the "3D Complex Render" method, and the bone tissue was modeled. The posterior mandibular bone was considered as Type 2, and the cortical bone thickness was determined to be 2 mm in all regions (9, 10). The bone width was modeled as 9 mm, and the height from the crest to the lower border of the mandible was 18 mm, in accordance with the implant placement.

The implant, abutment, and screw models in the library were transferred to Rhinoceros 4.0 software in (.stl) format. The implants selected in the study; NTA Shorter Plus 4.5×4.2 mm (Pilatus Swiss Dental GmbH, Egolzwil, Switzerland), NTA Shorter Plus 4.5×5.0 mm (Pilatus Swiss Dental GmbH, Egolzwil, Switzerland), NTA Shorter Plus 5.0×5.0 mm (Pilatus Swiss Dental GmbH, Egolzwil, Switzerland) and Medentika Microcone 5.0×6.5 mm (Medentika GmbH, Hügelsheim, Germany). The abutments with a platform diameter of 5.0 mm were modeled at three different lengths, increasing in parallel with the crown length. The mandibular left first molar was modeled by narrowing the occlusal table, based on the morphology and dimensions in Wheeler's Dental Anatomy (11). Crown lengths are designed in three different heights as 10 mm, 12.5 mm, and 15 mm, increasing in parallel with the amount of atrophy. The prosthetic restoration was applied as porcelain fused metal (Cr-Co) with not exceeding 2 mm of porcelain thickness.

In this way; cortical and cancellous bone, implant, abutment, infrastructure and superstructure in the mandible were moved to the model to reflect their true morphology (Fig. 1). The models were placed in the correct coordinates in 3D space in Rhinoceros software, and the modeling process was completed. Models made in Rhino were transferred to Fempro software by preserving 3D coordinates. A total of 12 study models were created.

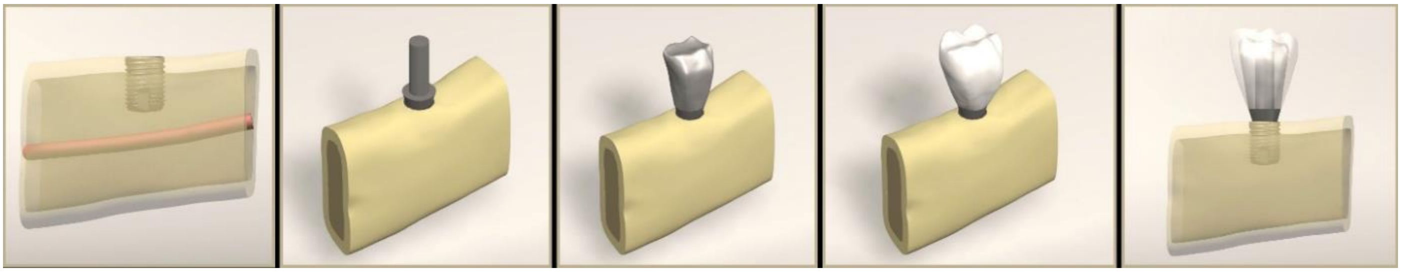

Figure 1. The 3D study models of Medentika Microcone implants prepared by integrating the models are shown

Boundary conditions and loading

The mandible was fixed to have 0 (zero) motion in DOF (Degree of freedom) in 3 axes. In the first scenario, 200 N force was applied to the central fossa of the crowns perpendicular to the implant. In the second scenario, oblique loading was applied to the buccal slopes of the lingual cusps at an angle of 45 degrees to the long axis of the implant buccolingually, with a total force of 100 N (4).

Parameters in the study:

1. Implant length (4.2 and 5.0 mm)
2. Implant diameter (4.5 and 5.0 mm)
3. Implant design (Plateau and threaded)
4. Crown heights (10, 12.5, 15 mm)
5. Loading conditions (200 N vertical, 100 N oblique)

Limitations discussion

All model elements were considered as linear, homogeneous, and isotropic materials. The connection between the implant, the mandibular bone, the abutment, and the prosthetic restorations is ensured with uninterrupted conduction. Osseointegration between bone and implants was assumed to be 100%. Metal-supported restorations were planned to be cemented to the abutments, but due to the thinness of the cement layer and the low material values, their effect on the measurements was neglected (12, 13).

Acquiring analysis results

Since the values obtained as a result of finite element stress analysis are the result of mathematical calculations without variance, statistical analyzes cannot be performed.

In the analysis results;

- Maximum and minimum principal stress values of cortical bone, which is a fragile material;
- The maximum Von Mises values of the tractile materials such as implant, abutment, screw, metal framework, and superstructure were examined.

Results

The stress values occurring in cortical bone, implant, abutment, framework, superstructure, and screws under axial and oblique forces are shown in Table 2.

Cortical bone

In the maximum and minimum principal stress values on the bone, positive values indicate tensile stresses, and negative values indicate compressive stresses. Whichever stress type has the greater absolute value in a stress element, this element is under the influence of that stress type, and it is that stress type that needs to be evaluated.

Higher stress values were determined in cortical bone under oblique loads compared to axial loads. The stresses are concentrated in the cortical bone adjacent to the implant neck.

For all groups; an increase in crown heights did not create a significant difference in stress values in the cortical bone under axial loading. On the other hand, in oblique loading, the increase in crown height increased the stress values in the cortical bone. With the increase of the crown height from 10 mm to 15 mm; in Group 1 implant, the tensile stresses in the cortical bone increased by 35.5% and the compressive stresses by 30.5%; in Group 2 implants, the tensile stresses on the cortical bone increased by 45.4% and the compression stresses by 23.8%, in Group 3 implants, the tensile stresses in the cortical bone increased by 45.4% and the compressive stresses by 23.8% and in Group 4 implants, tensile stresses in the cortical bone increased by 30.6% and compressive stresses by 20.8%.

Under oblique loads, tensile stresses are concentrated in the opposite direction of the applied force, while compression stresses are concentrated in the direction of the force. Compressive stresses were found to be effective in all groups under both loading conditions. The stresses are within the physiological limits of the cortical bone.

Under axial loads, at the same crown heights, increasing the length of the implant decreased the tensile stresses on the cortical bone and increased the compression-type stresses. Under oblique loads, at the same crown heights, the tensile and compression-type stresses on the cortical bone increased with the increase in the length of the implant.

Under axial and oblique loads, at the same crown heights, the increase in the diameter of the implant caused a decrease in the tensile and compression-type stresses in the cortical bone.

In this study, it was observed that the Group 2 implant with a longer implant length caused more stress on the bone compared to the Group 1 implant. The reason for the higher stress on the cortical bone when the crown height is kept constant, and the length of the implant increases may be due to the difference in implant design. The neck region of the Group 1 implant with a length of 4.2 mm is 0.5 mm longer and makes a wider angle with the long axis of the implant. However, the neck region of the 5.0 mm Group 2 implant is 1.0 mm longer and makes a smaller angle with the long axis of the implant. As a result of the design, the stress distribution of Group 1 implants on the cortical bone was distributed over a wider area. The design differences and stress distributions for Group 1 and 2 implants are shown in Figure 2.

Under the axial loads, at the same crown heights, in the plateau design (Group 3), although the length of the implant was 1.5 mm shorter, lower tensile and compression stresses were observed in the cortical bone. Under oblique loads, at the same crown heights, lower stresses were observed in the cortical bone in the screw implant system (Group 4).

Implants

The stresses on the implants are concentrated in the neck of the implant. When bone, implant, abutment, and restoration were evaluated, the highest stress values were observed in the implant. Oblique loads created higher stress values compared to axial loads. While the increase in crown heights under axial loading did not cause a significant difference in the stresses occurring in the neck region of the implant in all groups, it caused an increase in the stresses under oblique loading. In all groups, under axial loading, the lowest stress values in the implant neck region were observed at the highest crown height. The stresses that occurred on the implants are below the limits of titanium.

Under axial and oblique loads, at the same crown heights, the stresses in the neck region of the implant decreased with the increase in the length of the implant.

At the same crown heights, the stresses in the neck region of the implant increased with the increase in the diameter of the implant under both loading conditions.

Under axial and oblique loads, at the same crown heights, lower stresses were observed in the screwed implant system in the neck region of the implant (Fig. 3).

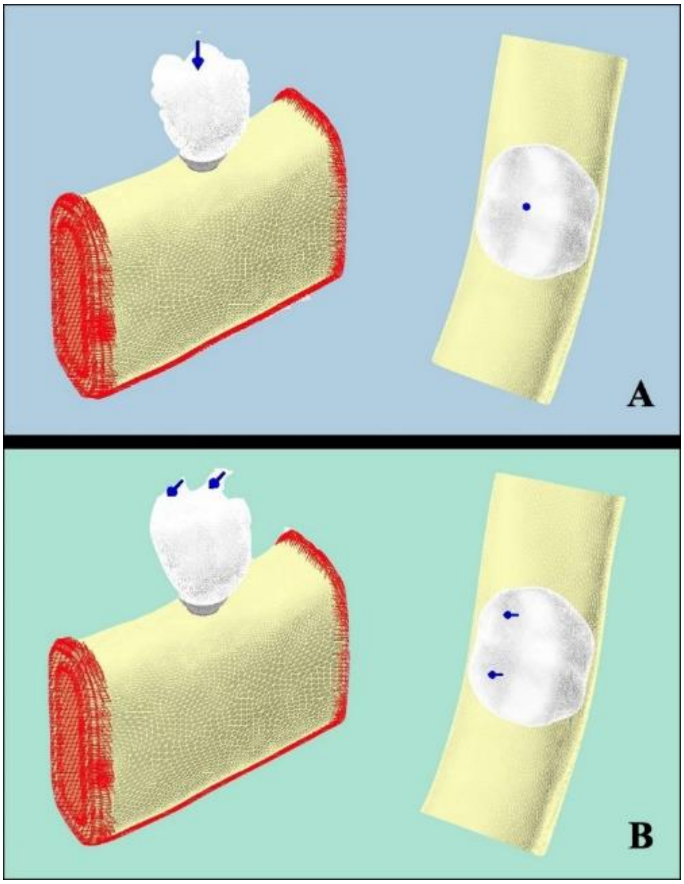

Figure 3. Comparison of stresses on implants of the same length with different diameters and control model with different abutment platforms

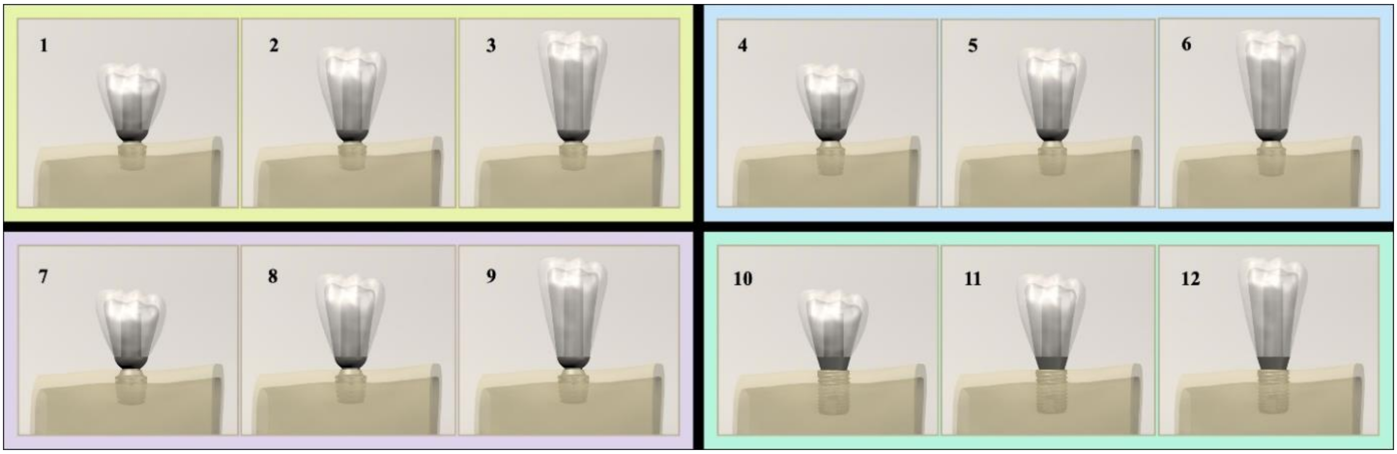

Figure 2. The design differences and stress distributions for Group 1 and 2 implants are shown

Table 2. Stress values in cortical bone, implant, abutment, substructure, superstructure, and screws under axial and oblique forces (MPa). A: axial; O:oblique

	Models	Cortical bone - Pmax	Cortical bone - Pmin	Implant	Abutment	Framework	Porcelain	Screw
Group 1	Model 1	A: 1.61	-17.6	321	89.6	43.8	12.8	X
		O: 31.9	-43.3	1002.4	266.9	110	31.2	
	Model 2	A: 1.63	-18.05	322	93.9	52.9	13.9	X
		O: 37.2	-48.4	1136.9	342.6	136.8	36.9	
	Model 3	A: 1.61	-17.5	319	87.7	47.2	12.7	X
		O: 42.9	-54.2	1292.4	345.3	227.7	43.2	
Group 2	Model 4	A: 1.0	-22.7	162.9	93.6	34.5	11.3	X
		O: 45.1	-59.5	505.8	284.3	76.2	31.4	
	Model 5	A: 1.0	-23.5	166	96.6	36.3	11.1	X
		O: 52.8	-69.2	607.9	353.3	93.3	32.9	
	Model 6	A: 0.9	-23.2	155	89.8	36.7	11.2	X
		O: 61.9	-77.4	708	372.5	186.3	42.4	
Group 3	Model 7	A: 1.83	-16.9	209.5	91.2	34.6	11.2	X
		O: 33.4	-41.7	641.5	276.4	76.5	31.1	
	Model 8	A: 1.83	-16.9	216	93	36.4	10	X
		O: 39.4	-47.6	783.8	339	93.6	32.3	
	Model 9	A: 1.82	-16.8	201	87	36.9	11.1	X
		O: 48.3	-52.5	843.6	358.3	178.2	41	
Group 4	Model 10	A: 2.5	-14.6	118	74.1	31	24.9	21
		O: 14.9	-23.9	301.7	224.3	64.8	59.7	73.7
	Model 11	A: 2.45	-14.4	107	75.3	36.2	24.6	24
		O: 17.4	-26.7	351.7	261	107.8	75.9	108.3
	Model 12	A: 2.45	-14.4	106	75.2	49	22.8	24.2
		O: 19.6	-28.8	382	292	176	85.3	118.1

Abutments

The highest Von Mises values in abutments were observed in the neck region of the implant-abutment connection in the direction of the applied loads. In oblique loading, an increase in the stresses on the abutments was observed in parallel with the increase in crown heights.

Under axial and oblique loads, at the same crown heights, although there was no significant difference, the stresses on the abutments increased with the increase in the length of the implant.

Under both loading conditions, at the same crown heights, the stresses on the abutments decreased with the increase in the diameter of the implant.

For all loading conditions at the same crown heights, the stresses on the abutment are lower in Group 4, which has a screwed implant system.

Screws

Only Group 4 implants have screws. Under axial and oblique loads, the stress on the screw increased as the crown length increased. The highest value on the screw was determined in the top threads. Under oblique loads, the stresses on the screw increased by 46.9% when the crown height increased from 10 mm to 12.5 mm, and increased by 60.2% when it increased to 15 mm.

Discussion

When deciding on the appropriate implant length for the patient, the quality and quantity of existing bone and bite forces should be considered. Advanced bone resorption, and anatomical limitations, such as proximity to important anatomical structures, make it difficult to place longer implants. The use of short implants has increased, especially in patients with early loss of permanent first molars and advanced bone resorption.

It has been stated that short implants have less success and lower survival rates compared to standard and long implants. The reason for these results was attributed to external hex connections with machined flat surfaces (14).

Dias et al (15), found a success rate of 97% for short implants and 92.6% for longer implants with grafting. They stated that there is a higher risk of complications in long implants with grafting and reported that a short implant can be preferred in the appropriate bone.

It is stated that the use of short implants gives better results in the mandible than in the maxilla (16). In the study of David French et al. (17) the success rates of short implants in the maxilla and mandible were reported as 87% and 100%, respectively. Because of the higher success rates, the study was carried out on the mandible.

With the increase in the maxillomandibular distance in atrophic crests, the ratio is in favor of the crown with the use of short implants. Studies are generally carried out on the relationship between increased crown/implant ratio and marginal bone loss, implant survival, biological and technical complications. An inappropriate crown/implant ratio acts as non-axial forces (18, 19).

Rokni et al (20), examined the effect of the crown/implant ratio (between 0.8 and 3) on the marginal bone level, and no correlation was found between crown height and marginal bone loss. Naert et al (21), stated that long abutments support crestal bone loss in the first six months after loading, and this relationship decreases in the following period. The studies generally refer to no relationship between the crown/implant ratio and marginal bone loss.

Finite element analysis (FEA) is frequently used to investigate the stress distribution on dental implants, prosthetic structures, and bone which is impossible to observe clinically. Baiamonte et al (22), evaluated the stresses on implants both *in vitro* and finite element methods to test the reliability of FEA studies in implantology. The obtained results were highly consistent with each other, and FEA is said to be safely applied in dental implantology. So, FEA was preferred, and the analyzes were carried out in three dimensions.

When finite element stress analysis studies are examined, the stress seems to be concentrated in the cortical bone region. In this study, the bone model prepared for the mandibular molar region was designed in the form of Type 2 bone, which is common in the related region and accepted by the literature, and the cortical bone thickness is considered 2 mm (9, 10).

A crown height of more than 15 mm is considered biomechanically unfavorable and has been reported to cause increased stress on the crestal bone/implant region. A crown height of 15 mm is considered the maximum height for fixed restorations (23, 24). In the study, a crown height of 15 mm was accepted as the worst-case scenario.

In the literature, the physiological limits of human cortical bone are 140-170 MPa against compression forces, 72-76 MPa against tensile forces, and its elastic limit is approximately 60 MPa (25). In the study, the tensile and compression stresses on the cortical bone were observed below the physiological limits of the cortical bone.

Bunnag et al (26), examined the effect of crown/implant ratio on stresses in 4 mm and 6 mm short implants in the mandible and reported that, as a result of oblique and axial forces, less stress is seen on the wider implant under the same conditions.

Contrary to the literature, more stress was seen in the larger diameter implant in this study. The reason might be the abutment on the 5.0 mm platform, which was placed on the narrower implant with a 4.5 mm diameter to ensure standardization in all models, and a new model was created, and a control study was carried out. This hypothesis was tested by designing a 4.5 mm diameter abutment on the 4.5 mm diameter implant and applying axial and oblique forces at 10 mm crown height. More stress was seen in the narrow implant compared to the previous situation. As a result of the control study, it was observed that more stress occurred in the neck region of the narrower diameter implant (Fig. 3), which was consistent with the literature (27, 28).

The reason for the lower stresses on the implant and abutment in the Group 4 compared to the Group 3 implant system may be the presence of a screw in the implant and the screw's role in stress distribution. Screws of Group 4 implants were mostly affected by the increase in crown heights.

Conclusion

The results obtained from our study, in which we have examined the effects of crown heights on ultrashort implants with different lengths, diameters, and designs using finite element analysis, can be summarized as:

1. Under axial loads; the increase in crown height did not have a significant effect on the stresses on the cortical bone, implant, abutment, screw, and crown.
2. Under oblique loads; the increase in crown height causes a significant increase in stresses on the cortical bone, implant, abutment, screw, and crown.
3. Among bone, implant and restoration, the highest stress values are observed on the implant, in the neck region of the implant.
4. In extra-short implants, there is a significant decrease in the stresses on the implant and its elements as the length of the implant increases.
5. With the increase of the implant diameter, the tensile and compressive stresses in the cortical bone decrease.
6. Short implants with plateau design cause less stress on cortical bone under vertical forces than threaded implants with longer lengths.
7. Short implants with plateau design cause more stress on the cortical bone under oblique forces compared to threaded implants with a longer length.
8. Plateau designed short implants are more stressed in the neck region than longer threaded implants.
9. The increase in crown heights is most effective on the stresses on the screws.
10. If the occlusion is adjusted to minimize the oblique forces, the use of short plateau designed implants will yield more successful results.

Disclosures

Peer-review: Externally peer-reviewed.

Author Contributions: Conception – E.İ.M.; Design – E.İ.M., S.A.; Supervision – S.A.; Materials – E.İ.M., S.A.; Data Collection and/or Processing – E.İ.M., S.A.; Analysis and/or Interpretation – E.İ.M.; Literature Review – E.İ.M.; Writer –E.İ.M.; Critical Review – S.A.

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