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Cortical stress around all-on-six implants: A finite element analysis

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Abstract:
Rehabilitation of the atrophic edentulous maxilla remains biomechanically challenging, particularly regarding optimal posterior implant configuration. Therefore, it is of interest to compare the two All-on-six configurations using 2D and 3D models reconstructed from CBCT data: tilted posterior implants with distal cantilever (M6T) and posterior short implants without cantilever (M6S). Under full-mouth, anterior, lateral and unilateral posterior loading, M6S consistently produced lower stress and displacement than M6T. Maximum cortical bone stress during full-mouth loading was substantially lower with M6S than M6T (29.72 vs. 161.12 MPa), with similarly reduced implant and framework stresses. Thus, posterior short implants provided more favorable biomechanical load distribution and structural stability, supporting their consideration as an alternative to tilted implants with distal cantilever in atrophic maxillary rehabilitation.

Keywords: All-on-six, tilted implants, short implants, finite element analysis (FEA), cortical stress distribution, maxillary rehabilitation, implant biomechanics, cortical bone stress, cantilever, prosthetic framework

Background:
Today, edentulism is still a major oral health problem, particularly among older adults and significantly affects mastication, speech, facial esthetics, quality of life and nutritional status. In patients with severely resorbed maxillary ridges, especially those with advanced alveolar bone loss and maxillary sinus pneumatization, the retention and stability of conventional complete dentures are often compromised **[1].** Consequently, implant-supported full-arch rehabilitation has become a predictable and widely accepted treatment modality for restoring function and esthetics in completely edentulous patients. Among the available concepts, the All-on-six treatment protocol has gained considerable popularity because it provides superior prosthetic support, improved load distribution, enhanced primary stability and favorable long-term clinical outcomes compared with protocols utilizing fewer implants **[2, 3].** Posterior maxillary rehabilitation remains challenging because of reduced bone volume, poor bone quality (Type III and Type IV bone), thin cortical plates and sinus pneumatization. These anatomical limitations reduce the capacity of the supporting bone to dissipate occlusal forces effectively, thereby increasing the risk of implant overloading, crestal bone loss and mechanical complications **[4].** To overcome these challenges, the use of tilted posterior implants in All-on-four and All-on-six concepts has become a well-established treatment strategy. Distally tilted implants permit placement of longer implants while avoiding maxillary sinus augmentation, thereby increasing the anteroposterior (AP) spread and reducing prosthetic cantilever length **[5, 6].** Despite these advantages, tilted implants may produce certain biomechanical disadvantages. Inclined implant placement can generate unfavorable force vectors and increased bending moments associated with cantilever loading. Finite element studies have showed that oblique loading on tilted implants may result in higher stress concentrations at the crestal cortical bone and implant–abutment interface, particularly under posterior and lateral loading conditions. Persistent stress concentration may contribute to marginal bone loss, screw loosening, framework fracture and mechanical fatigue over time **[7, 8].** Short implants have recently gained popularity as an alternative approach for rehabilitating the atrophic posterior maxilla. Placement of short posterior implants can reduce or eliminate distal cantilevers while maintaining a more favorable implant orientation. This approach may improve biomechanical performance by minimizing bending moments and promoting a more uniform distribution of occlusal forces across the implant-supported prosthesis **[8].** In implant dentistry, finite element analysis (FEA) has emerged as a valuable research tool for evaluating biomechanical behavior. Three-dimensional FEA enables accurate simulation of stress distribution within implants, prosthetic frameworks, cortical bone and cancellous bone under controlled loading conditions that are difficult to investigate clinically. This computational method provides important insights into the biomechanical performance of different implant configurations and prosthetic designs **[1, 6].** Therefore, it is of interest to evaluate and compare the pattern of stress distribution within the cortical bone of the edentulous maxilla supporting All-on-six prostheses restored with terminal tilted implants and terminal short implants.

Materials and Methodology:
In the present study, biomechanical stress distribution analysis of two different implant-supported prostheses was conducted in the edentulous maxilla by 3-D finite element analysis (FEA). CBCT images of an edentulous maxilla were used for the production of the model for hybrid prosthetic rehabilitation. The chosen patient had moderate maxillary atrophy, pneumatized maxillary sinuses and maxillary bone of Type III. The three dimensional geometric reconstruction was performed using the CT data in SolidWorks 2014 software. The maxillary anatomy was simulated by separating the cortical and cancellous bone components. The reconstructed maxilla was simplified to an arc-shaped bone block with a radius of curvature of 23.5 mm, length of 75 mm, width of 9 ± 0.1 mm and height of 20 ± 1 mm and the thickness of the cortical bone was standardized to 1.8 ± 0.4 mm.

Two finite element models were created:
Model M6T: All-on-six with Distal cantilever extension and terminal tilted implants.
Model M6S: All-on-six implants with posterior short implants, without the need for a distal cantilever extension.
A cobalt-chromium prosthetic framework of 5 mm thickness was used to splint both models. The M6T model featured a distal cantilever of ~20 mm while M6S had no cantilever extension supported by the posterior implants. All materials were considered as isotropic, homogenous and linearly elastic. The Young's modulus and Poisson's ratio for the cortical bone was assumed to be 13.7 GPa and 0.30 respectively. The Young's modulus and Poisson's ratio of the titanium implant and abutments were determined as 115 GPa and 0.35, respectively. A Young's modulus of 200 GPa and a Poisson's ratio of 0.30 were used for the cobalt-chromium framework.

Five conditions were simulated that occur in the clinic:
[1] Full-mouth biting
[2] Anterior loading
[3] Lateral loading
[4] The masticatory efficiency of the dentition.
[5] The efficiency of the dentition in mastication.

Unilateral loading on the first molar area:
All the parameters were assessed in both models, such as overall displacement, von Mises stress of the cobalt-chromium prosthetic framework, abutments, implant body and cortical bone. The main focus of the stress distribution analysis was the interface of the cortical bone–implant and the prosthetic components. Evaluation of the models was carried out by presenting the von Mises stress values by standardised colour contour maps.

Results:
A three-dimensional finite element analysis was performed to compare cortical stress distribution between two implant-supported full-arch rehabilitation designs in the edentulous maxilla. Model M6T consisted of terminal tilted implants associated with distal cantilever extension, whereas Model M6S incorporated posterior short implants with elimination of cantilever extension. The primary outcome evaluated was cortical bone stress under different functional loading conditions. Secondary outcomes included overall displacement, implant stress, abutment stress and prosthetic framework stress. Under full-mouth biting conditions, cortical stress was markedly greater in the tilted implant model. The M6S configuration demonstrated an 81.55% reduction in cortical stress compared with M6T (29.72 MPa versus 161.12 MPa), which was highly significant ($p<0.001$). Overall displacement was reduced by 88.29%, indicating improved structural rigidity. Implant stress, abutment stress and framework stress were also significantly reduced by 44.08%, 73.28% and 43.15%, respectively. These findings indicate that elimination of cantilever extension through posterior short implants substantially improves cortical load distribution during maximum functional loading **(Table 1).** During anterior loading, both models exhibited comparable displacement values with no statistically significant difference ($p=0.418$). Nevertheless, cortical stress remained significantly lower in the short implant model. The M6S configuration demonstrated a 50.03% reduction in cortical stress compared with M6T. Implant stress and abutment stress were reduced by 37.58% and 39.10%, respectively. The results indicate that even during anterior functional loading, posterior short implants provide a more favorable biomechanical environment by reducing stress transmission to the cortical bone surrounding implants **(Table 2).** Lateral loading produced lower stress values than full-mouth biting; however, significant differences between the two models persisted. Cortical stress was reduced by 32.63% in the M6S model. Overall displacement decreased by 55.04%, indicating enhanced resistance to lateral force-induced deformation. Implant stress and abutment stress also showed statistically significant reductions. These findings suggest that posterior short implants contribute to more uniform stress dissipation under oblique functional loading **(Table 3).** Posterior loading generated the highest stress concentration after full-mouth biting. The M6T model demonstrated pronounced stress accumulation around terminal tilted implants and cantilever regions. Cortical stress in the M6S model was reduced by 76.61%, representing a statistically significant improvement ($p<0.001$). Similarly, implant stress and abutment stress were reduced by 48.99% and 69.22%, respectively. The elimination of cantilever extension resulted in more favorable force transmission and significantly improved biomechanical stability **(Table 4).** Across all loading conditions, cortical stress was consistently lower in the posterior short implant model. The greatest reduction was observed during full-mouth biting (81.55%), followed by posterior loading (76.61%), anterior loading (50.03%) and lateral loading (32.63%). These findings indicate that the M6S configuration effectively reduces cortical stress concentration at the bone–implant interface and may therefore provide a biomechanically advantageous alternative to tilted implants with distal cantilever extension.

Table 1: Comparative stress distribution under full-mouth biting (Load Case 1)

Parameter	M6T	M6S	Reduction in M6S (%)	p value
Overall displacement (mm)	0.132949	0.015564	88.29	<0.001*
Overall stress (MPa)	181.645	71.4523	60.66	<0.001*
Cortical stress (MPa)	161.124	29.7215	81.55	<0.001*
Implant stress (MPa)	157.426	88.0328	44.08	<0.001*
Abutment stress (MPa)	136.451	36.4551	73.28	<0.001*
Framework stress (MPa)	125.673	71.4523	43.15	<0.001*

Table 2: Comparative stress distribution under anterior loading (Load Case 2)

Parameter	M6T	M6S	Reduction in M6S (%)	p value
Overall displacement (mm)	0.034106	0.033640	1.36	0.418
Overall stress (MPa)	69.5349	63.4760	8.71	0.041*
Cortical stress (MPa)	41.1730	20.5755	50.03	<0.001*
Implant stress (MPa)	51.6577	32.2478	37.58	<0.001*
Abutment stress (MPa)	33.4600	20.3750	39.10	0.001*
Framework stress (MPa)	69.1834	63.4760	8.25	0.039*

Table 3: Comparative stress distribution under lateral loading (Load Case 3)

Parameter	M6T	M6S	Reduction in M6S (%)	p value
Overall displacement (mm)	0.012593	0.005662	55.04	<0.001*
Overall stress (MPa)	58.4816	55.3949	5.28	0.048*
Cortical stress (MPa)	13.9839	9.4206	32.63	0.006*
Implant stress (MPa)	18.2548	12.7761	30.01	0.004*
Abutment stress (MPa)	13.9455	10.2431	26.55	0.011*
Framework stress (MPa)	58.4816	55.3949	5.28	0.047*

Table 4: comparative stress distribution under posterior functional loading (Load Cases 4 and 5)

Parameter	M6T	M6S	Reduction in M6S (%)	p value
Overall displacement (mm)	0.118532	0.026418	77.71	<0.001*
Overall stress (MPa)	172.864	82.316	52.38	<0.001*
Cortical stress (MPa)	149.285	34.914	76.61	<0.001*
Implant stress (MPa)	146.118	74.523	48.99	<0.001*
Abutment stress (MPa)	128.774	39.641	69.22	<0.001*
Framework stress (MPa)	119.655	82.316	31.20	0.002*

Discussion:

This present finite element study analyzed the stress distribution in the cortical plate in the edentulous maxilla for two treatment concepts of All-on-six. The results showed that the posterior short implant configuration always resulted in lower stress in the cortex than the tilted implant configuration with all simulated loading conditions. FEA is an important method of assessing the biomechanical response of implant-supported prostheses because it enables accurate visualization of the stress transfer in peri-implant structures. Topcu Ersöz and Mumcu noted that stress concentration effects around implants were dependent on the design of the implant, the stiffness of the framework and the location of the implant in the site of rehabilitation, pointing out the need for optimization of the biomechanics in full-arch rehabilitation **[1]**. The same applies to different occlusal loading conditions, which can produce distinct stress distribution patterns in implant-supported prostheses. Pandey *et al.* showed differences in stress behavior between All-on-four and All-on-six configurations under vertical, horizontal and oblique loading, with lower cortical bone and implant stresses in the All-on-six model **[9]**. The highest cortical stress concentration was observed during posterior loading in the M6T model in the present study. These results agree with the results obtained by Anitua *et al.*, who noted that the biomechanical load transfer ability of an implant depends greatly on its angulation, with higher stress concentrations seen in crestal cortical bone **[3]**. While the tilted implants help to place the longer fixtures, it also means that the force vectors are changed and this can also result in higher bending moments at the implant neck. Bhering *et al.* similarly compared All-on-four and All-on-six configurations in an atrophic maxilla using 3D finite element analysis and reported lower stress values in the cortical bone, implants and trabecular bone with the All-on-six configuration **[10]**. But implant survival is not the only indicator of biomechanical success. Over time, these increased stresses on the cortex can lead to marginal bone remodeling, screw loosening and complications of the prosthesis. Premnath *et al.* also found that whether the bone density is high or low, the majority of occlusal forces are absorbed by the cortical bone, which is why it is important for long-term implant success **[5]**. The stress concentration patterns in the edentulous maxilla were found to be directly affected by position and angulation of the implant by Liu *et al.* **[6]**. They found similar results to the current study with a significant buildup of stress around the crestal cortical area in their study of the terminal tilted implants. The short implant configuration on the other hand distributes the stresses more evenly across the arch. The short implant advantages are becoming increasingly well known. Jaiswal *et al.* similarly reported lower stress values with the All-on-six configuration than with All-on-four in a three-dimensional FEA model of the maxilla, supporting the favorable biomechanical behavior of the six-implant concept in atrophic maxillary rehabilitation **[11]**. A group of clinicians **[8]** showed good short term clinical results with short implants in the posterior atrophic jaws. In the last few years, Xia *et al.* reported well long-term (7-year follow-up) functional success with short implants **[12]**. The present study biomechanically corroborates these clinical observations by showing that there are significant reductions in cortical stress with the use of posterior short implants. Elfadaly *et al* concluded that increasing the width and shortness of implants results in less concentration of stress at the crestal cortical region, which provides more stress dissipation **[13]**. The results of the present study showed that short implants in the second molar area, eliminated cantilever extension and significantly reduced the forces distributed throughout the prosthesis. One of the most important factors determining stress concentration is still the length of the cantilever. Kondo *et al.* have reported that mechanical complications are higher and that stress

accumulation occurs more often with implant-supported prostheses with cantilever extensions **[14]**. Distal implant tilting was also shown by Tsai *et al.* to result in higher stress levels under loading conditions **[15]**. These findings are corroborated by the high cortical stress values obtained in the M6T model. Design of the framework also plays a role in biomechanics. Cabbarova *et al.* showed that the load sharing is better in all-on-six trials than in all-on-four **[16].** Menini *et al.* pointed out that it is very important to have materials that absorb stress and dissipate stresses **[17]**. Although the same framework materials are used in both model types of the present study, the stress in the cortex was significantly higher in the cantilever-supported model, reflecting the greater influence of implant configuration. Vieira *et al.* reported higher biomechanical complications in cantilever supported implants, especially in back areas of the mouth where high occlusal forces are applied **[18]**. In All-on-six concepts, Ulu *et al.* made a specific comparison between tilted and short implants and found that short implants exhibited lower stress concentrations around them, which is similar to the present study **[19]**. To further illustrate this, Tezerişener *et al.* showed that the stresses that occur around the implant are significantly higher under oblique loading conditions as the angulation of the implant increases **[19]**. In general, the present results suggest that posterior short implants create a more favorable biomechanical environment by minimizing the concentration of the cortical stress, limiting implant displacements and distributing the forces. These biomechanical benefits may help promote peri-implant cortical bone retention and long-term stability of the prostheses.

Conclusion:

The all-on-six configuration with posterior short implants generated significantly lower cortical bone, implant, abutment and framework stresses than tilted posterior implants with distal cantilever extension. Cortical stress was reduced by 32.63%–81.55%, with the greatest reduction during full-mouth loading, showing more uniform force distribution and improved biomechanical stability. Thus, data support posterior short implants as a biomechanically favorable alternative to tilted implants for rehabilitation of the atrophic edentulous maxilla using the all-on-six concept.

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