IDR International Dental Research

Int Dent Res 2024; 14(S1): 81-89
https://doi.org/10.5577/indentres.566

Original Article Open Access

The effect of different implant-bone levels on stress distribution in three-unit monolithic zirconia restorations: A 3D finite element analysis

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Received: 10 October 2024
Accepted: 25 November 2024

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How to cite this article:

Alioğlu Koparal NS, Tunçdemir AR, Demirel MG, Mohammadi R, Keçeci M. The effect of different implant-bone levels on stress distribution in three-unit monolithic zirconia restorations: A 3D finite element analysis. Int Dent Res. 2024;14(S1):81-89
https://doi.org/10.5577/indentres.566

Abstract

Aim: The aim of this study is to investigate the stress distribution in implant-supported three-unit monolithic zirconia restorations according to different bone levels at which implants are placed in the mandible, using three-dimensional finite element analysis.

Methodology: For this study, mucosal, trabecular, and cortical bone pieces were designed using the SolidWorks program to simulate an edentulous mandibular jawbone. Two implants were positioned in areas numbered 44 and 46 with different subcrestal placements (0 mm, 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm). In each model, dental implants, abutments (TiBase), monolithic zirconia crowns, abutment screws, and bone tissues were simulated. The obtained data were exported as Standard Tesselation Language (STL) files and imported into the Exocad program for the design of prosthetic restorations and custom abutments. The STL files were then imported into the Geomagic Design X program to merge the implants, abutments, and restorations on the digital model. The final models were saved as STP files and transferred to the ABAQUS software for finite element analysis. Subsequently, an oblique load of 150 N in the buccolingual direction was applied to the occlusal table for 1000 cycles, and the mandibular jawbone was fully constrained (encastre) in all directions (both movement and rotation). Stress distribution values were recorded in von Mises (vMS) units, and fatigue performances were measured using the Seegers method.

Results: As the implant bone levels increased, the vMS increased on the prosthetic restoration. Specifically, vMS increased on the abutment of implant 44 but decreased on implant 46. Fatigue performance worsened on the abutment of implant 44 but improved on the abutment, and screws of implant 46. Abutment screws proved most durable, with abutments experiencing early failures.

Conclusion: According to the results of the study, it has been observed that the implant bone level affects the stresses occurring in prosthetic restoration.

Keywords: Zirconia, implant-bone level, monolithic zirconia, finite element analysis, stress distribution, Von Mises stress

Introduction

Dental implants, including abutments, abutment screws, and implant screws, are widely used in routine dental practice. Their high success rates in different indications and protocols have facilitated their inclusion in the treatment plans of patients who need to replace missing teeth.

The abutment is a part of the implant that serves to support the prosthesis. Titanium alloys have been successfully used for implant abutments because of their high corrosion resistance, low modulus of elasticity, and perfect biocompatibility (1). Titanium abutments (TiBase) have ideal construction characteristics.

In prosthetic treatment, subcrestal implant placement has emerged as a primary protocol intended to conserve peri-implant bone levels. Subcrestal placement of dental implants avoids exposure of the implant grooves and allows an adequate aesthetic emergence profile for prosthetic restorations (2). Subcrestal implant placement also positively affects papilla formation and crestal bone preservation (3). During functional movements, implants transfer stresses to the surrounding tissues. Therefore, the characteristics of the bone quality and quantity around the implant are critical in terms of biomechanics in dentistry. (4). Ensuring optimal biomechanical conditions is important for determining the prognosis of implant treatments. The materials used in implant-supported restorations can influence the distribution of stress (5). The materials used for implant-supported restorations can influence stress distribution, along with restoration design (6).

Several factors must be considered when selecting the prosthetic framework to ensure long-term success, stability, functionality, and aesthetics of the restoration (7, 8). Metal-ceramic combinations have traditionally been used because of their strength, stability, and satisfactory aesthetics. Advancements in materials science have propelled the popularity of zirconia, a ceramic variant known for its enhanced strength, durability, and aesthetic appeal (9, 10). Zirconia restorations are suitable for implant-supported prostheses owing to their high biocompatibility and mechanical properties (11, 12). However, it is reported that porcelain chipping is a common problem in implant-supported zirconia substructured porcelain restorations (13). Therefore, monolithic zirconia has been developed to overcome the chipping problem of zirconia substructured porcelain restoration (14).

Testing the stress on the bone surrounding implants is challenging in both in vitro and in vivo studies (15). Finite element analysis (FEA) is a computational virtual modeling method that predicts how different materials respond to applied forces, making it useful for evaluating stress-related outcomes by mimicking clinical conditions. In FEA studies, von Mises stress (vMS) values are commonly used to calculate the stress distribution.

A literature review found that no other study has compared bone implant levels in implant-supported fixed restorations from a prosthetic perspective.

The aim of this study was to investigate the stress distribution in implant-supported three-member monolithic zirconia restorations according to the different bone levels at which implants are placed in the mandible using 3D FEA. The null hypothesis was that there is no difference in the stress distribution of the implant, abutment, abutment screw, and prosthetic restoration when the bone-implant level changes.

Materials and Methods

For this study, the mucosa, trabecular, and cortical bone parts were designed using the SolidWorks program to simulate a toothless mandibular jawbone. At sites 44 and 46, two implants 3.7 mm in diameter and 12 mm in length with different subcrestal placements (0 mm, 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm) were positioned according to the information obtained from Bilimplant. In each model, dental implants (Fig. 1), implant abutments (TiBase abutment) (Fig. 2), monolithic zirconia crowns (Fig. 3), abutment screws (Fig. 4), and bone tissues (Fig. 5) were simulated.

The data obtained were exported as Standard Tesselation Language (STL) files and transferred to the Exocad program to design prosthetic restorations and custom abutments. The STL files were transferred to the Geomagic Design X program, and the implants, abutments, and restorations were combined on the digital model (Fig. 6).

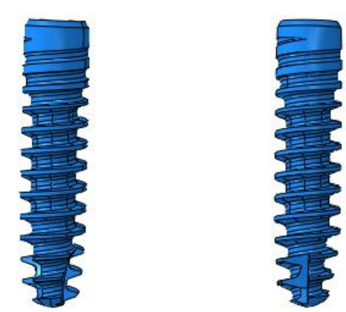


Figure 1. Three-dimensional design of implant

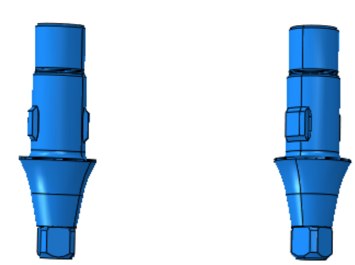


Figure 2. Three-dimensional design of TiBase Abutment

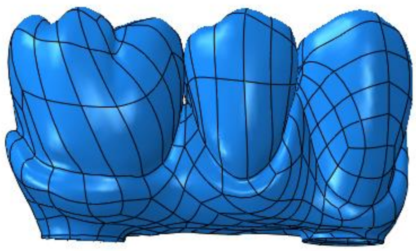


Figure 3. Three-dimensional design of monolithic zirconia crowns

Figure 4. Three-dimensional design of abutment screws

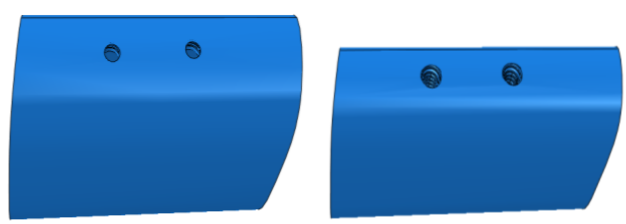


Figure 5. Three-dimensional design of cortical and trabecular bone tissues

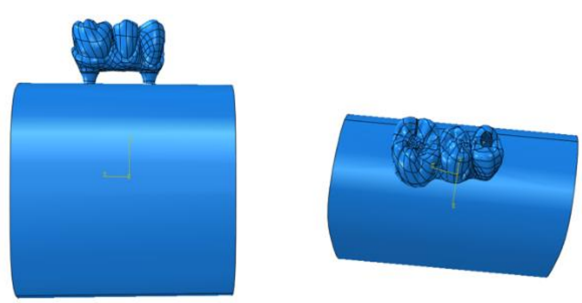


Figure 6. Combining implants, abutments, and restorations in a three-dimensional digital model

The final models were saved as a Standard for the Exchange of Product Model Data (STP) files and transferred to ABAQUS (2020 Dassault Systems Simulation Corp., Johnston, RT, USA) for the finite element analysis. In the ABAQUS program, material properties (Table 1) were applied to the individual components, and connections between the components were created. Then, a 30-degree oblique load of 150 N in the buccolingual direction was applied to the occlusal table for 1000 cycles, and the mandibular mandible was subjected to ENCASTRE (restriction of both motion and rotation in all directions). The stress distribution values were recorded in terms of the VMS values, and the fatigue performance was measured using the Seegers method. The implant was assumed to be fully osteointegrated with the bone, and the implant components were fully restricted in all directions (X, Y, and Z) on the surface of the implant.

The contact type used to describe the quality of integration between the abutment, fixture, abutment screw interface, and fixture was frictional. The frictional coefficient was 0.3. The equation for the screw tightening moment was as follows:

T = K x D x F (1),

where the values for T, D, F, and K are the screw tightening moment (N-cm), with a screw diameter (m), screw preload (N), and screw factor (also known as torque coefficient)with a typical value of 0.2 (16). This equation can be utilized to determine the screw preload value when the abutment screw experiences a tightening moment.

For a favorable long-term outcome, the fatigue life of the implant must meet stringent durability criteria, ideally approaching infinity. Fatigue analysis or physical testing can be used as assessment methods. This study employed the following equations via FEA modeling to forecast the fatigue lifespan of implants.

$$\frac{\gamma}{2} + \frac{\Delta\varepsilon_N}{2} = 1.65\frac{\sigma_f' - \sigma_{N,m}}{E}\left(2N_f\right)^b + 1.75\varepsilon_f'\left(2N_f\right)^c \quad (2),$$

where the average normal stress on the critical plane is denoted by $\sigma_{N,m}$ in this equation. The number of reversals at crack initiation is shown by $2N_f$. The shear-stress amplitude is represented by γ/2. The normal strain on the critical plane is denoted by $\Delta\varepsilon_N$. The fatigue strength and ductility coefficients are represented by σ_f' and ε_f', accordingly. The elastic modulus is symbolized by E, the fatigue ductility exponent by c, and the fatigue strength exponent by b. The fatigue ductility exponent and coefficient are determined through application of the Coffin-Manson law (17):

$$\varepsilon_p = \varepsilon_f'\left(2N_f\right)^c \quad (3)$$

Basquin's law provides the fatigue strength exponent and coefficient, as follows:

$$\varepsilon_e = \frac{\sigma_a}{E} = \frac{\sigma_f'}{E}\left(2N_f\right)^b \quad (4)$$

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{(\sigma_{max} - \sigma_{min})}{2}, \quad (5)$$

where ε_e is the elastic portion of the cyclic strain amplitude, and σ_a is the cyclic stress amplitude. Material characteristics were approximately calculated using the Seegers method with the help of rescaling the traditional ultimate tensile strength (UTS) (18). Table 2 shows the values of all pertinent parameters for titanium according to the Seegers method.

Table 1. Young's modulus (elastic modulus) and Poisson's ratio in each component

Material	Young's Modulus(E MPa)	Poisson's Ratio (v)	Shear Modulus (G MPa)
Cortical Bone (19)	E_1 12,600 E_2 12,600 E_3 19,400	V_{12} 0.300 V_{23} 0.253 V_{13} 0.253 V_{21} 0.300 V_{32} 0.390 V_{31} 0.390	G_{12} 4850 G_{23} 5700 G_{13} 5700
Trabecular Bone (19)	E_1 1.148 E_2 0.210 E_3 1.148	V_{12} 0.055 V_{23} 0.010 V_{13} 0.322 V_{21} 0.010 V_{32} 0.055 V_{31} 0.322	G_{12} 68 G_{23} 68 G_{13} 434
Bone Graft (20)	3,450	0.31	
Mucosa (21)	2.8	0.40	
Titanium (22)	110,000	0.33	
Composite Resin (23)	12,000	0.33	
Monolithic Zirconia (24)	210	0.25	
Dual-Cure Resin Cement (25)	18.6[55]	0.28[55]	

Table 2. Material parameters by the Seegers method (26, 27)

σ'_f	ε'_f	b	c
1554.71	0.35	-0.095	-0.69

Table 3. Maximum main stress values according to material (MPa)

	Bone-Implant Levels				
	0 mm	0.5 mm	1 mm	1.5 mm	2 mm
Implant #44	232.5	216	169.4	76.88	42.54
Implant #46	24.45	25.87	26.45	27.46	29.26
Abutment #44	107.4	110.9	116.8	128.2	135.2
Abutment #46	106.3	103.7	98.99	90.68	88.62
Abutment Screw #44	6.560	4.873	4.498	4.067	3.903
Abutment Screw #46	6.723	6.253	6.077	4.975	4.305
Cement #44	55.33	54.90	53.66	52.96	51.68
Cement #46	58.94	58.01	57.12	56.42	47.60
Prosthetic Restoration	91.59	109.9	117.5	126.6	148.8
Cortical Bone	6.862	4.290	3.444	2.432	1.862
Trabecular Bone	1.112	2.498	4.307	10.72	12.83

Table 4. Fatigue performance

	Bone-Implant Levels				
	0 mm	0.5 mm	1 mm	1.5 mm	2 mm
Implant #44	1.558×10^{20}	4.396×10^{20}	5.868×10^{20}	7.008×10^{20}	2.349×10^{21}
Implant #46	1.811×10^{20}	8.237×10^{20}	8.763×10^{20}	8.954×10^{20}	1.763×10^{21}
Abutment #44	1.511×10^{16}	1.432×10^{16}	1.400×10^{16}	1.256×10^{16}	9.873×10^{15}
Abutment #46	2.136×10^{16}	3.983×10^{16}	4.537×10^{16}	6.320×10^{16}	8.735×10^{16}
Abutment Screw #44	1.466×10^{28}	3.350×10^{29}	7.783×10^{29}	2.247×10^{30}	3.466×10^{30}
Abutment Screw #46	1.132×10^{28}	2.428×10^{28}	3.278×10^{28}	2.693×10^{29}	1.235×10^{30}

Results

As the bone level of the implants increased, the vMS values in the prosthetic restoration (Fig. 7) increased, whereas the vMS stress values on the cements (Fig. 8) decreased.

As the bone level of the implants increased, the vMS values decreased on the cortical bone and increased in the trabecular bone (Fig. 9).

As the implant-bone level increased, the vMS value on implant 44 decreased, while the VMS value on the abutment of the same implant increased (Fig. 10).

As the implant-bone level increased, the vMS value on implant 46 increased, while the VMS value on the abutment of implant 46 decreased (Fig. 11).

The vMS values on the abutment screws decreased on both screws (Fig. 12).

As the bone level increased, the strength of the abutment screw of implant 44 increased, whereas the strength of the abutment of the same implant decreased.

As the bone level increased, the strength of the abutment, abutment screws and implants of implant 46 increased.

The abutment screw was the most durable component, whereas the earliest failure occurred in the abutments.

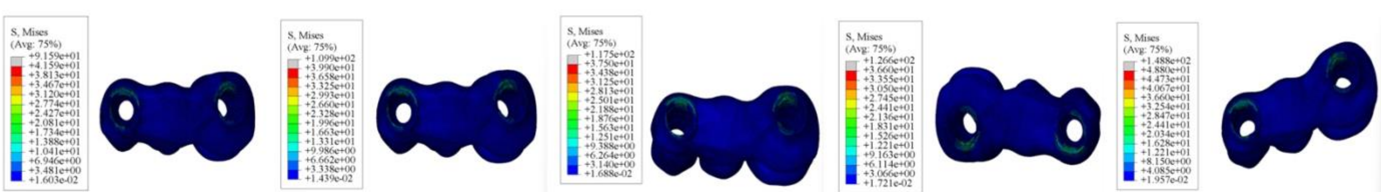
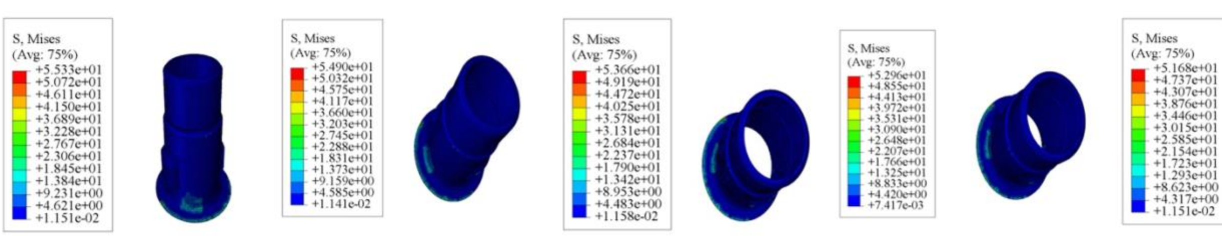
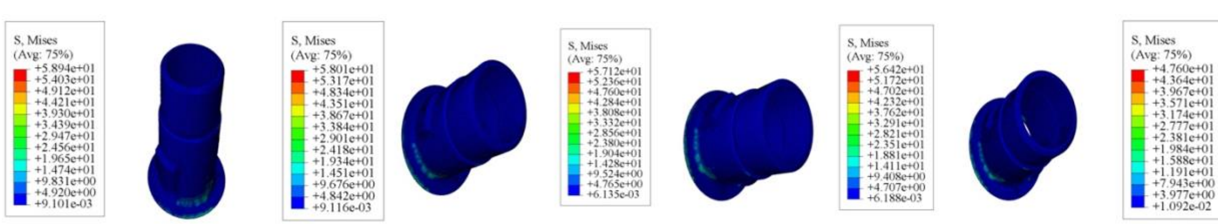


Figure 7. vMS values on prosthetic restoration

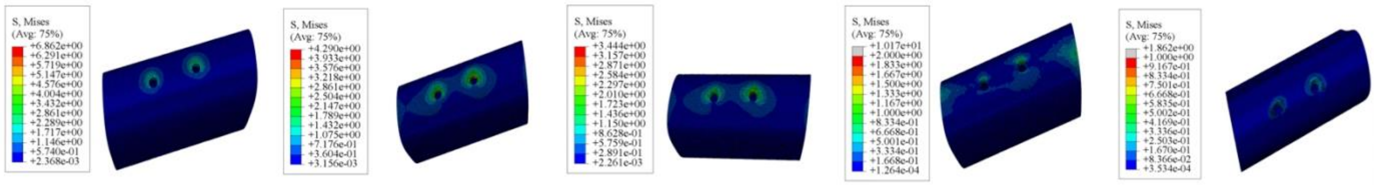


a) Cement #44

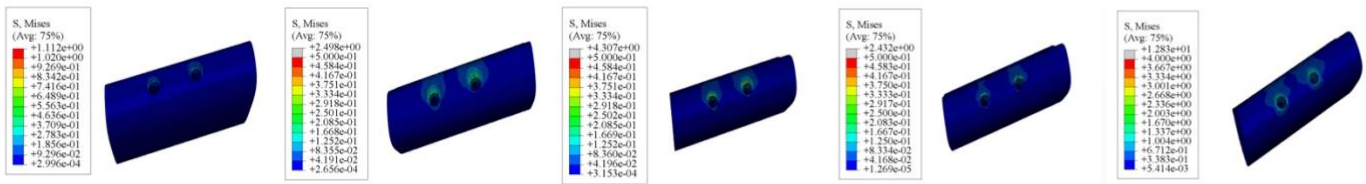


b) Cement #46

Figure 8. vMS values on cements

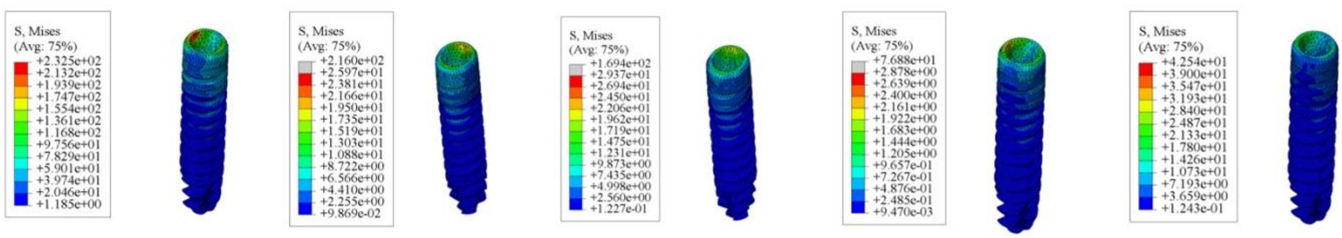


a) Cortical Bone

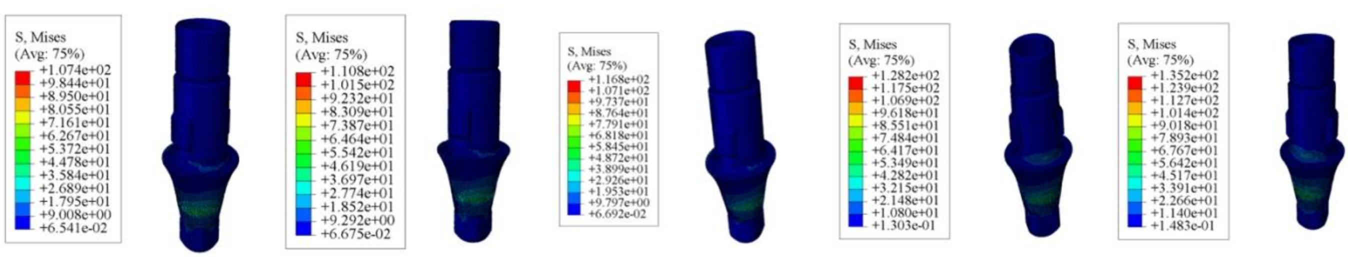


b) Trabeculer Bone

Figure 9. vMS values on cortical bone and trabecular bone

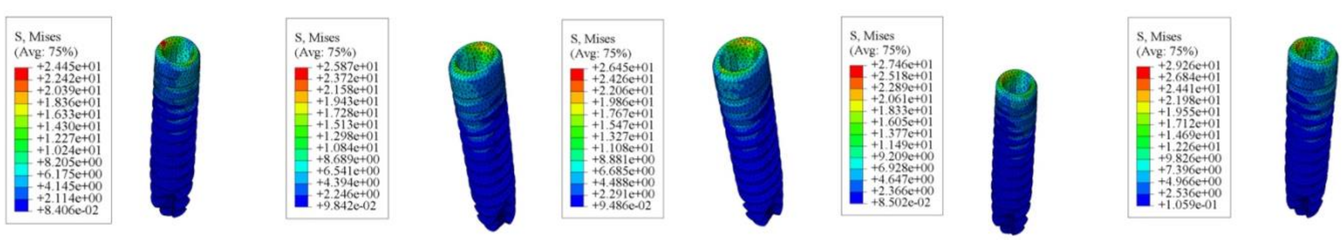


a) Implant #44

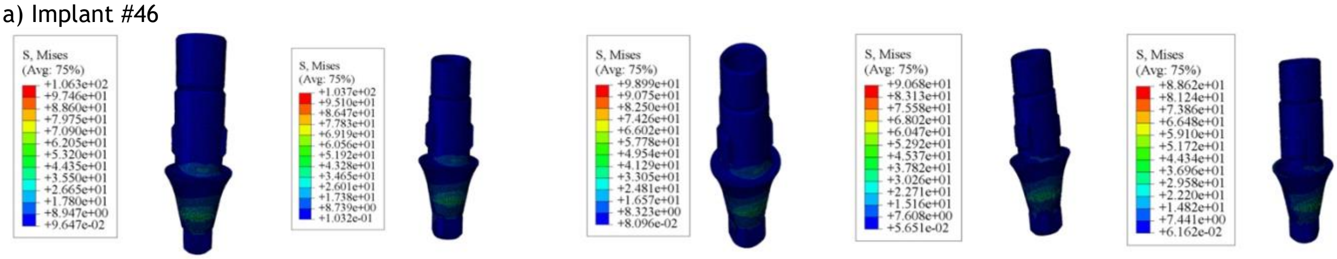


b) Abutment #44

Figure 10. VMS values on implant 44 and its abutment



a) Implant #46



b) Abutment #46

Figure 1. vMS values on implant 46 and its abutment

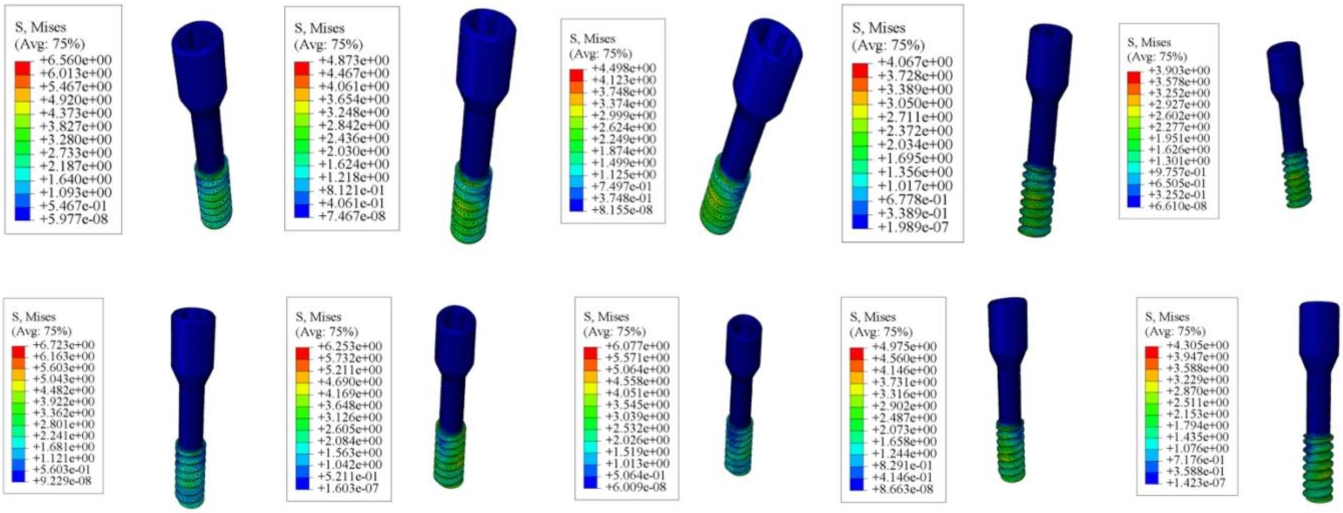


Figure 2. vMS values on abutment screws 44 and 46

Discussion

This study aimed to evaluate the stress distribution created by loads on implants, implant abutments, abutment screws, prosthetic restorations, and bone at different bone-implant levels. Considering the differences in stress distribution on implants and the surrounding bone due to different bone-implant levels and designs, the null hypothesis was evaluated and rejected.

In a study by Poovarodom et al. in 2023, 3.0 mm bone depth showed the highest density increase in trabecular bone among all models, while 0 mm bone depth showed the lowest (28). Similarly, in this study, the stress value in the trabecular bone increased as the implant-bone level increased. In conclusion, the implant should be placed more superficially in areas with dense trabecular bone.

When the TiBase abutment was compared with the other elements, higher stress values were found in 60% of the results (Table 3). This finding indicates that the TiBase abutment significantly contributes to the distribution of occlusal forces across the implant, peri-implant bone, and abutment screw (29). This finding is consistent with another study that concluded that TiBase contributes to better stress distribution on the implant in a TiBase zirconia restoration by absorbing stress internally (30). In conclusion, the choice of TiBase as an abutment may help to reduce the likelihood of implant fractures.

In a study conducted in 2019, abutment screw loosening ranged from 7% to 11%, and the incidence of abutment screw fracture was found to be 0.6%. Abutment screw loosening has been reported as the most common prosthetic complication, ahead of the more difficult abutment screw fracture and implant fracture (31). Between 1966 and 2006, a systematic review of single-tooth implant-supported crowns with a 5-year follow-up period revealed an abutment screw loosening rate of 5.8%. However, abutment or screw fracture accounts for only 0.35 percent of mechanical complications, while implant fractures account for 0.14 percent (32). In another study by Poovarodom et al., the majority of high von Mises stress values were found in the anti-rotation portion of the abutment and Morse conical connection, the abutment screw, and the first groove of the implant on the buccal side (33). Based on the provided data and clinical observations, abutment screw loosening and fracture have emerged as significant and frequently encountered challenges in the prosthetic domain of dental implants. However, in this study, the abutment screw was found to be the most durable part. In the study, all implant parts were combined the most ideal way. In fact, the result we obtained in this study may explain that the passive fit of the restoration cannot be applied 100% in the clinical setting.

As in this study, most finite element analysis studies assume 100% osseointegration of the bone-implant interface, indicating perfect attachment of trabecular and cortical bones to the implant surface. First, the research predominantly focused on numerical simulations (finite element analysis) rather than empirical data derived from clinical trials. Although finite element analysis offers valuable insights, actual clinical outcomes may differ due to biological variations and individual patient-specific factors. These factors constitute limitations of FEA studies, and these limitations should be considered when interpreting the results.

Conclusion

Within the limitations of this study, it was observed that the implant-bone level affects the stresses generated in prosthetic restorations.

- Abutment screws have the highest survival probability among all components of the implant system.
- Abutments are the most unsuccessful part of the implant system.
- When evaluated in terms of stress in the prosthetic restoration, the depth of implant placement should be superficial.
- Cortical bone density is a success factor in implant placement.

Disclosures

Acknowledgments: This study has been presented at the Necmettin Erbakan University 3rd International Dentistry Congress in Konya, Türkiye, held between May 24-26, 2024.

Peer-review: Externally peer-reviewed.

Author Contributions: Conception – N.S.A.K.; Design – N.S.A.K., R.M.; Supervision – A.R.T.; Materials – N.S.A.K., A.R.T.; Data Collection and/or Processing – N.S.A.K., A.R.T.; Analysis and/or Interpretation – R.M., M.G.D., M.K.; Literature Review – N.S.A.K., A.R.T., M.G.D., M.K.; Writer – N.S.A.K.; Critical Review – A.R.T., M.G.D.

Conflict of Interest: No conflict of interest was declared by the authors.

Funding: The authors declared that this study has received no financial support.

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