Dental Research Journal

Original Research

A comparative finite element analysis of titanium, poly-ether-ether-ketone, and zirconia abutment on stress distribution around maxillary anterior implants

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Received: 31-Dec-2023
Revised: 14-Feb-2024
Accepted: 26-Feb-2024
Published: 26-Mar-2024

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ABSTRACT

Background: The aim of this study was to investigate the influence of abutment material, alveolar bone density, and occlusal forces on stress distribution around maxillary anterior implants.

Materials and Methods: An *in-vitro* study was conducted. The maxillary anterior implant was modeled using a three-dimensional finite element model in D2 and D3 bones with three different abutment materials: titanium, zirconia, and poly-ether-ether ketone (PEEK). Von Mises stress was evaluated after the application of vertical and oblique loads of 100 N, 175 N, and 250 N. Statistical analysis was done by Friedman–Wilcoxon signed-rank test, Mann–Whitney *U* test, and Kruskal–Wallis test. The probability value <0.05 is considered a significant level.

Results: Stress distribution around D3 bone was higher than D2 bone in all the abutment materials with greater values seen in oblique load than vertical load with insignificant difference ($P > 0.05$). Statistically insignificant stress values were seen greater in PEEK than titanium or zirconia abutment ($P > 0.05$). A statistically significant difference was observed between 100 N and 175 N of load ($P < 0.05$).

Conclusion: PEEK, zirconia, and titanium as abutment material in the anterior region showed similar properties. The stress on the bone was proportionately increased during the vertical and oblique loads suggesting the influence of mechanical load in crestal bone loss rather than the type of abutment material.

Key Words: Bone density, dental implant-abutment, dental implants, dental stress analyses, poly-ether-ether ketone, single tooth

INTRODUCTION

Single endosteal dental implant-supported crown has long-term success rates as high as 90%–95%.[1] Although the literature shows an extensive success rate, Henry *et al*. reported 96.6% success associated with a 10% esthetic failure rate in a 5-year multicenter study for single tooth replacements in the anterior maxilla.[2,3] Mechanical factors, especially the type of abutment material, affect the stability of the mucosa and crestal bone.[4,5] Ingemar Abrahamsson *et al*. observed an increase in the amount of bone loss following the abutment connection.[6] Although titanium abutments are the most widely considered standard treatment

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How to cite this article: Elias A, Banu RF, Vaidyanathan AK, Padmanabhan TV. A comparative finite element analysis of titanium, poly-ether-ether-ketone, and zirconia abutment on stress distribution around maxillary anterior implants. Dent Res J 2024;21:22.

option for implant-supported restorations, they have an inherent esthetic disadvantage. Increased demands for highly esthetic restoration contribute to the development of nonmetallic abutment materials with improved material characteristics.[7] However, ceramic abutments exhibited a complication of 2%, with a higher degree of fractures than metallic abutments that lead to implant failure.[8-10]

The mechanical properties of zirconia with an elastic modulus (210 Gpa) similar to those of metals were used as abutments to improve the esthetic outcome of an implant-supported prosthesis.[11,12] However, an abutment material with an elastic modulus similar to bone was known to decrease the stress distribution to the supporting tissues.[7] Poly-ether-ether ketone (PEEK), which is a dominant member of the poly-aryl-ether-ketone polymer family, exhibits an elastic modulus that varies from 3 to 4 Gpa. Moreover, the addition of fillers such as carbon fiber can modify the elastic modulus of PEEK from 3 GPa to 18 Gpa equivalent to cortical bone.[7] PEEK, as a healing abutment, lowers the risk for marginal bone loss and soft-tissue recession during the initial healing period when compared to Titanium.[13] Santing *et al.* suggested that the fracture strength of composite resin provisional crowns fabricated over PEEK and titanium abutments is comparable.[14] However, the studies on PEEK abutments are limited to validate their application as a conventional implant abutment. Furthermore, the location and magnitude of occlusal forces can affect the quality and quantity of induced strain and stress in all components of the bone–implant prosthesis complex.[15]

The role of abutment material on the effective stress transmission around implants to reduce the marginal bone loss and facial marginal recession for an optimal esthetic outcome is still questionable. Hence, the purpose of the present study was to investigate the influence of different abutment materials such as titanium, zirconia, and PEEK on stress distribution around maxillary anterior implants under varied alveolar bone density and occlusal forces using a three-dimensional (3D) finite element analysis (FEA). The objective of the study was to analyze the stress distribution around the anterior maxillary implant with:

i. Different abutment materials: titanium, zirconia, and PEEK
ii. Different bone densities: D2 and D3 in each abutment material
iii. Different oblique and vertical loads under varying densities for each abutment material.

MATERIALS AND METHODS

An *in vitro* study was conducted by FEA in the present study. A 3D FEA was done using the ANSYS (Analysis System Software, Ansys, Inc., Canonsburg, Pennsylvania, United States) Pro/Engineer Wildfire 2.0 software. The bone, implant, and abutment were modeled from the computed tomography scan obtained from a similar clinical situation. A 3D finite element model of a maxillary anterior section of bone with a single dental implant in the incisor region with two different bone qualities and three different abutment materials was constructed. Six FEA models were constructed with three different forces, and the loads were applied at the chosen coordinates.

Bone was constructed with a height of 24 mm and a width of 7 mm having a cortical bone thickness of 1 mm and 2 mm on the labial and palatal bone, respectively. The properties of the bone approximated the D2 and D3 as classified by Lekholm and Zarb.[16] A 3.7 mm width, 11.5 mm length solid tapered screw-type implant that has a threaded helix and internal hex connection was modeled in the bone.

Three different abutment materials titanium, zirconia, and PEEK of the same dimensions (3 mm diameter and 6 mm length) were used. The abutments were prepared 1.5 mm on the incisal, buccal, and lingual aspects with a 0.5 mm width of chamfer margin. Porcelain fused to the metal crown was designed with a 10 mm length and a diameter of 8.5 and 7 mm in mesiodistal and labiolingual aspects, respectively. The crown had a 2 mm thickness of feldspathic porcelain laid over a 0.8 mm thickness of Co-Cr alloy that was cemented to the abutment with an intervening cement thickness of 50 µm.[17]

All the materials used in the models were isotropic, homogeneous, and linearly elastic considering 100% osseointegration of the implants. The Young's modulus and the Poisson's ratio for each material were taken from existing literature [Table 1].[1,18,19] External loads of 100 N, 175 N, and 250 N were applied in the vertical and oblique directions. The vertical load was applied along the long axis of the implant prosthesis, and the oblique load was applied on the cingulum of the incisor crown at a 135° inclination.[1]

The methodology was reviewed by an independent statistician, and the collected data were analyzed with the SPSS 28.0 version(IBM, SPSS Inc, Armonk, New York, United States). To describe the descriptive statistics, the mean and standard deviation were used. To find the significant difference between the bivariate samples in paired groups (vertical and oblique loads), the Friedman–Wilcoxon signed-rank test was used. Mann–Whitney *U* test was to find the significant difference between independent groups (cervical, medial, and apical regions of abutment), and Kruskal–Wallis test was used for the multivariate analysis (cervical, medial, and apical regions of abutment). In all the above statistical tools, the probability value < 0.05 is considered a significant level.

RESULTS

The stress distribution at the peri-implant area was compared between nine groups (Ti 100 N, Ti 175 N, Ti 250 N, Zi 100 N, Zi 175 N, Zi 250 N, PEEK 100 N, PEEK 175 N, and PEEK 250 N) in both D2 and D3 bone quality [Tables 2, 3 and Figures 1-6]. There was no statistical difference between the three materials in any of the six types of load that was assessed. However, higher stress values were observed with PEEK abutment ($P > 0.05$) [Table 4]. The results showed a generalized increase in the stress values on the D3 bone when compared to the D2 bone in all the groups with statistical insignificance ($P > 0.05$) [Table 5]. The stress on the peri-implant area significantly increased from 100 N to 175 N and 100–250 N ($P < 0.05$) which was more predominant with an oblique load [Table 6].

Table 1: Material properties used in the model

Material	Elastic modulus GPa	Poisson's ratio (μ)
Cortical bone	13.7	0.3
D2 cancellous bone	5.5	0.3
D3 cancellous bone	1.6	0.3
Titanium	110	0.36
Zirconia	210	0.36
PEEK	18	0.4
Co-Cr alloy	218	0.33
Porcelain	82.8	0.35
Cementing medium	7.3	0.35

PEEK: Poly-ether-ether ketone

DISCUSSION

Among the various abutment materials used as an implant superstructure, PEEK had an elastic modulus closer to the bone. Hence, the study was aimed at comparison of PEEK abutment material with titanium and zirconia abutment to evaluate the stress in the peri-implant bone around maxillary anterior implants for an optimal esthetic outcome. Clinically, it is impossible to assess the stress and strain distribution of implant-supported prostheses, although strain gauges may be used to measure strains at the abutment level. The use of simulation models such as the photoelastic method had disadvantage of being non-transparent, and stress-strain analysis had the

Table 2: Stress distribution in D3 bone with different abutment materials and varying loads

Abutment material	Load	Direction of load	Cervical		Middle		Apical	
			Mean (MPa)	SD	Mean (MPa)	SD	Mean (MPa)	SD
Titanium	250	Vertical	7.3	1.0	2.0	0.34	2.6	0.1
Titanium	250	Oblique	20.0	3.1	1.6	0.98	1.8	0.1
PEEK	250	Vertical	16.1	0.13	2.2	0.16	1.2	0.02
PEEK	250	Oblique	31.0	7.6	1.5	1.1	0.86	0.02
Zirconium	250	Vertical	6.3	0.96	1.4	0.79	2.9	0.1
Zirconium	250	Oblique	17.6	3.3	1.2	0.49	2.1	0.2
Titanium	175	Vertical	5.2	1.1	1.4	0.07	1.6	0.1
Titanium	175	Oblique	13.4	2.2	1.0	0.55	1.3	0.1
PEEK	175	Vertical	9.8	0.77	1.3	0.05	0.80	0.04
PEEK	175	Oblique	21.0	6.2	1.1	0.77	0.6	0.06
Zirconium	175	Vertical	3.9	0.17	1.4	0.07	1.8	0.09
Zirconium	175	Oblique	13.1	2.7	1.1	0.64	1.4	0.5
Titanium	100	Vertical	2.9	0.27	0.83	0.04	1.0	0.02
Titanium	100	Oblique	8.9	2.0	0.63	0.41	0.78	0.08
PEEK	100	Vertical	5.4	0.16	0.79	0.03	0.43	0.01
PEEK	100	Oblique	13.0	3.6	0.74	0.61	0.34	0.03
Zirconium	100	Vertical	2.5	0.09	0.82	0.007	1.0	0.1
Zirconium	100	Oblique	7.3	1.6	0.64	0.38	0.84	0.1

PEEK: Poly-ether-ether ketone; SD: Standard deviation

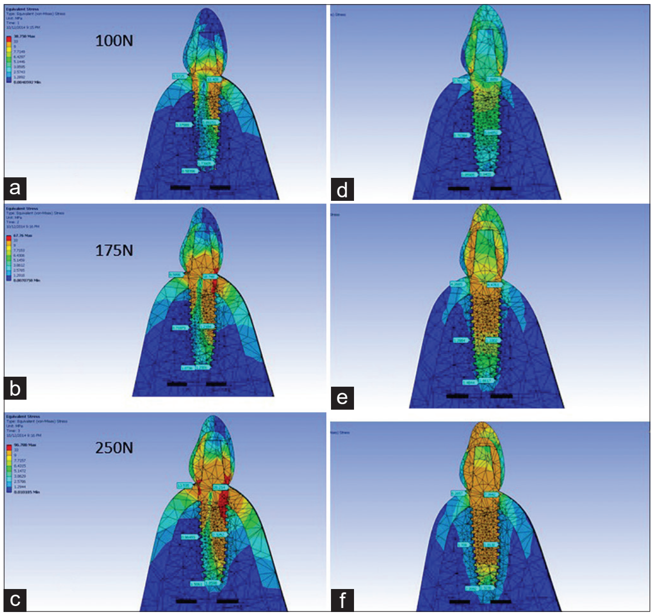

Figure 1: Stress distribution in titanium abutment with D2 bone: (a) 100 N oblique load, (b) 175 N oblique load, (c) 250 N oblique load, (d) 100 N vertical load, (e) 175 N vertical load, (f) 250 N vertical load.

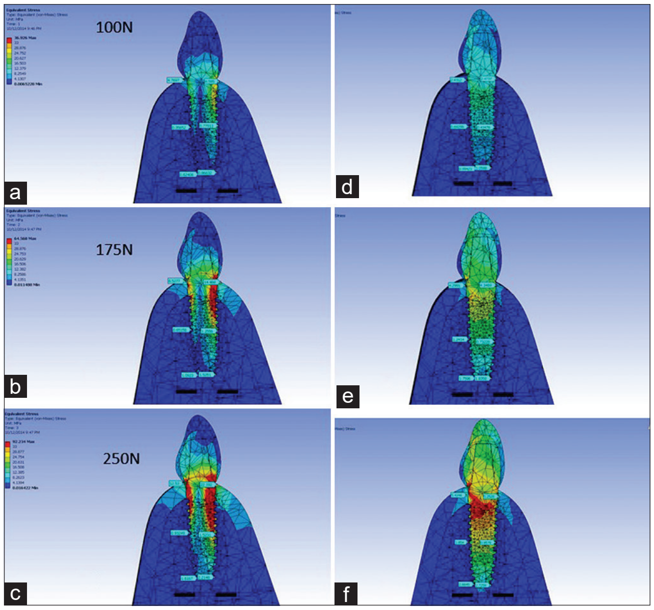

Figure 3: Stress distribution in zirconia abutment with D2 bone: (a) 100 N oblique load, (b) 175 N oblique load, (c) 250 N oblique load, (d) 100 N vertical load, (e) 175 N vertical load, (f) 250 N vertical load.

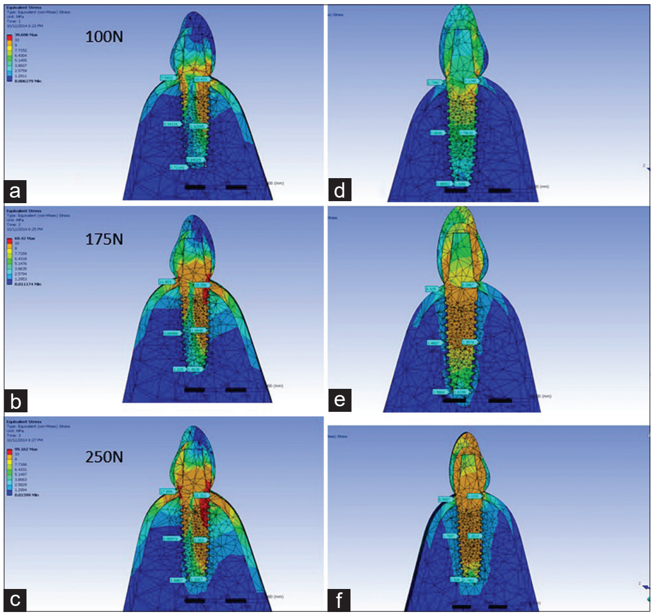

Figure 2: Stress distribution in titanium abutment with D3 bone: (a) 100 N oblique load, (b) 175 N oblique load, (c) 250 N oblique load, (d) 100 N vertical load, (e) 175 N vertical load, (f) 250 N vertical load.

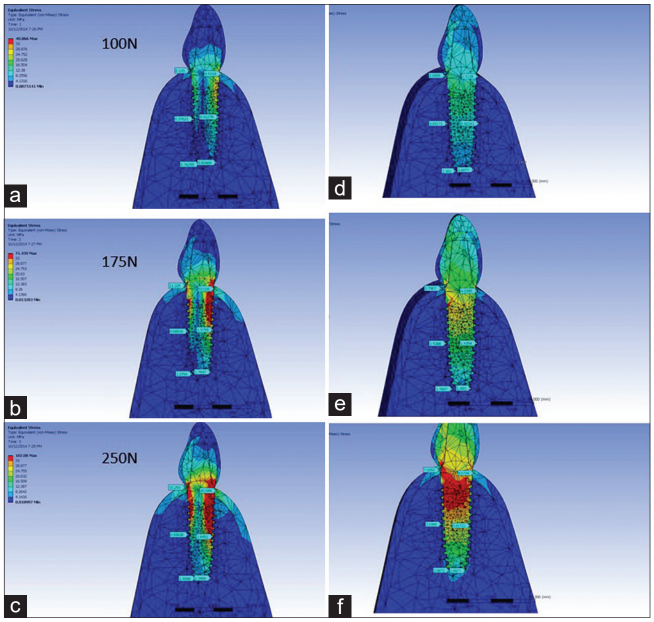

Figure 4: Stress distribution in zirconia abutment with D3 bone: (a) 100 N oblique load, (b) 175 N oblique load, (c) 250 N oblique load, (d) 100 N vertical load, (e) 175 N vertical load, (f) 250 N vertical load.

disadvantage of having poor stress output. However, FEA has the remarkable advantage of analyzing areas that are difficult to access without risks to a living subject during the investigation and allows researchers to predict the biomechanical performance of dental implant designs.[20]

We modeled the implants as threaded design with fine meshing to ensure greater accuracy and to prevent the underestimation of the stress generated at the bone-to-implant interface.[21] Furthermore, porcelain fused to metal was used as the crown material, as there was no difference in the stress distribution

Table 3: Stress distribution in D2 bone with different abutment materials and varying loads

Abutment material	Load	Direction of load	Cervical		Middle		Apical	
			Mean (MPa)	SD	Mean (MPa)	SD	Mean (MPa)	SD
Titanium	250	Vertical	6.8	0.79	1.5	0.28	2.2	0.07
Titanium	250	Oblique	20.8	10.3	1.6	0.96	1.6	0.24
PEEK	250	Vertical	11.2	0.70	2.0	0.00	0.99	0.02
PEEK	250	Oblique	35.6	21.2	1.3	0.88	0.72	0.09
Zirconium	250	Vertical	5.3	0.12	1.4	0.62	2.6	0.04
Zirconium	250	Oblique	17.3	6.8	1.2	0.41	1.9	0.41
Titanium	175	Vertical	4.3	0.14	1.3	0.02	1.5	0.12
Titanium	175	Oblique	14.1	6.4	0.96	0.34	1.1	0.11
PEEK	175	Vertical	7.6	0.25	1.2	0.02	0.60	0.00
PEEK	175	Oblique	21.2	10.8	0.96	0.54	0.51	0.04
Zirconium	175	Vertical	4.3	0.03	0.98	0.36	1.8	0.05
Zirconium	175	Oblique	11.5	4.2	0.95	0.43	1.3	0.30
Titanium	100	Vertical	2.8	0.09	0.67	0.03	0.90	0.05
Titanium	100	Oblique	7.9	3.4	0.63	0.36	0.80	0.08
PEEK	100	Vertical	5.0	0.14	0.60	0.00	0.38	0.01
PEEK	100	Oblique	15.4	9.0	0.58	0.36	0.29	0.03
Zirconium	100	Vertical	2.4	0.02	0.56	0.18	1.0	0.04
Zirconium	100	Oblique	6.6	2.7	0.57	0.29	0.74	0.1

PEEK: Poly-ether-ether ketone; SD: Standard deviation

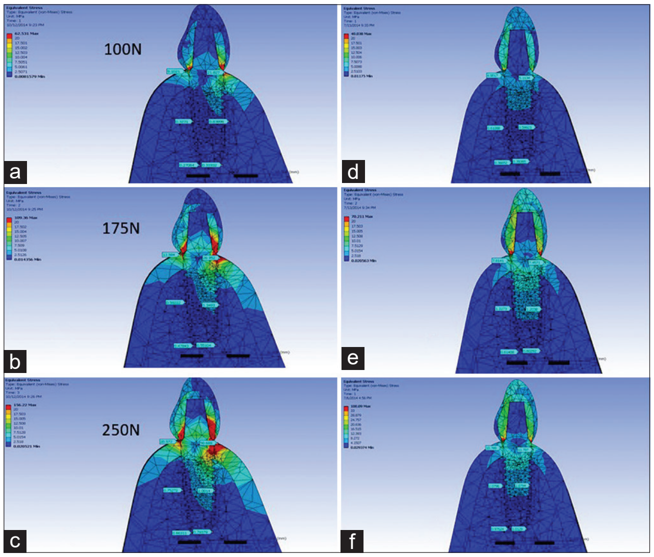

Figure 5: Stress distribution in PEEK abutment with D2 bone: (a) 100 N oblique load, (b) 175 N oblique load, (c) 250 N oblique load, (d) 100 N vertical load, (e) 175 N vertical load, (f) 250 N vertical load.

between the porcelain fused to metal and zirconia crown.[22] The fracture resistance of zirconia is very high, which could deviate the stress developed due to the abutment, and hence, porcelain fused to metal was used as the crown material.

PEEK (18 Gpa) though being closer to the elastic modulus of bone when compared to titanium (110 Gpa) and zirconia (210 Gpa),[7,11,23,24] we observed insignificant higher stress values around PEEK abutment material. The outcome of the study was in concurrence with Sarot *et al*., indicating that PEEK had higher stress concentration in the implant neck and the adjacent bone, due to decreased stiffness and higher deformation.[7] However, our comparative study revealed that the increased stress observed with PEEK was comparable with titanium and zirconia abutments.

Further, stress observed in both vertical and oblique loads in D2 and D3 bones with titanium and zirconia abutment was indifferent from the PEEK abutment. The titanium abutment distributed the stresses in a more homogeneous manner in our study due to lesser deformation of the material. However, we observed that the zirconia abutment showed the least stress compared to the other two abutment materials. The literature claims that titanium abutments exhibit the highest bending than zirconia,[25] and the stress distribution in zirconia was less than titanium with the least bacterial contamination.[26,27]

We observed that both on D2 and D3 bones, stress on the peri-implant area increased up to 175 N with higher stress observed for D3 bone, but at a load above 175 N, the changes were insignificant. The absence of stiffer cortical bone to support the implant neck in a low-density bone and the implant being stiffer than the surrounding cancellous bone could have increased stress concentration in D3 bone.[18] However, D2 and D3 bones did not have any difference at a load

Table 4: Friedman–Wilcoxon signed-rank test to compare between different abutment materials

Abutment material	250 N vertical load (*P*)	250 N oblique load (*P*)	175 N vertical load (*P*)	175 N oblique load (*P*)	100 N vertical load (*P*)	100 N oblique load (*P*)
Titanium	0.558	0.779	0.717	0.979	0.563	0.558
PEEK						
Zirconium						

PEEK: Poly-ether-ether ketone

Table 5: Mann–Whitney test to compare D2 and D3 bones at different loading forces in vertical and oblique directions

Abutment material	Load (N)	Direction of load	*Z*	*P*
Titanium	250	Vertical	−0.961	0.394
Titanium	250	Oblique	0.000	1.000
PEEK	250	Vertical	−0.962	0.394
PEEK	250	Oblique	−0.480	0.699
Zirconium	250	Vertical	−0.641	0.589
Zirconium	250	Oblique	−0.480	0.699
Titanium	175	Vertical	−0.641	0.589
Titanium	175	Oblique	−0.481	0.699
PEEK	175	Vertical	−0.961	0.394
PEEK	175	Oblique	−0.641	0.589
Zirconium	175	Vertical	−0.080	0.937
Zirconium	175	Oblique	−0.480	0.699
Titanium	100	Vertical	−0.722	0.485
Titanium	100	Oblique	0.000	1.000
PEEK	100	Vertical	−0.961	0.394
PEEK	100	Oblique	−0.323	0.818
Zirconium	100	Vertical	−0.801	0.485
Zirconium	100	Oblique	−0.480	0.699

PEEK: Poly-ether-ether ketone

Table 6: Kruskal–Wallis test to compare between different loads at 100, 175, and 250 N

Abutment material	Direction of load	250 N and 175 N		250 N and 100 N		175 N and 100 N	
		Z	*P*	*Z*	*P*	*Z*	*P*
Titanium	Vertical	−1.790	0.078	−2.368	0.017	−2.310	0.020
Titanium	Oblique	−1.444	0.160	−2.252	0.024	−1.531	0.128
PEEK	Vertical	−1.559	0.128	−2.310	0.020	−1.878	0.060
PEEK	Oblique	−1.415	0.160	−1.647	0.101	−1.445	0.160
Zirconium	Vertical	−1.444	0.160	−2.743	0.005	−1.963	0.052
Zirconium	Oblique	−1.242	0.219	−2.252	0.024	−1.646	0.010

PEEK: Poly-ether-ether ketone

of 250N. There was also a generalized insignificant increase in stress on the labial bone compared to the palatal bone, and the maximum stress values were observed in the cortical bone compared to the cancellous bone. Although the present study revealed maximum stress in cortical bone compared to cancellous bone in the anterior maxilla, previous studies suggest that under buccolingual load, the strain was concentrated in the cancellous bone.[17]

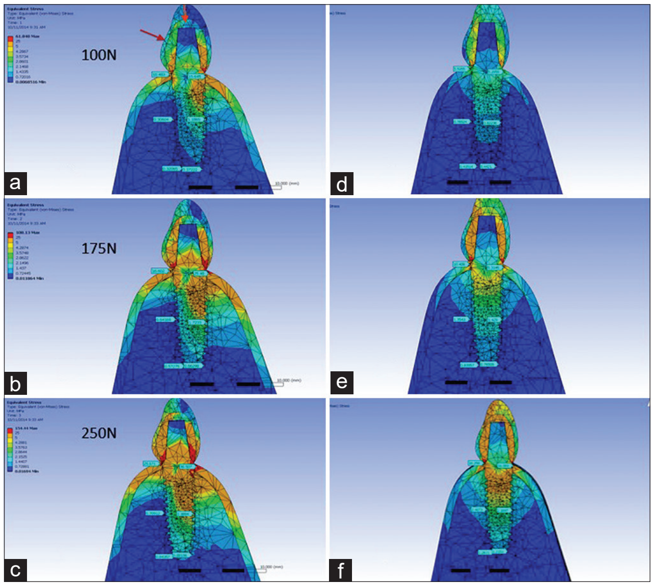

Figure 6: Stress distribution in PEEK abutment with D3 bone: (a) 100 N oblique load, (b) 175 N oblique load, (c) 250 N oblique load, (d) 100 N vertical load, (e) 175 N vertical load, (f) 250 N vertical load.

Our study also reveals maximum stress values in the cervical aspect compared to the middle and apical third which was in concurrence with the previous study. Bone qualities D2 and D3 showed maximum stress concentration at the implant neck within the cortical bone surrounding the implant for both vertical and oblique loads.[1] Abrahamsson I *et al*. concluded that increased load can result in increased stress, thereby increasing marginal bone loss.[5,6]

The outcome of our study suggests that PEEK can be a viable option in the treatment modality to be used as an abutment for anterior implants, especially with D2 bone. Despite the best efforts to model the structure accurately, the model has several limitations. Masticatory forces are dynamic, whereas this study was conducted under static loads. Bone is a viscoelastic, anisotropic, and heterogeneous material, whereas in the present study, it was assumed to be linearly elastic and homogeneous. The resultant stress values obtained may not be accurate quantitatively, though they are generally accepted qualitatively. The merging of the colors in the model makes it difficult to ascertain the definitive range, and hence, subjective variation cannot be eliminated.

CONCLUSION

PEEK abutments were comparable to titanium and zirconia abutments in anterior implant prosthetic rehabilitation, though generalized higher stress was observed. The stress on the bone proportionately increased in both vertical and oblique loads suggesting the influence of mechanical load in crestal bone loss rather than the abutment material.

Acknowledgment

The methodology was reviewed by independent statistician, Dr. S. Venkatesan, MSc, MPhil, PhD, Proprietor, Zigma Analytics, Chennai.

Financial support and sponsorship

Nil.

Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, and financial or non-financial in this article.

REFERENCES

1. Sevimay M, Turhan F, Kiliçarslan MA, Eskitascioglu G. Three-dimensional finite element analysis of the effect of different bone quality on stress distribution in an implant-supported crown. J Prosthet Dent 2005;93:227-34.
2. Henry PJ, Laney WR, Jemt T, Harris D, Krogh PH, Polizzi G, *et al.* Osseointegrated implants for single-tooth replacement: A prospective 5-year multicenter study. Int J Oral Maxillofac Implants 1996;11:450-5.
3. Naert I, Koutsikakis G, Duyck J, Quirynen M, Jacobs R, van Steenberghe D. Biologic outcome of implant-supported restorations in the treatment of partial edentulism. part I: A longitudinal clinical evaluation. Clin Oral Implants Res 2002;13:381-9.
4. Linkevicius T, Apse P. Influence of abutment material on stability of peri-implant tissues: A systematic review. Int J Oral Maxillofac Implants 2008;23:449-56.
5. Abrahamsson I, Berglundh T, Glantz PO, Lindhe J. The mucosal attachment at different abutments. An experimental study in dogs. J Clin Periodontol 1998;25:721-7.
6. Abrahamsson I, Berglundh T, Sekino S, Lindhe J. Tissue reactions to abutment shift: An experimental study in dogs. Clin Implant Dent Relat Res 2003;5:82-8.
7. Sarot JR, Contar CM, Cruz AC, de Souza Magini R. Evaluation of the stress distribution in CFR-PEEK dental implants by the three-dimensional finite element method. J Mater Sci Mater Med 2010;21:2079-85.
8. Brunski JB, Puleo DA, Nanci A. Biomaterials and biomechanics of oral and maxillofacial implants: Current status and future developments. Int J Oral Maxillofac Implants 2000;15:15-46.
9. Pjetursson BE, Zarauz C, Strasding M, Sailer I, Zwahlen M, Zembic A. A systematic review of the influence of the implant-abutment connection on the clinical outcomes of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2018;29 Suppl 18:160-83.
10. Sailer I, Philipp A, Zembic A, Pjetursson BE, Hämmerle CH, Zwahlen M. A systematic review of the performance of ceramic and metal implant abutments supporting fixed implant reconstructions. Clin Oral Implants Res 2009;20 Suppl 4:4-31.
11. Özkurt Z, Kazazoğlu E. Zirconia dental implants: A literature review. J Oral Implantol 2011;37:367-76.
12. Gehrke P, Dhom G, Brunner J, Wolf D, Degidi M, Piattelli A. Zirconium implant abutments: Fracture strength and influence of cyclic loading on retaining-screw loosening. Quintessence Int 2006;37:19-26.
13. Koutouzis T, Richardson J, Lundgren T. Comparative soft and hard tissue responses to titanium and polymer healing abutments. J Oral Implantol 2011;37:174-82.
14. Santing HJ, Meijer HJ, Raghoebar GM, Özcan M. Fracture strength and failure mode of maxillary implant-supported provisional single crowns: A comparison of composite resin crowns fabricated directly over PEEK abutments and solid titanium abutments. Clin Implant Dent Relat Res 2012;14:882-9.
15. Sahin S, Cehreli MC, Yalçin E. The influence of functional forces on the biomechanics of implant-supported prostheses – A review. J Dent 2002;30:271-82.
16. Zarb GA, Schmitt A. The longitudinal clinical effectiveness of osseointegrated dental implants: The Toronto study. Part I: Surgical results. J Prosthet Dent 1990;63:451-7.
17. Tada S, Stegaroiu R, Kitamura E, Miyakawa O, Kusakari H. Influence of implant design and bone quality on stress/strain distribution in bone around implants: A 3-dimensional finite element analysis. Int J Oral Maxillofac Implants 2003;18:357-68.
18. Okumura N, Stegaroiu R, Kitamura E, Kurokawa K, Nomura S. Influence of maxillary cortical bone thickness, implant design and implant diameter on stress around implants: A three-dimensional finite element analysis. J Prosthodont Res 2010;54:133-42.
19. Yu W, Jang YJ, Kyung HM. Combined influence of implant diameter and alveolar ridge width on crestal bone stress: A quantitative approach. Int J Oral Maxillofac Implants 2009;24:88-95.
20. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: A review of the literature. J Prosthet Dent 2001;85:585-98.
21. Zampelis A, Rangert B, Heijl L. Tilting of splinted implants for improved prosthodontic support: A two-dimensional finite element analysis. J Prosthet Dent 2007;97:S35-43.
22. Lemos CA, Verri FR, Noritomi PY, de Souza Batista VE, Cruz RS, de Luna Gomes JM, *et al.* Biomechanical evaluation of different implant-abutment connections, retention systems, and restorative materials in the implant-supported single crowns using 3D finite element analysis. J Oral Implantol 2022;48:194-201.
23. Lautenschlager EP, Monaghan P. Titanium and titanium alloys as dental materials. Int Dent J 1993;43:245-53.

24. Eschbach L. Non-resorbable polymers in bone surgery. Injury 2000;31:D22-7.
25. Truninger TC, Stawarczyk B, Leutert CR, Sailer TR, Hämmerle CH, Sailer I. Bending moments of zirconia and titanium abutments with internal and external implant-abutment connections after aging and chewing simulation. Clin Oral Implants Res 2012;23:12-8.
26. Wakimoto M, Matsumura T, Ueno T, Mizukawa N, Yanagi Y, Iida S. Bone quality and quantity of the anterior maxillary trabecular bone in dental implant sites. Clin Oral Implants Res 2012;23:1314-9.
27. Scarano A, Piattelli M, Caputi S, Favero GA, Piattelli A. Bacterial adhesion on commercially pure titanium and zirconium oxide disks: An *in vivo* human study. J Periodontol 2004;75:292-6.