ORIGINAL RESEARCH

Influence of Abutment Type on Stress Distribution around Single Implant with Cantilever Prosthesis by Means of Photoelastic Analysis: An *In Vitro* Study

Vikraman Rakshagan[1], Ranganathan Ajay[2], Jai Krishna Srikanth Kolliboyana[3], Mohan Prasanna Hariprasad[4], K Ramesh[5], Parthasaradhi Thakkalapati[6]

Received on: 10 January 2025; *Accepted on:* 14 February 2025; *Published on:* 14 October 2025

Abstract

Aim: To evaluate the influence of standard abutment on stress distribution around a single implant with a cantilever prosthesis using photoelastic analysis in a patient-simulated mandibular three-dimensional (3D) photoelastic model.

Materials and methods: A photoelastic model with eight implants ($n = 8$) in relation to 36 was fabricated. Screw-retained cantilever prosthesis with wide platform abutment (Group I) ($n = 4$) and screw-retained cantilever prosthesis with standard platform abutment (Group II) ($n = 4$) were connected to the implant and loaded with 6, 7, and 8 kg. The load was applied to both the cantilevered premolar and molar area of the prosthesis simultaneously. The photoelastic model was analyzed in a circular polariscope. The highest fringe order, depicting stress intensity, was recorded and described for the coronal, middle, and apical third regions around the implant. Data were tabulated and subjected to a qualitative descriptive analysis.

Results: Photoelastic analysis showed that Group I (wide platform abutment) exhibited high crestal stress, with stress pocketing increasing from 6 kg (237.20 N) to 8 kg (316.20 N). In contrast, Group II (platform-switching) demonstrated more uniform stress distribution, with no stress pocketing at 6 and 7 kg, and only mild pocketing at 8 kg. Independent *t*-tests confirmed a significant difference between groups at all loads ($p < 0.05$), indicating that platform-switching reduces crestal stress and enhances biomechanical performance.

Conclusion: The implant-supported screw-retained cantilever prosthesis with wide platform abutment showed higher stress distribution in the coronal zone compared to that with standard platform abutment (platform-switching) upon loading. The increase in stress intensity was proportional to the increase in load application.

Clinical significance: The findings highlight the importance of selecting the appropriate abutment design for implant-supported cantilever prostheses to minimize stress distribution on the implant and surrounding bone. The results may guide clinicians in optimizing prosthesis design for better long-term outcomes.

Keywords: Dental implant loading, Dental implant, Dental prosthesis implant-supported, Dental prosthesis, Single tooth.

World Journal of Dentistry (2025): 10.5005/jp-journals-10015-2584

Introduction

Osseointegrated implants have proved to improve the quality of life of edentulous patients by helping them with the replacement of missing teeth.[1] Biomechanics is one of the primary factors for achieving long-term success of implant-supported prostheses.[2] Implants with marginal annual bone loss of <0.2 mm following the first year of functional loading have been accepted as successful. Many experimental studies implicate peri-implantitis and occlusal overload as the main factors leading to marginal bone loss.[3] Biological and mechanical factors work together to shape the environment around dental implants, both before and after marginal bone changes occur. These changes can happen at either a normal (physiological) level or a disease-related (pathological) level.[3,4]

Load transfer around an implant with compromised marginal bone condition would be further complicated in the presence of inflammatory bacterial infiltration. Therefore, understanding the biomechanical consequences of impairment at the bone-implant interface, specifically at early stages, is very important.[5] Various studies have shown that crestal bone loss around implants can be prevented by applying the platform-switching concept.[6,7] Analysis of the stresses transferred to the bone via implants is desirable for

[1]Department of Prosthodontics, Saveetha Dental College and Hospital, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India

[2]Department of Prosthodontics and Crown and Bridge, Vivekanandha Dental College for Women, Tiruchengode, Tamil Nadu, India

[3]General Dentist, Round Rock, Texas, United States of America

[4]Amrita School of Engineering, Amritapuri, Kerala; Department of Applied Mechanics, Indian Institute of Technology, Chennai, Tamil Nadu, India

[5]Department of Applied Mechanics, Indian Institute of Technology, Chennai, Tamil Nadu, India

[6]Department of Periodontics, Tagore Dental College and Hospital, Rathinamangalam, Tamil Nadu, India

Corresponding Author: Vikraman Rakshagan, Department of Prosthodontics, Saveetha Dental College and Hospital, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India, Phone: +91 9841990565, e-mail: rakshga@yahoo.com

How to cite this article: Rakshagan V, Ajay R, Kolliboyana JKS, *et al.* Influence of Abutment Type on Stress Distribution around Single Implant with Cantilever Prosthesis by Means of Photoelastic Analysis: An *In Vitro* Study. World J Dent 2025;16(8):702–708.

Source of support: Nil

Conflict of interest: None

© The Author(s). 2025 Open Access. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by-nc/4.0/), which permits unrestricted use, distribution, and non-commercial reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The Creative Commons Public Domain Dedication waiver (http://creativecommons.org/publicdomain/zero/1.0/) applies to the data made available in this article, unless otherwise stated.

more effective use of implants. Direct clinical evaluation would be the surest method to analyze the biomechanical response of implant treatment. However, the complexity of the structures makes direct clinical evaluation nearly impossible, considering the difficulty of the methodology, the potential ethical issues, and the long period of time that would be required for this type of study.[8,9]

To overcome these limitations, several studies have used computational, analytical, and experimental models by means of digital image correlation (DIC), finite element analysis (FEA), photoelasticity, and strain gauges to evaluate the biomechanics of dental implants. The greatest advantage of the photoelastic method is the ability to visualize the stresses in complex structures such as oral structures and to observe the stress patterns in the whole model, allowing the clinician to localize and quantify the stress magnitude.[10] With the increase in the need for fixed restoration, it is important to understand the role of implant geometry and prosthetic design on stress distribution around implants.[11] Hence, the present *in vitro* study was aimed at comparatively evaluating the force transmissions of cantilever-supporting single implant-supported prosthesis with two different implant abutment designs in different regions of bone around the implants, namely, coronal, middle, and apical regions, by means of photoelastic analysis in patient-simulated photoelastic mandibular 3D models.

Null hypothesis: There is no difference in the stress distribution between screw-retained cantilever prosthesis with wide abutment and screw-retained cantilever prosthesis with standard abutment design.

Alternate hypothesis: There is a difference in the stress distribution between screw-retained cantilever prosthesis with wide abutment and screw-retained cantilever prosthesis with standard abutment design.

Materials and Methods

Study Design

This is an *in vitro* study in which models were obtained from patients, conducted at the Indian Institute of Technology, Chennai, India, from August 2014 to July 2016, for a duration of 2 years. Institutional approval was obtained prior to initiating the study to ensure compliance with ethical and procedural standards.

Sample Size Calculation

The sample size was calculated by G*Power based on the study by Rakshagan[11] with *p*-value 0.05 and 95% power with effect size 0.636. Our calculated sample size was 8.

This study involved 8 samples, which were divided based on the abutment designs used for the screw-retained cantilever prosthesis: Group I—screw-retained cantilever prosthesis with wide platform abutment ($n = 4$) and Group II—screw-retained cantilever prosthesis with standard platform abutment ($n = 4$) (platform-switching). The study was approved by the Scientific Review Board and Institutional Ethical Committee. Informed consent was obtained from the patients for using the models.

Selection Criteria

Patients aged 18 years or older with a partially edentulous situation involving missing mandibular second premolars and first molars, intact adjacent and antagonist teeth, and stable natural or restored occlusion were included. The partially edentulous space needed to have an interarch distance of 6–10 mm and a mesiodistal space of 15–18 mm to accommodate the restoration of a mandibular second premolar and first molar. Additionally, a sufficient amount of hard tissue at the mandibular first molar site was required to support the placement of an implant 10 mm in length and 5 mm in diameter.

Patients younger than 18 years, those with systemic illnesses or terminal diseases, and those unwilling to participate in the study were excluded.

Procedure

The Digital Imaging and Communication in Medicine (DICOM) data were obtained using a high-caliber cone beam computerized tomography (CBCT) machine (CS 9300, Carestream Dental Products, New York, USA) with a slice thickness of 0.2 mm, recorded in DICOM format. The mandibular 3D model was created through 3D printing (Objet n350v Connex, Minnesota, USA) using photopolymer resin. Incremental additions of 16 µm of photopolymer resin were performed, and the resin was cured using a laser beam. This process produced a patient-simulated mandibular 3D model replicating the patient's bony anatomy, excluding the soft tissue.

The index of the patient's model was fabricated using regular-set soft putty polyvinyl siloxane impression material (Aquasil, Dentsply, Germany). Laboratory silicone gingival mask material (Gingifast Elastic, Zhermack, Italy) was dispensed into the putty index using an auto-mixing gun (3M Espe, USA).

The DICOM data were uploaded into planning software (MIS Mguide software, Israel), and a three-dimensional (3D) image of the mandible was generated. The inferior alveolar nerve was tracked to the mental foramen, and the occlusal plane was oriented to the horizontal plane. The casts obtained from maxillary to mandibular impressions were scanned individually and in occlusion using the Intellidenta 3D scanner (Intellidenta AG, Switzerland). Aestro 3D dental scan software was used to produce virtual images of the maxillary and mandibular casts. The occlusal relationship between the casts was obtained from the scan of the casts in occlusion.

Virtual planning was performed using Exo CAD (Fraunhofer). The scanned casts were virtually articulated, and the missing mandibular teeth were virtually designed. A virtual wax-up was completed in occlusion with the supporting virtual maxillary cast. The design was exported into an STL file format and saved.

In the planning software (MIS Mguide software, Israel), the DICOM data from the CBCT, the STL format of the scanned cast, and the virtual wax-up data were imported and merged. These datasets were combined in all three planes of the axis, incorporating hard tissue from the CBCT data, soft tissue from the cast data, and the wax-up from the virtual wax-up data. A virtual implant was imported from the implant library, and placement was performed virtually in the mandibular first molar region. The implant's position and angulation were adjusted in the software to ensure sufficient distance from adjacent natural teeth. Vital structures such as the inferior alveolar nerve canal were also considered during the virtual planning. A virtual implant measuring 10 mm in length and 5 mm in diameter from the MIS Seven series (MIS Implants, Israel) was selected and positioned. Screw-retained cantilever prostheses with wide and standard platforms were fabricated.

A soft tissue mask with the same thickness as the patient's soft tissue was fabricated over the 3D model using the index obtained from the patient's model to simulate a clinical situation. The surgical template was placed on the RP model, and a routine oral-simulated sequential osteotomy procedure was performed for implant placement. After implant placement, the prostheses were fabricated, and the model was duplicated using duplication

silicone. A specialized method was employed to fabricate a 3D photoelastic model.

The cantilever prosthesis with a wide-platform abutment was connected to an implant on the photoelastic model, which was immersed in a bath of fluid epoxy resin (without hardener) to match the refractive index of the model. Light was passed through the Group I models, and the fringe patterns were observed and photographed after loading with 6 kg (237.20 N), 7 kg (276.10 N), and 8 kg (316.20 N). The second set of prostheses was connected to the same models after the complete elimination of stresses and loaded in a similar manner.

The load transfer characteristics of the prosthetic designs were analyzed using a quasi-three-dimensional photoelastic stress analysis technique. This combined two- and three-dimensional analysis by passing polarized light through the mandibular model obtained via rapid prototyping. The fringe patterns generated were observed and photographed using a polariscope.

Photographic records of the samples were analyzed to determine stress intensity based on the qualitative analysis of Caputo and Standlee.[12] According to this analysis, a higher fringe order indicated greater stress. The fringe order was identified based on the sequence of colors observed: gray, white, violet, yellow, blue, orange, green, red, yellow, purple, orange, and deep blue. The order of the colors represented the order of intensity. The purple fringe, referred to as the tint of passage, was used to mark increments in relative retardation equal to a fringe order of unity ($N = 1$). Higher fringe orders ($N = 2$, $N = 3$, etc.) were assigned by observing subsequent occurrences of the tint of passage.

Stress levels were categorized as follows: low stress (2 or fewer fringes), moderate stress (2–4 fringes), and high stress (>4 fringes). The stress intensity indicated by the fringe order was compared for each cantilever prosthesis in the same photoelastic model after the complete elimination of the previously applied load. Fringe orders were analyzed in the coronal (Zone A), middle (Zone B), and apical (Zone C) regions of the implant.

To ensure accuracy and reliability of results, every test was conducted in triplicate to minimize the potential for bias.

Statistical Analysis

Statistical Package for the Social Sciences (SPSS) version 23.0 (IBM, Chicago, Illinois) was used to analyze the data. Descriptive statistics were presented as mean and standard deviation. An independent *t*-test was used to compare the fringe orders between both groups at different stress levels, with $p < 0.05$.

Results

Photoelastic analysis demonstrated significant differences in stress distribution between Group I (wide-platform abutment) and Group II (platform-switching abutment) under all loading conditions. In Group I, high stress concentrations were observed in the crestal region (Zone A), with increasing stress pocketing as the load increased. At 6 kg (237.20 N), the fringe order values in the crestal region were 4.1 mesial and 4.2 distal, which further increased to 4.7 mesial and 4.8 distal at 7 kg (276.10 N). The highest stress levels were recorded at 8 kg (316.20 N), reaching 5.4 mesial and 5.8 distal.

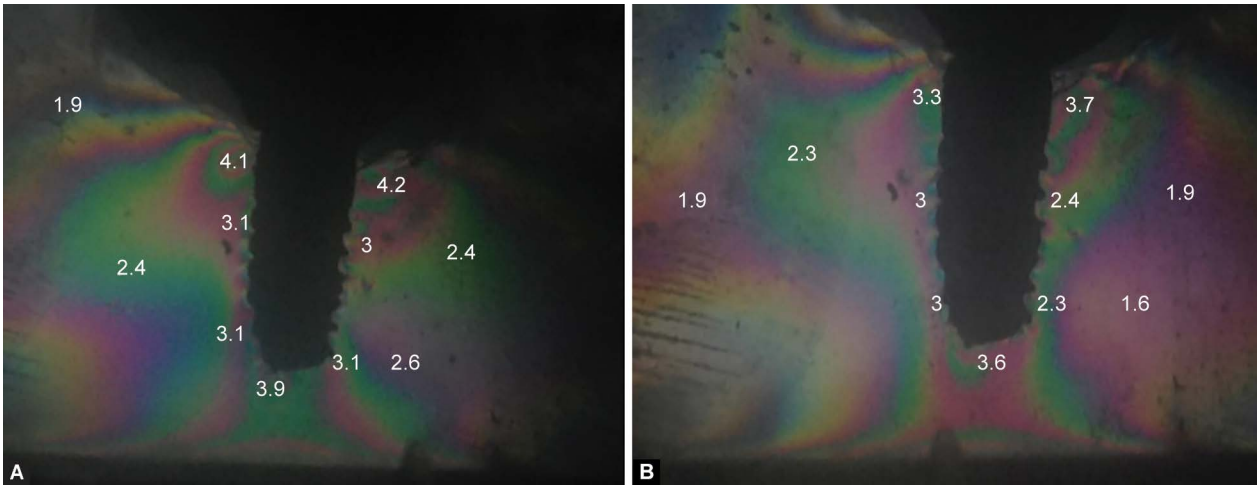
In contrast, Group II exhibited a more uniform stress distribution with lower crestal stress. At 6 kg, the fringe orders in Zone A were 3.3 mesial and 3.7 distal, with no stress pocketing observed. At 7 kg, the values increased slightly to 3.8 mesial and 3.9 distal, but the stress remained evenly distributed without pocketing. At 8 kg, stress pocketing began to appear; however, the stress levels were still significantly lower than those in Group I, with fringe orders of 3.4 mesial and 3.2 distal (Figs 1 to 4 and Tables 1 and 2).

In the middle (Zone B) and apical (Zone C) regions, Group I showed moderate stress levels, increasing as the load increased. In Zone B, fringe orders ranged from 3.1 to 3.9 mesial and 3.0 to 3.9 distal across all loading conditions, while in Zone C, the values varied from 3.1 to 3.9 mesial and 3.1 to 3.8 distal. Group II, however, exhibited consistently lower stress levels in these regions, with Zone B fringe orders ranging from 3.0 to 3.9 mesial and 2.4 to 3.4 distal, and Zone C values ranging from 3.0 to 3.2 mesial and 2.3 to 3.2 distal. Statistical analysis using independent t tests confirmed that the difference in stress patterns between the two groups at all loading conditions was significant ($p < 0.01$) (Tables 3 to 5).

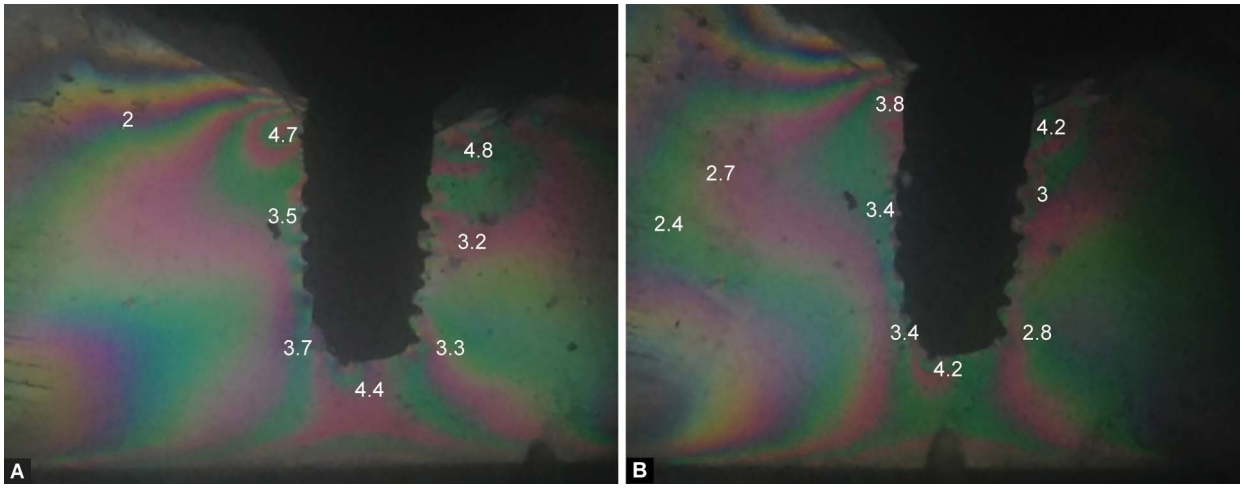
These findings suggest that platform-switching abutments effectively reduce crestal stress and improve stress distribution compared to wide-platform abutments. The even distribution



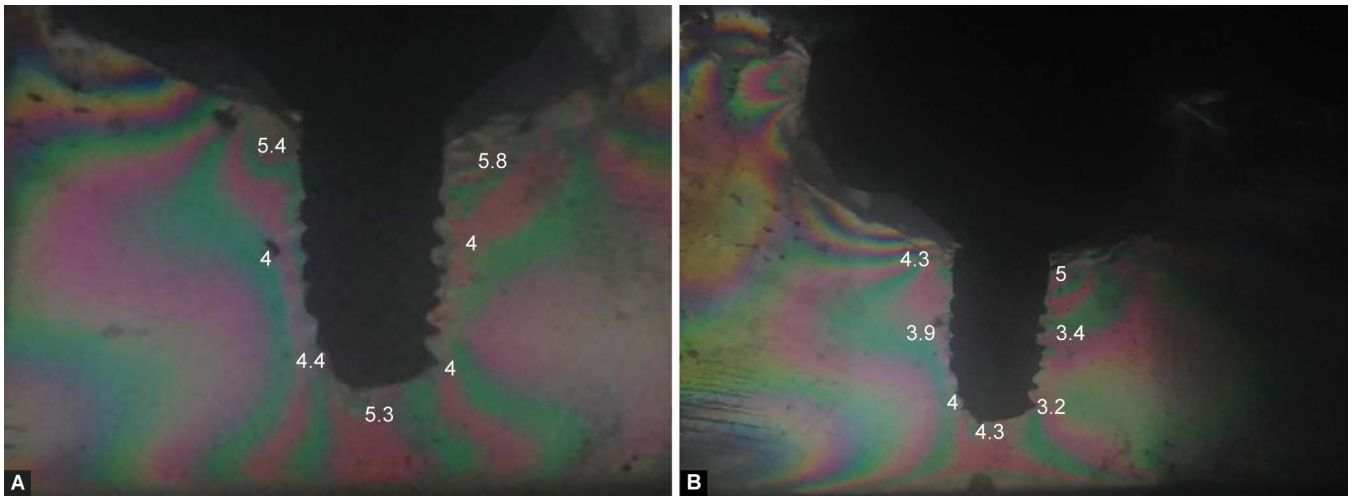
Fig. 1: Relation between stress level and fringe order, showing the correlation between stress and observed fringe patterns



Figs 2A and B: Group I screw-retained cantilever prosthesis with wide platform—fringe order for abutment at (A) 6 kg/237.20 N and (B) 7 kg/276.10 N



Figs 3A and B: (A) Group I fringe order for 8 kg/316.20 N; (B) Group II fringe order for 6 kg/237.20 N (screw-retained cantilever prosthesis with standard platform abutment, platform switching)



Figs 4A and B: Group II screw-retained cantilever prosthesis with standard platform abutment (platform switching)—fringe order for abutment at (A) 7 kg/276.10 N and (B) 8 kg/316.20 N

Table 1: Fringe levels of Group I samples at different stress

Group I samples (Screw retained cantilever prosthesis with wide platform abutment)	*Stress (fringe order)*								
	6 kg/237.20 N			*7 kg/276.10 N*			*8 kg/316.20 N*		
		Mesial	*Distal*		*Mesial*	*Distal*		*Mesial*	*Distal*
	Zone A	4.1	4.2	Zone A	4.7	4.8	Zone A	5.4	5.8
	Zone B	3.1	3	Zone B	3.5	3.2	Zone B	3.9	3.9
	Zone C	3.1	3.1	Zone C	3.7	3.3	Zone C	3.9	3.8

Table 2: Fringe levels of Group II samples at different stress

Group II samples (Screw retained cantilever prosthesis with standard platform abutment)	*Stress (fringe order)*								
	6 kg/237.20 N			*7 kg/276.10 N*			*8 kg/316.20 N*		
		Mesial	*Distal*		*Mesial*	*Distal*		*Mesial*	*Distal*
	Zone A	3.3	3.7	Zone A	3.8	3.9	Zone A	3.4	3.2
	Zone B	3	2.4	Zone B	3.4	3	Zone B	3.9	3.4
	Zone C	3	2.3	Zone C	3.4	2.8	Zone C	3.2	3.2

Table 3: Independent *t*-test showing the stress distribution at 6 kg/237.20 N

	Group I	*Group II*	*p-value*
Stress			$p < 0.01$*
Zone A			
Mesial	4.1	3.3	
Distal	4.2	3.7	
Zone B			
Mesial	3.1	3	
Distal	3	2.4	
Zone C			
Mesial	3.1	3	
Distal	3.1	2.3	

* indicates a statistically significant difference between Group I and Group II in the "Stress" variable

Table 4: Independent *t*-test showing the stress distribution at 7 kg/276.10 N

	Group I	*Group II*	*p-value*
Stress			$p < 0.01$*
Zone A			
Mesial	4.7	3.8	
Distal	4.8	3.9	
Zone B			
Mesial	3.5	3.4	
Distal	3.2	3	
Zone C			
Mesial	3.7	3.4	
Distal	3.3	2.8	

* indicates a statistically significant difference between Group I and Group II in the "Stress" variable

Table 5: Independent *t*-test showing the stress distribution at 8 kg/316

	Group I	*Group II*	*p-value*
Stress			$p < 0.01$*
Zone A			
Mesial	5.4	3.4	
Distal	5.8	3.2	
Zone B			
Mesial	3.9	3.9	
Distal	3.9	3.4	
Zone C			
Mesial	3.9	3.2	
Distal	3.8	3.2	

* indicates a statistically significant difference between Group I and Group II in the "Stress" variable

of stress observed in Group II makes platform-switching a biomechanically favorable design for screw-retained cantilever prostheses, potentially minimizing stress concentration and enhancing long-term prosthetic success.

Discussion

The findings of the present study indicate that platform-switching abutments reduce stress concentration in the crestal zone and lead to a more uniform stress distribution along the implant body. These results are consistent with prior research on platform switching in implant dentistry.[13,14]

Conflicting reports exist in the literature regarding the effects of occlusal overloads on bone response. Animal studies have shown that occlusal overloading can lead to peri-implant bone resorption if forces exceed the physiological tolerance of the alveolar bone.[15,16]

Clinical studies also associate high occlusal stress with marginal bone loss, though some studies do not corroborate these findings.[17,18] From a biomechanical standpoint, implant design influences stress magnitudes in peri-implant bone, though its impact on marginal bone remodeling remains poorly understood.[19]

Occlusal forces transmitted through the implant prosthesis to the peri-implant bone are difficult to quantify in terms of magnitude and direction.[20] However, when these forces exceed the mechanical or biological load-bearing capacity of the implant or prosthesis, they can lead to mechanical failure or loss of integration, termed overload. The resulting strain in bone depends on the applied stress and the stiffness of the bone, meaning the same force can have varying effects on different bone tissues.[21]

Several studies have demonstrated the biomechanical advantage of platform-switching abutments in reducing crestal bone loss. Gupta et al.[22] conducted a systematic review highlighting that platform-switching implants provide superior marginal bone preservation, further supporting our results.

In contrast, studies have also explored the impact of occlusal loading on marginal bone loss. Naert et al.[15] emphasized that occlusal overload could contribute to peri-implant bone loss, particularly in cases where high stress concentrations occur in the crestal region. Our study findings corroborate this, as Group I implants (wide-platform abutment) demonstrated significant stress pocketing in the crestal zone under increased loading, which could potentially contribute to marginal bone loss.

Platform switching has been extensively studied in various implant configurations, including splinted, multiple, and single implants, and has consistently demonstrated high success rates.[22,23] Photoelastic analysis, a unique and precise technique, allows visualization and quantification of full-field stress distribution.[24] This method has been widely applied in biomechanical studies to investigate the effects of implant design, prosthesis type, connection, and loading conditions on stress transfer around implants.[25,26]

Biomechanical evaluations using photoelastic analysis have been employed in several studies to assess stress distribution. Pellizzer et al.[25] used a similar photoelastic methodology and reported that stress was highest in the crestal zone, decreasing toward the apical zone. This observation mirrors our findings, wherein both groups exhibited high stress intensity in the coronal zone, with diminishing stress levels in the middle and apical regions. Additionally, Bernardes et al.[24] analyzed implant-abutment interfaces and concluded that platform switching results in improved stress distribution, a trend evident in our study as well.

The influence of cantilevered prostheses on stress distribution has also been examined in the literature. Rubo and Cappo Bianco[3] noted that cantilever extensions generate increased stress at the implant-abutment interface, potentially leading to mechanical complications. Our study supports this assertion, as Group I implants exhibited higher stress accumulation in the crestal region, likely due to the cantilevered design. Conversely, Group II implants demonstrated a more favorable stress distribution pattern, suggesting that platform switching may

mitigate some of the biomechanical drawbacks associated with cantilever prostheses.

Furthermore, finite element analysis (FEA) studies, such as those by Tribst et al.,[9] have reinforced the concept that implant design significantly influences stress magnitudes in peri-implant bone. These studies highlight that platform-switching designs effectively distribute stress more uniformly along the implant body, findings that are in accordance with our photoelastic analysis results.

Despite the strong alignment of our findings with existing literature, some discrepancies exist. While some studies, such as Afrashtehfar and Afrashtehfar,[17] argue that occlusal overload does not necessarily correlate with peri-implant tissue loss, our study suggests that increased stress concentrations in the crestal region of wide-platform abutments could lead to potential biomechanical complications. This discrepancy may be attributed to variations in study designs, loading protocols, and implant configurations.

Various studies have been done using photoelasticity to evaluate the influence of implant design, type of prosthesis, connection, magnitude, and direction of load on the stress transfer around implants.[27,28] Few studies have been done on situations simulating clinical conditions with a single implant with a cantilever prosthesis.[20] Also, the influence of platform switching on stress around implants with a single-implant-supported cantilever prosthesis is sparsely documented.

The present study assessed stress distribution around implants connected to cantilever prostheses with and without platform switching under various occlusal loads. A 3D photoelastic model, created using the RP model from a CBCT scan, simulated a clinical scenario with wide-diameter implants in the molar region.

For both prosthetic designs, stress intensity decreased from the coronal to the apical zones after loading. Stress was highest in the coronal zone, aligning with findings from previous studies,[29–31] and attributable to the implant-abutment interface design.[32,33] The wide-abutment group exhibited stress pocketing and higher stress intensity at the coronal zone, while the platform-switching group showed reduced stress intensity and a more uniform stress distribution toward the middle and apical zones. These findings are consistent with earlier studies[33–35] and underscore the importance of the implant-abutment interface in reducing stress around implants with cantilever prostheses.[36–38]

This study employed a precise and reliable photoelastic analysis method, enabling the evaluation of stress distribution under clinically relevant loading conditions. The direct comparison of wide-platform abutments and platform-switching designs provided valuable biomechanical insights. Realistic loading conditions (6, 7, and 8 kg) enhanced clinical applicability, while a comprehensive evaluation across coronal, middle, and apical zones provided a holistic understanding of stress distribution. Statistical analysis confirmed the significance of the differences observed, highlighting the advantages of platform switching in reducing stress concentration and improving prosthetic design.

The photoelastic model used in the study is homogeneous and does not replicate the varying properties of cancellous and cortical bone. Implants integrated into photoelastic resin models do not mimic the anchorage in real trabecular bone, which has lower elastic properties than cortical bone. Additionally, the photoelastic technique lacks the numerical resolution to discern stress gradients around the microthreads in the coronal region, limiting detailed analysis of their influence.

The results of this study are specific to the prosthetic designs tested. Given the wide range of implant-abutment interfaces available in the market, each design may have unique advantages and disadvantages.

Conclusion

The implant-supported, screw-retained cantilever prosthesis with a wide-platform abutment showed higher stress distribution in the coronal zone compared to that with a standard-platform abutment (platform switching) upon loading. The increase in stress intensity was proportional to the increase in load application.

Ethical Guidelines

All the procedures have been performed in accordance with the ethical guidelines laid down by the Declaration of Helsinki (1964).

References

1. Barter S, Stone P, Brägger U. A pilot study to evaluate the success and survival rate of titanium-zirconium implants in partially edentulous patients: results after 24 months of follow-up. Clin Oral Implants Res 2012;23:873–881. DOI: 10.1111/j.1600-0501.2011.02231.x
2. Ahmed KM, Elfatah SA, Katamish MAEM. Crestal bone loss of standard implant versus platform switch implant design using minimal invasive technique. Future Dent 2016;2:74–79. DOI: 10.1016/j.fdj.2016.09.001
3. Rubo JH, Cappo Bianco V. Biomechanics of Cantilevered Implant-Supported Prosthesis (Biomechanics in Implant Prosthodontics). Implant Dentistry - The Most Promising Discipline of Dentistry. 2011. DOI: 10.5772/17853
4. Araby Y, Agamy E. Implant stability and marginal bone loss in mandibular implant retained overdenture cases: a comparative study using two stud attachment systems. Egypt Dent J 2016;62:1065–1073. DOI: 10.21608/edj.2016.95420
5. Al-Zordk W, Awad S, Saker S. Peri-implant bone loss and esthetic outcome of single-tooth implant in patients with type 2 diabetes. Egypt Dent J 2019;65:793–802. DOI: 10.21608/edj.2019.72866
6. Kamal M. Implant stability and peri-implant marginal bone loss around two different threads design implants. Egypt Dent J 2020;66:2607–2619. DOI: 10.21608/edj.2020.41252.1237
7. Pillai A K, Thomas S, Dubey R, et al. Evaluation of volumetric bone loss during osteotomy between crestal implant and basal implant before implant placement. Dent Oral Maxillofac Res 2019;5. DOI: 10.15761/domr.1000304
8. Çehreli M. Biomechanics of Dental Implants: Handbook of Researchers. Nova Science Publishers, Incorporated; 2012. p. 365.
9. Tribst JPM, Dal Piva AM de O, Blom EJ, et al. Dental biomechanics of root-analog implants in different bone types. J Prosthet Dent 2022. DOI: 10.1016/j.prosdent.2022.10.005
10. Pellizzer EP, de Mello CC, Santiago Junior JF, et al. Analysis of the biomechanical behavior of short implants: the photo-elasticity method. Mater Sci Eng C Mater Biol Appl 2015;55:187–192. DOI: 10.1016/j.msec.2015.05.024
11. Rakshagan V. Influence of platform switching on stress distribution around implant with cantilever prosthesis: a photoelastic study. Repository-tnmgrmu.ac.in. 2016.
12. Caputo AA, Standlee JP. Biomechanics in Clinical Dentistry. Chicago (IL): Quintessence Publishing; 1987.
13. Kayumi S, Takayama Y, Yokoyama A, et al. Effect of bite force in occlusal adjustment of dental implants on the distribution of occlusal pressure: comparison among three bite forces in occlusal adjustment. Int J Implant Dent 2015;1:14. DOI: 10.1186/s40729-015-0014-2
14. Türker N, Büyükkaplan US, Sadowsky SJ, et al. Finite element stress analysis of applied forces to implants and supporting tissues using the

"all-on-four" concept with different occlusal schemes. J Prosthodont 2019;28(2):185–194. DOI: 10.1111/jopr.13004
15. Naert I, Duyck J, Vandamme K. Occlusal overload and bone/implant loss. Clin Oral Implants Res 2012;23(Suppl 6):95–107. DOI: 10.1111/j.1600-0501.2012.02550.x
16. Dellepiane E, Menini M, Canepa P, et al. Effect of plaque accumulation and occlusal overload on peri-implant bone loss. J Biol Res 2017;90:6212. DOI: 10.4081/jbr.2017.6212
17. Afrashtehfar KI, Afrashtehfar CD. Lack of association between overload and peri-implant tissue loss in healthy conditions. Evid Based Dent 2016;17(3):92–93. DOI: 10.1038/sj.ebd.6401193
18. Misch CE, Suzuki JB, Misch-Dietsh FM, et al. A positive correlation between occlusal trauma and peri-implant bone loss: literature support. Implant Dent 2005;14:108–116. DOI: 10.1097/01.id.0000165033.34294.db
19. Zhang WT, Cheng KJ, Liu YF, et al. Effect of the prosthetic index on stress distribution in Morse taper connection implant system and peri-implant bone: a 3D finite element analysis. BMC Oral Health 2022;22(1):431. DOI: 10.1186/s12903-022-02465-y
20. Revilla-León M, Jiang P, Sadeghpour M, et al. Intraoral digital scans—Part 1: Influence of ambient scanning light conditions on the accuracy (trueness and precision) of different intraoral scanners. J Prosthet Dent 2020;124(3):372–378. DOI: 10.1016/j.prosdent.2019.06.003
21. Ikar M, Grobecker-Karl T, Karl M, et al. Mechanical stress during implant surgery and its effects on marginal bone: a literature review. Quintessence Int 2020;51(2):142–150. DOI: 10.3290/j.qi.a43664
22. Gupta S, Sabharwal R, Nazeer J, et al. Platform switching technique and crestal bone loss around the dental implants: a systematic review. Ann Afr Med 2019;18:1. DOI: 10.4103/aam.aam_15_18
23. Mejía J, Wakabayashi K, Nakano T, et al. Marginal bone loss around dental implants inserted with static computer assistance in healed sites: a systematic review and meta-analysis. Int J Oral Maxillofac Implants 2016;31:761–775. DOI: 10.11607/jomi.4727
24. Bernardes SR, de Araujo CA, Neto AJF, et al. Photoelastic analysis of stress patterns from different implant-abutment interfaces. Int J Oral Maxillofac Implants 2009;24(5):781–789. PMID: 19865617.
25. Pellizzer EP, Carli RI, Falcón-Antenucci RM, et al. Photoelastic analysis of stress distribution with different implant systems. J Oral Implantol 2014;40(2):117–122. DOI: 10.1563/AAID-JOI-D-11-00138
26. Ramesh K, Hariprasad MP, Bhuvanewari S. Digital photoelastic analysis applied to implant dentistry. Opt Lasers Eng 2016;87:204–213. DOI: 10.1016/j.optlaseng.2016.03.022
27. Serag M, Al Nassar T, Avondoglio D, et al. A comparative study of the accuracy of dies made from digital intraoral scanning vs. elastic impressions: an *in vitro* study. J Prosthodont 2018;27:88–93. DOI: 10.1111/jopr.12481
28. Boehnen C, Flynn P. Accuracy of 3D Scanning Technologies in a Face Scanning Scenario. Fifth International Conference on 3D Digital Imaging and Modeling (3DIM'05). DOI: 10.1109/3dim.2005.13
29. Dhatrak P, Shirsat U, Sumanth S, et al. Numerical investigation on stress intensity around bone-implant interface by 3-dimensional FEA and experimental verification by optical technique. Mater Today Proc 2021;39:35–41. DOI: 10.1016/j.matpr.2020.06.097
30. Gulati D, V AKK, Dubey P. Platform Switching in Dental Implants. Lap Lambert Academic Publishing GmbH KG; 2015. p. 72.
31. Dhatrak P, Shirsat U, Sumanth S, et al. Finite element analysis and experimental investigations on stress distribution of dental implants around implant-bone interface. Mater Today Proc 2018;5(2 Part 1):5641–5648. DOI: 10.1016/j.matpr.2017.12.157
32. Kim S, Lee JW, Kim JH, et al. The impact of Morse taper implant design on microleakage at implant-healing abutment interface. Dent Mater J 2022;41(5):767–773. DOI: 10.4012/dmj.2022-022
33. Amjadi M, Khajavi A, Youssefi N, et al. The effect of dynamic loading on bacterial microleakage of the dental implant fixture-abutment interface: an *in vitro* study. J Indian Prosthodont Soc 2021;21(4):420–424. DOI: 10.4103/jips.jips_96_21
34. Atieh MA, Ibrahim HM, Atieh AH. Platform switching for marginal bone preservation around dental implants: a systematic review and meta-analysis. J Periodontol 2010;81(10):1350–1366. DOI: 10.1902/jop.2010.100232
35. Canullo L, Fedele GR, Iannello G, et al. Platform switching and marginal bone-level alterations: the results of a randomized-controlled trial. Clin Oral Implants Res 2010;21(1):115–121. DOI: 10.1111/j.1600-0501.2009.01867.x
36. Merchant A, Nallaswamy D, Velayudhan A, et al. Radiographic evaluation of marginal accuracy of metal coping in sectioned and unsectioned 3D printed models and gypsum models. World J Dent 2020;11(5):386–391. DOI: 10.5005/jp-journals-10015-1761
37. Parekar D, Selvaganesh S, Nesappan T. Comparative evaluation of accuracy of adjacent parallel implant placements between dynamic navigation and static guide: a prospective study. Cureus 2024;16(3):e57331. DOI: 10.7759/cureus.57331
38. Chhabra K, Selvaganesh S, Nesappan T. Hybrid navigation technique for improved precision in implantology. Cureus 2023;15(9):e45440. DOI: 10.7759/cureus.45440