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Effect of Implant Diameter, Implant Length, and Prosthesis Splinting on Stress Distribution in Posterior Maxillary Implant-Supported Restorations: A Three-Dimensional Finite Element Analysis

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ABSTRACT:

Purpose:To evaluate and compare the influence of implant diameter, implant length, and prosthetic splinting on stress distribution in posterior maxillary implant-supported restorations using three-dimensional finite element analysis.

Materials and Methods:Ten three-dimensional finite element models of the posterior maxilla with simulated D3 bone quality were developed using SolidWorks software and analysed in ANSYS R17. Five models represented splinted implant-supported restorations, whereas five represented non-splinted restorations. Implants of varying diameters (3.75, 4.2, 5.0, and 6.0 mm) and lengths (10 and 6.25 mm) were evaluated. All models were subjected to nonlinear loading conditions consisting of a 400 N axial load and a 200 N oblique load. Maximum von Mises stresses were analysed in cortical bone, cancellous bone, implant, and prosthetic superstructure.

Results:Cortical bone demonstrated the highest stress concentration in all models,

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whereas cancellous bone exhibited comparatively lower stress values. Increasing implant diameter progressively reduced cortical bone stress in both splinted and non-splinted restorations. Shortening implant length resulted in only a modest increase in stress concentration. Splinted restorations demonstrated a more uniform distribution of stresses throughout the implant–prosthesis–bone complex than non-splinted restorations. The lowest cortical bone stress was observed in the non-splinted model with a 6-mm-diameter, 6.25-mm-long implant, whereas the highest stress occurred in the splinted model with a 3.75-mm-diameter, 10-mm-long implant.

Conclusion:Implant diameter and prosthetic splinting exerted a greater influence on stress distribution than implant length. Increasing implant diameter significantly reduced cortical bone stress and partially compensated for reduced implant length. Splinted restorations promoted a more favourable biomechanical stress distribution than non-splinted restorations, suggesting that wider implants and splinted prosthetic designs may represent biomechanically advantageous treatment options for posterior maxillary rehabilitation.

INTRODUCTION

Implant-supported restorations have become a predictable treatment option for replacing missing teeth, with high long-term survival rates. However, rehabilitation of the posterior maxilla remains challenging because of reduced bone density, sinus pneumatization, and limited residual bone height, which may compromise implant stability and increase stress concentration in the surrounding bone.[1–3]

To overcome inadequate bone height, sinus augmentation and bone grafting are frequently performed before placement of standard-length implants. Although these procedures are clinically successful, they increase surgical complexity, treatment time, cost, and patient morbidity. Consequently, short implants have emerged as a less invasive alternative. However, concerns remain regarding their biomechanical performance because reduced implant length decreases the bone–implant contact area and may increase peri-implant stress.[4–6]

Implant diameter and prosthetic design are important factors influencing stress distribution around implants. Increasing implant diameter enlarges the bone–implant contact area and may reduce stress concentration, whereas splinting adjacent implant-supported restorations allows more favourable distribution of occlusal loads compared with non-splinted restorations. Despite numerous finite element studies, the combined influence of implant diameter, implant length, and prosthetic splinting in posterior maxillary bone remains inadequately investigated.[7–10]

Therefore, the present three-dimensional finite element analysis was undertaken to evaluate and compare the effects of implant diameter, implant length, and prosthetic splinting on stress distribution in posterior maxillary implant-supported restorations. The null hypothesis was that implant diameter, implant length, and prosthetic splinting would not significantly influence stress distribution within the implant–bone–prosthesis complex.

2. MATERIALS AND METHODS

A three-dimensional finite element analysis (3D-FEA) was performed to evaluate the influence of implant diameter, implant length, and prosthetic splinting on stress distribution in posterior maxillary implant-supported restorations.

A three-dimensional model of the posterior maxilla representing D3 bone quality was constructed using SolidWorks (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA). The model consisted of an outer cortical bone layer (0.8 mm thick) surrounding cancellous bone. Three implants replacing the maxillary first premolar, second premolar, and first molar were positioned in the edentulous region (Figure 1).

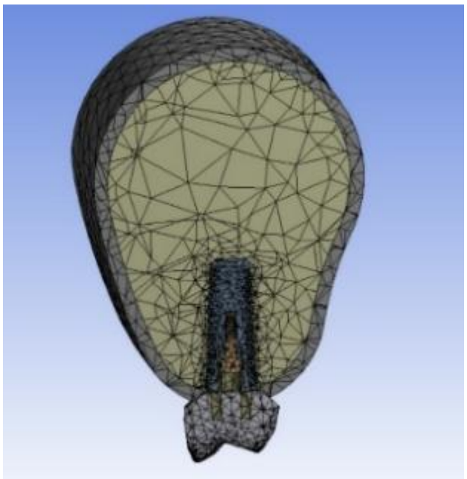


Figure-1- Three-dimensional finite element model of the posterior maxilla showing cortical bone, cancellous bone, implants, and prosthetic components

Ten finite element models were generated(Table I).

Table I. Configuration of finite element models

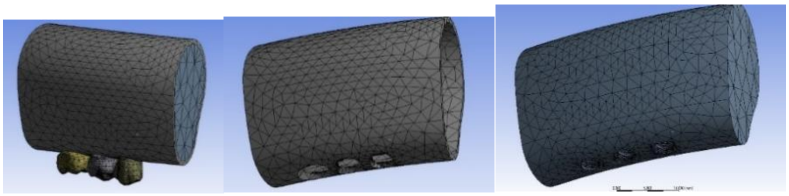
Model	Prosthesis design	Length of implant (mm)	Diameter of implant(mm)
1	Splinted	10	3.75
2	Splinted	10	4.2
3	Splinted	10	5
4	Splinted	6.25	5
5	Splinted	6.25	6
6	Non-Splinted	10	3.75
7	Non-Splinted	10	4.2
8	Non-Splinted	10	5
9	Non-Splinted	6.25	5
10	Non-Splinted	6.25	6

The geometric models were imported into ANSYS R17 (ANSYS Inc., Canonsburg, PA, USA) for finite element analysis. Meshing was performed using tetrahedral solid elements to obtain an accurate representation of the implant–prosthesis–bone complex (Figure 2).

All materials were assumed to be homogeneous, isotropic, and linearly elastic. Complete osseointegration between the implant and surrounding bone was assumed. The mechanical properties assigned to cortical bone, cancellous bone, titanium alloy, and prosthetic components were obtained from previously published literature (Table II).

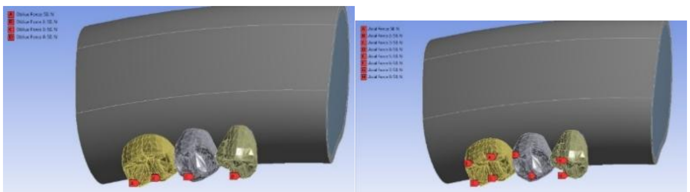
Table II – Mechanical Properties Different Materials

MATERIAL	YOUNG`S MODULUS	POISSON`S RATIO	TENSILE STRENGTH	DENSITY
CORTICAL BONE	13700MPa	0.30	114MPa	1990Kg/m³
CANCELLOUS BONE	1370MPa	0.30	52 MPa	1847kg/m³
TITANIUM ALLOY	110000MPa	0.35	834MPa	4400kg/m³



(B) **(C)**

(D) **(E)** **(f)**



(g) **(h)**

Figure 2. Finite element mesh and loading conditions. (A) Complete three-dimensional model. (B) Cortical bone. (C) Cancellous bone. (D) Implant. (E) Splinted prosthesis. (F) Non-splinted prosthesis. (G) Oblique loading (200 N). (H) Axial loading (400 N)

The inferior and lateral surfaces of the bone model were constrained in all directions to prevent displacement during loading.

To simulate functional occlusal loading, each model was subjected to a nonlinear loading protocol consisting of a 400 N axial load and a 200 N oblique load. The applied load was distributed equally (50 N) over the internal inclines of the functional cusps to simulate posterior occlusal contacts (Figure 2).

Maximum von Mises stress (MPa) was recorded for cortical bone, cancellous bone, implant, and prosthetic superstructure.

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The stress values obtained from the ten models were compared to evaluate the influence of implant diameter, implant length, and prosthetic splinting on biomechanical stress distribution.

3. RESULTS

The maximum von Mises stress values obtained from the finite element analysis are presented in **Tables III and IV**.

Table III. Maximum von Mises Stress Values (MPa) in Splinted Models

Model	Implant-Dimensions (mm)	Cortical Bone	Cancellous Bone	Implant	Prosthesis
M1	3.75 × 10	125.71	5.33	90.48	754.19
M2	4.2 × 10	115.13	5.63	87.73	881.71
M3	5 × 10	106.73	6.83	68.23	686.51
M4	5 × 6.25	117.67	6.07	67.25	799.52
M5	6 × 6.25	89.69	4.37	97.59	799.66

Table IV. Maximum von Mises Stress Values (MPa) in Non-Splinted Models

Model	Implant Dimensions (mm)	Cortical Bone	Cancellous Bone	Implant	Prosthesis
M6	3.75 × 10	97.42	6.34	59.34	674.03
M7	4.2 × 10	76.95	8.61	76.60	808.01
M8	5 × 10	88.08	9.46	77.96	819.19
M9	5 × 6.25	94.16	7.68	72.30	819.17
M10	6 × 6.25	70.45	6.28	72.66	819.16

Among all evaluated structures, cortical bone demonstrated the highest stress concentration, whereas cancellous bone exhibited comparatively lower stress values in both splinted and non-splinted models.

In the **splinted group**, cortical bone stress decreased progressively with increasing implant diameter. The maximum cortical stress was recorded in **Model 1 (3.75 × 10 mm)** - 125.71 MPa, whereas the minimum stress was observed in **Model 5 (6 × 6.25 mm)** - 89.69 MPa). Reducing implant length from 10 mm to 6.25 mm at a constant implant diameter of 5 mm increased cortical bone stress from **106.73 MPa** to **117.67 MPa**.

In the **non-splinted group**, the highest cortical bone stress was observed in **Model 6 (3.75 × 10 mm)** (97.42 MPa), while the lowest value was recorded in **Model 10 (6 × 6.25 mm)** (70.45 MPa). Increasing implant diameter resulted in a progressive reduction in cortical bone stress, whereas reducing implant length produced only a slight increase in stress values.

Stress values within cancellous bone were substantially lower than those observed in cortical bone in all models. Implant and prosthetic components demonstrated variable stress patterns with changes in implant dimensions and prosthetic design; however, no consistent trend comparable to cortical bone was observed.

The percentage changes in cortical bone stress following alterations in implant diameter and implant length are summarized in **Table V**. Increasing implant diameter from **3.75 mm to 5 mm** reduced cortical bone stress by **15.1%** in splinted restorations and **9.6%** in non-splinted restorations. Increasing implant diameter from **5 mm to 6 mm** in short implants reduced cortical bone stress by **23.8%** and **25.2%**, respectively. In contrast, reducing implant length from **10 mm to 6.25 mm** at a constant implant diameter of 5 mm increased cortical bone stress by **10.3%** in splinted restorations and **6.9%** in non-splinted restorations.

Table V. Percentage change in cortical bone stress following modifications in implant dimensions.

Comparison	Stress Change	Percentage Change
M1 (3.75×10) → M2 (4.2×10)	125.71 → 115.13 MPa	8.4% reduction
M2 (4.2×10) → M3 (5×10)	115.13 → 106.73 MPa	7.3% reduction
M1 (3.75×10) → M3 (5×10)	125.71 → 106.73 MPa	15.1% reduction
M3 (5×10) → M4 (5×6.25)	106.73 → 117.67 MPa	10.3% increase
M4 (5×6.25) → M5 (6×6.25)	117.67 → 89.69 MPa	23.8% reduction
M6 (3.75×10) → M7 (4.2×10)	97.42 → 76.95 MPa	21.0% reduction
M6 (3.75×10) → M8 (5×10)	97.42 → 88.08 MPa	9.6% reduction
M8 (5×10) → M9 (5×6.25)	88.08 → 94.16 MPa	6.9% increase
M9 (5×6.25) → M10 (6×6.25)	94.16 → 70.45 MPa	25.2% reduction

4. DISCUSSION

The principal findings of this study were that cortical bone consistently exhibited the highest stress concentration among all evaluated structures, implant diameter had a greater influence on stress distribution than implant length, and splinted restorations demonstrated a more favourable pattern of stress distribution than non-splinted restorations.

This finding of investigation consistent with the biomechanical behaviour of peri-implant bone and agrees with previous finite element studies by **Himmlová et al.**, **Petrie and Williams**, and **Baggi et al.**, who reported that cortical bone acts as the primary load-bearing structure because of its higher elastic modulus and greater stiffness than cancellous bone. Consequently, functional occlusal forces are predominantly transferred to the crestal cortical bone, resulting in higher stress concentration in this region. This observation also corresponds with clinical findings that marginal bone loss around dental implants commonly initiates at the crestal cortical bone following functional loading.[11-13]

A major finding of the present study was the significant influence of implant diameter on stress distribution. Progressive increases in implant diameter resulted in a marked reduction in cortical bone stress in both splinted and non-splinted restorations.

Similar observations have been reported by **Petrie and Williams**, who demonstrated that increasing implant diameter was more effective than increasing implant length in reducing peri-implant stress. Likewise, **Baggi et al.** reported that wider implants significantly decreased stress concentration in cortical bone because of improved load transfer characteristics. More recently, systematic reviews evaluating finite element studies have also concluded that implant diameter has a greater influence on peri-implant stress distribution than implant length, particularly in low-density posterior maxillary bone. Therefore, the findings of the present study further support the use of wider implants, whenever clinically feasible, to improve biomechanical performance and reduce stress concentration around implants placed in the posterior maxilla.

Another important finding of the present study was the influence of prosthetic splinting on stress distribution. Splinted restorations demonstrated a more favourable and uniform distribution of stresses throughout the implant–prosthesis–bone complex than non-splinted restorations. Biomechanically, splinting allows occlusal forces to be shared between adjacent implants, thereby reducing localized stress concentration around individual implants. This load-sharing mechanism is particularly advantageous in the posterior maxilla, where low-density D3 bone is subjected to relatively high occlusal forces.

The present findings are in agreement with the finite element studies of **Sahin et al.**, **Menicucci et al.**, and **Clelland et al.**, who reported that splinting adjacent implant-supported restorations distributes occlusal loads more evenly and reduces peak stresses within the peri-implant cortical bone.[13-15] Similarly, **Geramy and Morgano** demonstrated that splinted prostheses decrease bending forces acting on individual implants, thereby improving biomechanical stability. In contrast, non-splinted restorations transfer functional loads independently to each implant, resulting in greater stress concentration around the implant neck and crestal bone.[16] Although non-splinted prostheses offer advantages such as improved oral hygiene, easier maintenance, and prosthesis retrievability, these biomechanical considerations should be carefully evaluated, particularly in patients with poor bone quality or limited bone volume.

The results of the present investigation therefore support the use of splinted implant-supported restorations in the posterior maxilla when clinically indicated, particularly in situations involving D3 bone or short implants. By promoting more favourable stress distribution, splinting may contribute to preservation of peri-implant bone and improved long-term biomechanical performance.

CONCLUSION

Within the limitations of this 3D finite element analysis, implant diameter and prosthetic splinting were found to have a greater influence on stress distribution than implant length in posterior maxillary implant-supported restorations. Cortical bone exhibited the highest stress concentrations in all models, indicating its primary role in load transfer. Increasing implant diameter significantly reduced cortical bone stress, whereas reducing implant length resulted in only a modest increase in stress concentration. Wide-diameter short implants demonstrated favourable biomechanical behaviour and were capable of compensating for the reduced length. Furthermore, splinted restorations promoted a more uniform distribution of stresses throughout the implant–prosthesis–bone complex compared with non-splinted restorations. Therefore, the use of wider diameter implants and splinted prosthetic designs may represent a biomechanically advantageous treatment approach in the posterior maxilla with limited available bone height.

The data used to support the findings of this study are included within the article.

Conflicts of Interest

No potential conflict of interest was reported by the author..

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