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ORIGINAL ARTICLE

Finite Element Analysis of the Stress Distribution Associated With Different Implant Designs for Different Bone Densities

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Abstract

Purpose: The main objective of this study was to investigate the influence of implant design, bone type, and abutment angulation on stress distribution around dental implants.

Materials and methods: Two implant designs with different thread designs, but with the same length and brand were used. The three-dimensional geometry of the bone was simulated with four different bone types, for two different abutment angulations. A 30° oblique load of 200 N was applied to the implant abutments. Maximum principal stress and minimum principal stresses were obtained for bone and Von misses stresses were obtained for dental implants.

Results: The distribution of the load was concentrated at the coronal portion of the bone and implants. The stress distributions to the D4 type bone were higher for implant models. Increased bone density and increased cortical bone thickness cause less stress on bone and implants. All implants showed a good distribution of forces for non-axial loads, with higher stresses concentrated at the crestal region of the bone-implant interface. In implant types using straight abutments there was a decrease in stress as the bone density decreased. The change in the abutment angle also caused an increase in stress.

Conclusions: The use of different implant threads and angled abutments affects the stress on the surrounding bone and implant. In addition, it was observed that a decrease in density in trabecular bone and a decrease in cortical bone thickness increased stress.

KEYWORDS
Bone quality, dental implants, stress distribution, thread design, variable-thread design, finite element analysis

Currently, the use of implants is considered the first-line treatment of edentulism.[1] Many dentists routinely place implants to replace one or more teeth or reconstruct the entire dental arch.[2] Although many long-term implant studies have reported survival rates exceeding 95%, the potential for clinical failure and other limitations are major concerns for clinicians.[3–5] The presence of osseointegration is crucial to the success of the implant.[6]

One of the most important conditions for osseointegration is primary stability following implant placement.[7] Until osseointegration is achieved, the implant must have sufficient primary stability to resist micromovements.[8,9] If immediate loading following implant placement is desired, a high degree of primary stability is necessary for prosthetic attachment to progress safely without micro-movements. Micromovements prevent osseointegration and compromise the overall outcome of treatment.[2,10–14] For immediate loading, a prosthesis can be applied immediately after implant surgery to restore a single tooth or full arch. This strategy has distinct advantages for both patients and physicians. Many studies of immediate loading have reported survival rates comparable to conventional loading.[1,15,16]

Various mechanical factors contribute to an effective connection between the implant and surrounding bone.[6] The most important of these factors is implant design, which determines primary stability and stress distribution during osteointegration.[1] Most previous studies focused on producing a dental implant design that optimizes stress distribution

TABLE 1 Type and abutment angles of implants in mandibular models

	Implant type	Abutment degree	Number of nodes and elements
Model 1	Straumann BLT	Straight	Nodes: 477852
	4.1-10 mm		Elements: 334766
Model 2	Straumann BLT	17°	Nodes: 484247
	4.1-10 mm		Element: 339068
Model 3	Model 3: Straumann	Straight	Nodes: 535145
	BLX 4.0-10 mm		Elements: 379478
Model 4	Model 3: Straumann	17°	Nodes: 561214
	BLX 4.0-10 mm		Elements: 396439

with high primary stability under the applied forces.[7,9,17–21] These studies suggested that optimally designed implants can improve the osseointegration and primary and secondary stability of the implant.

Implants have microdesigns and macrodesigns. The microdesign includes implant material, surface finish, and morphology, while the macrodesign includes thread geometry and implant shape.[22] For immediate loading, mechanical locking rather than osseointegration provides primary stability of the implants.[19] Therefore, the macrostructure plays an important role in the primary stability of the dental prosthesis integrated with the surrounding bone tissue.

Finite element analysis (FEA) is used to explore the influence of implant thread design by examining the load and stress distribution in areas surrounding the implant. In FEA analyses, maximum principal [P(max)] stress and minimum principal [P(min)] stresses are obtained for cortical and trabecular bone.

Currently available implants have different thread designs that provide a high level of primary stability to the prosthetic connection, which allows for immediate loading.[2,11,12,23] The Straumann BLX implant (Straumann, Andover, MA) is conical in shape and has a progressive, variable double-thread design that allows the implant to self-cut, self-thread, and self-graft during insertion.[2] Based on its thread design, the BLX implant is predicted to provide superior primary stability for immediate loading of bones.[2] However, no previous studies have compared aggressively threaded implants in terms of the stress on different bone types, except for finite element studies of a few thread designs.[17,19,20,22,24–26]

The null hypothesis of this study was that there is no difference in the stress levels of different thread designs of implants with different bone types and different abutment angles.

MATERIALS AND METHODS

The aim of this study was to evaluate the stress generated by implants with two different thread designs from the same manufacturer, abutting 4 bone types at different angles, using the finite element analysis method.

Models

Four bone types were used in models of a completely edentulous mandible: D1, completely homogeneous compact bone; D2, 2-mm-thick cortical bone surrounding dense trabecular bone; D3, 1-mm-thick cortical bone surrounding dense trabecular bone; and D4, 1-mm-thick cortical bone surrounding low density trabecular bone. The models are described in Table 1.

Modeling

In this study, bone models were created based on computed tomography images showing the lower jaw premolar region (height × mesio-distal size: 20 × 30 mm) and tooth loss; the model was created using Solidworks software (SolidWorks Corp., Waltham, MA). Surface modeling techniques were used to create solid gingival soft tissue models and mandibular models with four bone types (Fig 1A).

Implants, abutment screws, titanium copings, and occlusal screws were modeled using the Solidworks software and fitted separately in accordance with their actual dimensions. Two designs were created: a 10-mm-long, 4.1-mm-diameter implant with a reverse buttress thread design (Straumann Bone Level Tapered [BLT]) (Institut Straumann AG, Basel, Switzerland), and a 10-mm-long, 4.0-mm-diameter implant with a variable double threaded design (Straumann Bone Level X [BLX]) (Institut Straumann AG) (Fig 1B).

Mandibular cortical bone, cancellous bone, implant, and implant elements were transferred to the model to reflect the real morphology. Solid models created with Solidworks software were transferred to Ansys software (version 18.1; Ansys Inc., Canonsburg, PA) with preserved 3D coordinates; in Ansys software, physical properties of the models, i.e., elastic modulus and Poisson ratio values, were defined for cortical bone, trabecular bone, and titanium components (Table 2). All models were meshed with quadratic tetrahedral elements, readily available in the software. In the mathematical models, an average of 491,849 nodes and 337,312 elements were used. Detailed information for each model is given in Table 1.

A tight connection was assumed across the entire interface between bone and implants, assuming that the implants were

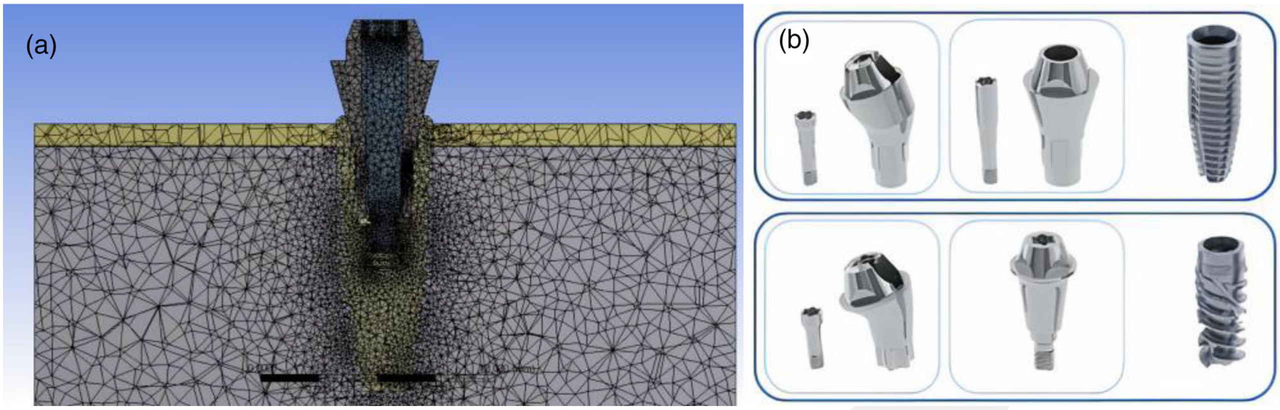

FIGURE 1 A, Mesh image of modeling. B, Modeling of dental implants, straight abutments, 17° abutments, and abutment screws

TABLE 2 Elastic modulus and Poisson ratios

	Elastic modulus (MPa)	Poisson ratio
Cortical bone	13700	0.30
Trabeculer bone	1370	0.30
Titanium	110000	0.35

fully osseointegrated into the bone. All other contacts were considered rigidly bonded. The contact condition between the abutment and implant was set as a frictional coefficient (μ) of 0.3.[27] In addition, the models were homogeneous and isotropic, and used linear elastic materials.

Limits and loading conditions

While establishing loading conditions, the basement of bone model was fixed at x, y, and z axes in order to prevent movement in each degree of freedom. Forces of 200 N were applied at a 30° inclination (Fig 2).

Analyses

A linear analysis was employed by using ANSYS software. Stresses in the implant, abutment, and screw were calculated as von Mises stress values; the minimum and maximum principal stress values were also calculated to evaluate the stress on trabecular and cortical bones. The highest four stress values for each structure were recorded and their average values are reported in megapascals (MPa).

RESULTS

Stress on bone types

Higher stress levels accumulated in D4 type bone than the other bone types (Fig 3). The stress was generally concentrated in the cervical part of the implant socket (Fig 4).

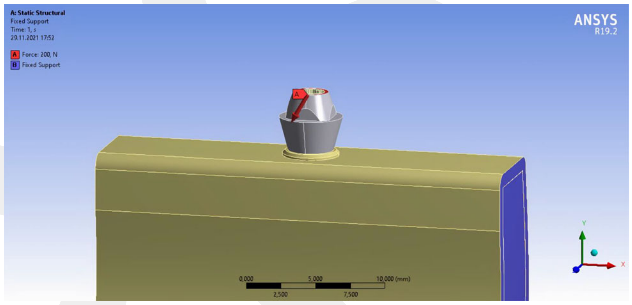

FIGURE 2 The applied occlusal forces. (Red arrows show the direction of the force; the red areas on the occlusal of the abutment show the region where the force is applied. Blue area shows the fixed support and the other side of the bone is fixed as well.)

Among the different implant models using straight-angle abutments, the lowest stress level was observed at 6.18 MPa as the maximum principal and −12.12 MPa as the minimum principal around the socket of the BLT implant in D1 bone; the highest stress level was 61.69 MPa as the maximum principal and −118.07 MPa as the minimum principal in BLX implants placed in D4 bone type (Fig 3). Evaluation of the compressive and tensile forces on angled abutments showed that the BLX implant had the highest maximum principal (61.69 MPa) and lowest minimum principal (−118.07 MPa) forces on D4 bone (Fig 4).

The compressive and tensile forces transmitted to the bone surrounding the implant were evaluated, and Pmax increased, while Pmin decreased, with reduced trabecular bone density (Fig 3). The BLX implant, which had a more aggressive thread design, generated greater stress on the bone than the BLT implant in all scenarios.

Stress on implants

The von Mises stress values for the implants showed similar stress distributions in the implant neck among the models (Fig 5). The highest value was found in the neck of the BLX implant (861.35 MPa) with a 17° angle abutment in D3 bone

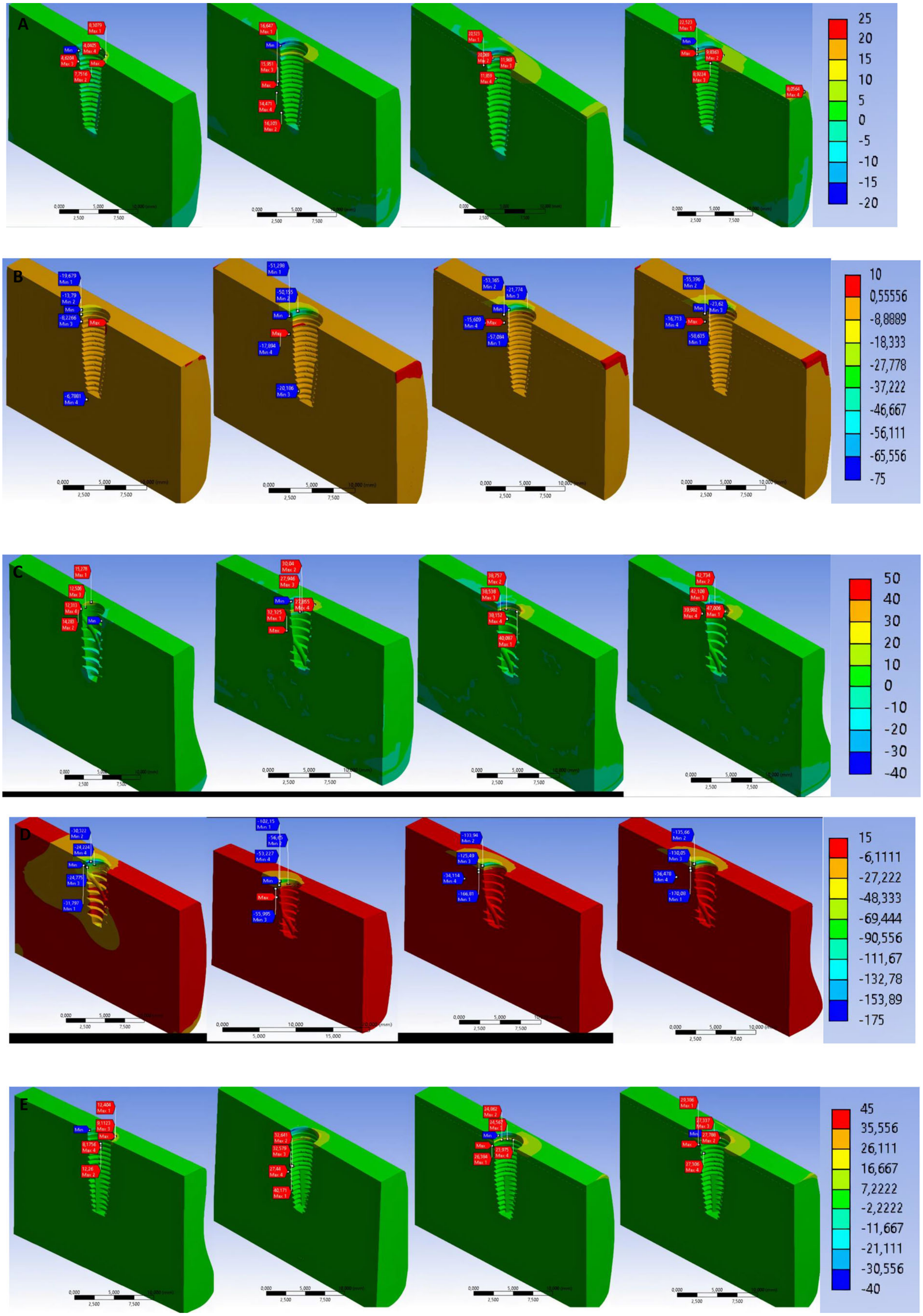

FIGURE 3 Pmin (red) and Pmax (green) stress values in bone types; A, Pmax values of BLT straight abutment at D1-D2-D3-D4 bone types (left to right); B, Pmin values of BLT straight abutment at D1-D2-D3-D4 bone types (left to right); C, Pmax values of BLX straight abutment at D1-D2-D3-D4 bone types (left to right); D, Pmin values of BLX straight abutment at D1-D2-D3-D4 bone types (left to right); E, Pmax values of BLT 17° abutment at D1-D2-D3-D4 bone types (left to right); F, Pmin values of BLT 17° abutment at D1-D2-D3-D4 bone types (left to right); G, Pmax values of BLX 17° abutment at D1-D2-D3-D4 bone types (left to right); and H, Pmin values of BLX 17° abutment at D1-D2-D3-D4 bone types (left to right)

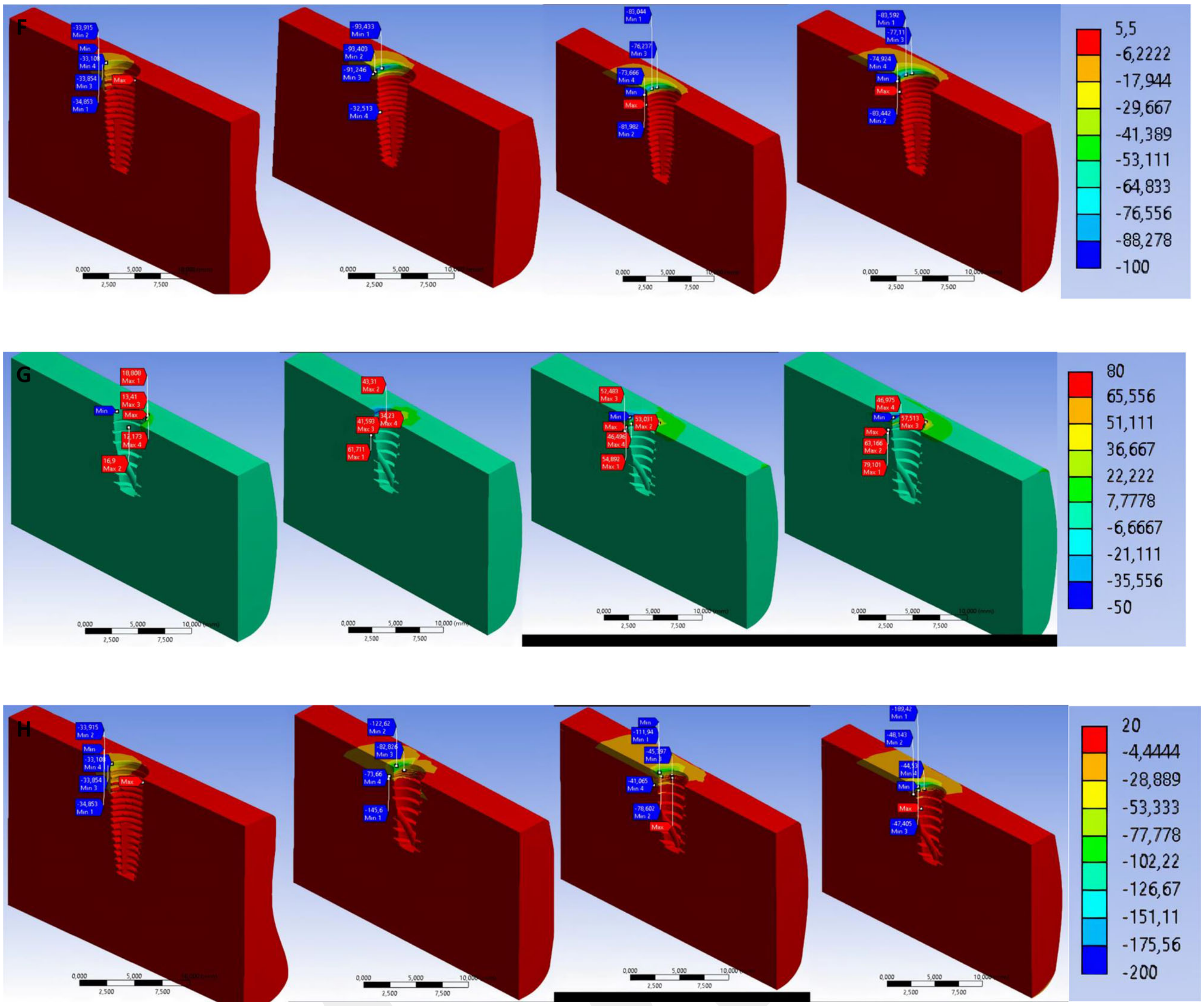

FIGURE 3 Continued

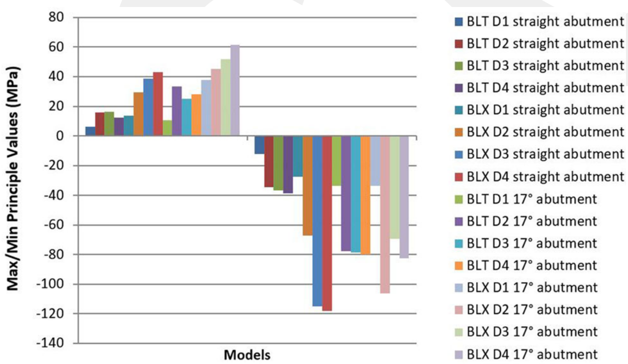

FIGURE 4 Stress values in bone types (MPa)

type (Fig 6). Among implants with straight abutments, the highest stress value was found in D1 bone type; a decrease in the stress value was observed with decreased bone density (Fig 5). Significantly higher von Mises stress values were observed for the BLX implant with more aggressive threads.

Stress on the abutments

Regarding the stress on the abutments of the models, the highest stress levels in all scenarios were observed in the neck area, which abutted the implant (Fig 7). The highest von Mises stress values were 839.21 MPa with 17° abutment of BLT in D3 bone (Fig 7). The lowest stress value was observed in D4 bone type with a straight BLX abutment (175.77 MPa) (Fig 7).

Stress on abutment screws

Stress on the screws of flat BLT abutments in different bone scenarios was generally concentrated on the screw head (Fig 8). Stress on the screws of BLX straight abutments was

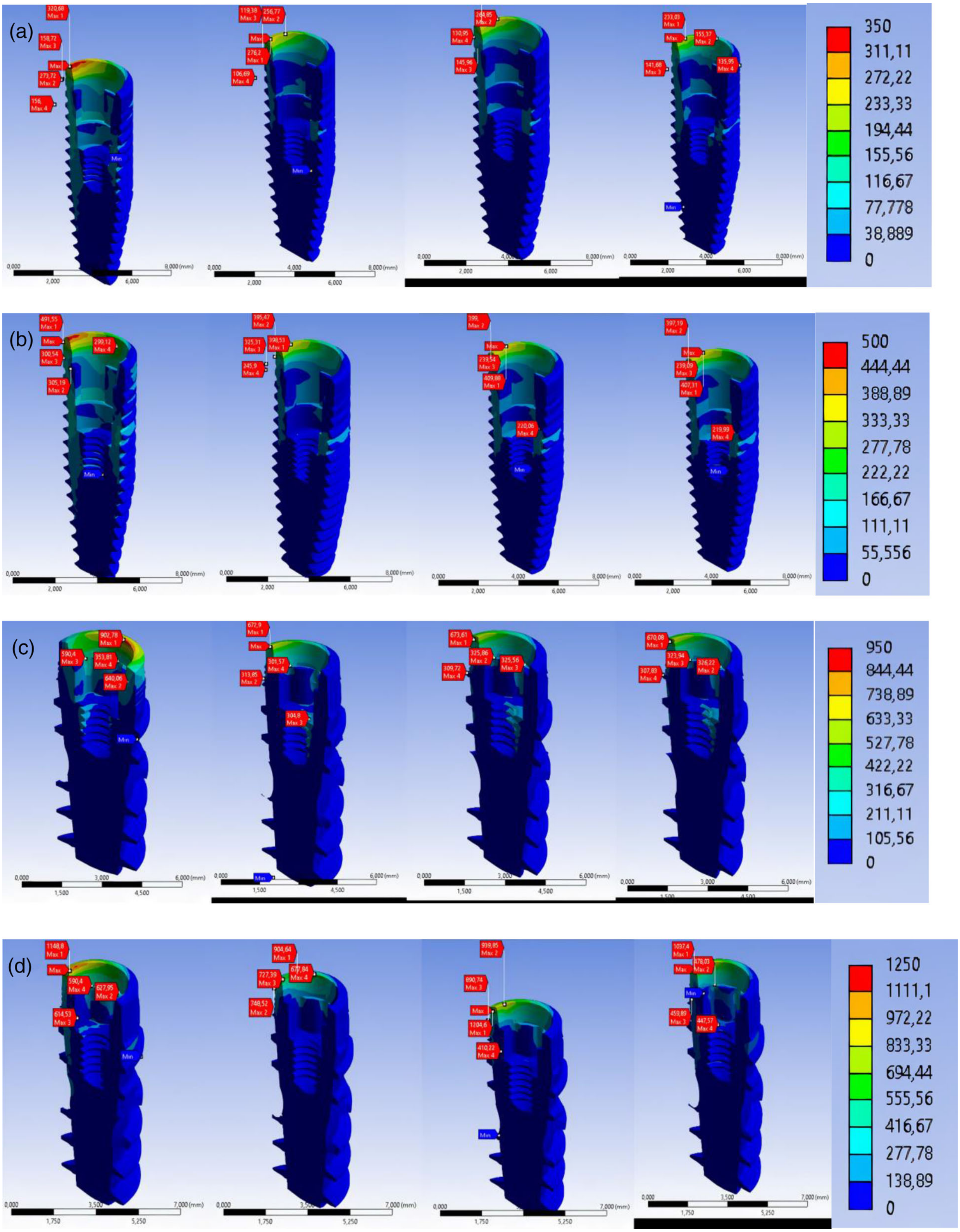

FIGURE 5 Von Mises stress values on implants. (a), Model 1-D1, Model 1-D2, Model 1-D3, Model 1-D4 (left to right); (b), Model 2-D1, Model 2-D2, Model 2-D3, Model2-D4 (left to right); (c), Model 3-D1, Model 3-D2, Model 3-D3, Model 3-D4 (left to right); (d), Model 4-D1, Model 4-D2, Model 4-D3, Model 4-D4 (left to right)

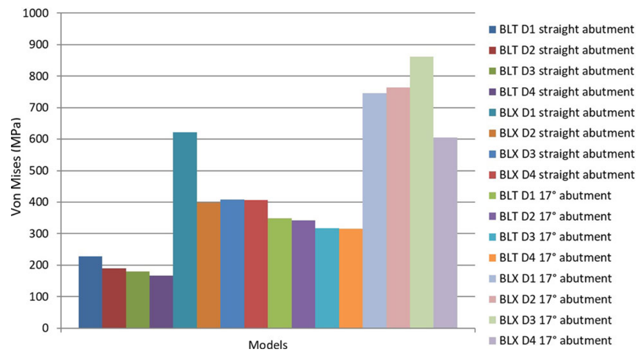

FIGURE 6 Stress values on implants (MPa)

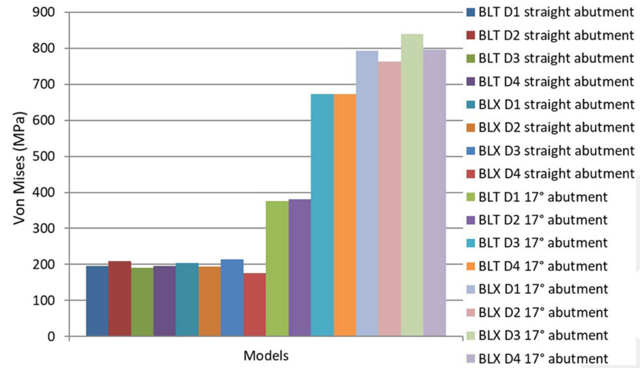

FIGURE 7 Stress values at abutments (MPa)

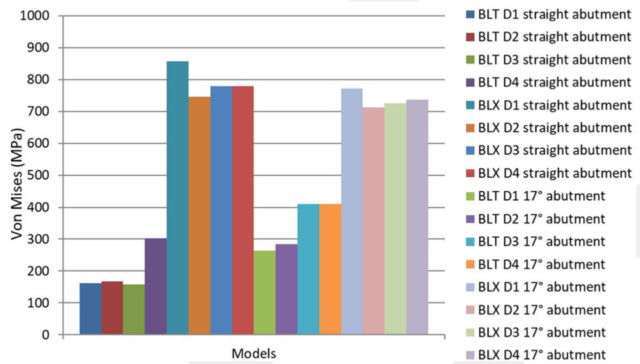

FIGURE 8 Stress values on abutment screws (MPa)

concentrated around the first thread, whereas it was concentrated on the screw neck in the BLT and BLX models using 17° abutments (Fig 8). In angled and straight abutment models using BLT implants, stress levels on screws in all bone types were lower than in models using BLX implants. The highest stress level among the abutment screws was 857.21 MPa in the D1 bone with the BLX straight abutment screw; the lowest stress level among the abutment screws was 158.8 MPa in the D3 bone with the BLT straight abutment screw (Fig 8).

DISCUSSION

The aim of this study was to compare stress levels between implants with different abutment angles, thread designs, bone types, and structural components. Thread shape, abutment type, and bone type affect the stress levels on the surrounding bone and implant elements.

The stress intensity/level on the bone surrounding the dental implant is an important factor affecting osseointegration and implant success.[28] Bones at the site of implant placement may be cortical or spongy/medullary. Therefore, primary stability depends on the macrodesign of the implant, properties of the surrounding bone, and load distribution on the implant.[26] Four bone types were modeled in the study.

Misch et al divided bone quality into four classes (D1-D4) to evaluate implant success.[29] Primary stability in D4 bone type is lower compared to other bone types.[30] Differences between implant designs are more pronounced for D4 bone type, which has lower primary stability.[21] Therefore, it is essential that the selected implant design increases the primary stability in low-density bones.[31] In the present study, the models with the lowest stress level in D4 bone were the straight and 17° angled BLT implant models. In addition, the stress intensity was decreased in the BLT implant.

In this study, stress was generally concentrated in the cervical part of the implant socket, regardless of the scenario. Eraslan et al analyzed the stress caused by different thread shapes under 100 N axial loading on a single bone type. They reported that the stress was concentrated around the first thread in the cervical cortical region.[25] Shigemitsu et al suggested that the stress level was significantly higher in the implant neck area of cortical bone.[32] Olivera et al evaluated 3 implant designs in 2 bone types, and reported maximum von Mises stress values in the cortical bone surrounding the implants, regardless of the scenario.[26] The same study reported that stress levels increase with decreased cortical bone thickness and bone density.[26] These results are consistent with those of the present study. In other words, increased bone density and cortical bone thickness reduce the stress on bone and implants, consistent with previous studies of different implant designs and bone types.[21,33]

After the implant has been placed, bone is constantly remodeled against external stress (homeostasis). If the applied force is within physiological limits, new bone is formed and remodeling continues. In 1892, Wolff theorized that new bone formation is accelerated in response to increased stress, but bone resorption increases with reduced stress.[34] Later researchers suggested that bone destruction also occurs under extreme stress.[35] Although initial high stress levels promote bone formation, extreme stress levels cause micro-fractures in the bone structure. If bone formation is not sufficiently rapid to repair the damage, the bone defect may enlarge and cause implant failure.[1] Therefore, implant threads must be designed to increase the transmission of optimal stresses, while preventing extreme stress at the bone-implant interface. In addition, implant threads should enhance primary stability and increase the surface contact area of the implant.

Although the BLX implant, which has a variable double thread design, transmits more stress to the bone compared to BLT in all scenarios, the maximum and minimum principal stress values for the BLX implant were within physiological limits.[36,37]

A similar stress distribution was observed on the implant neck among the models in this study. The stress level decreased with reduced bone density in implants using straight abutments. In addition to the decrease in bone density, a change in abutment angle led to increased stress levels.

Kao et al reported that an abutment angle up to 25° increased the stress around the implant by 18%.[38] Lin et al stated that 20° abutments generated higher stress levels on the implant and cortical bone compared to straight abutments, similar to the findings of the current study.[39]

This study is different from previous ones on this topic because stress levels among implants with different threads, bone types, implant elements, and abutment angles were compared. In the present study, the highest stress in all scenarios was transmitted to the neck part of the abutment, where the bone abuts the implant. Stress levels in angled abutments were significantly higher compared to those in straight abutments. Although stress in the screws of straight BLT abutments in different bone scenarios was generally concentrated in the screw head, it was concentrated in the screw neck in all models with angled abutments. Lee et al compared 4 implant designs with different connection types and loading conditions, and reported that stress was concentrated in the neck of the abutments in all models.[40]

In their finite element analysis study on implant models with different engaged and nonengaged abutment connection types, Savignano et al[41] reported that the stress on the implants was between 516 and 1106.9 MPa, while the stress on the abutments was between 554.62 and 779.3 Mpa. The stress on the screws was 698.8 to 902.5 Mpa. It has been emphasized that since the values reported in the same study exceed the yield strength of the titanium alloy, it may cause wear and deformation between the implant components. Likewise, Won-kyung et al simulated the stress on two different implant systems under different conditions, and obtained results ranging from 163 to 1587 MPa on the implant, abutment, and screw.[42] Although the values obtained in the present study have high stress concentrations for some implant scenarios, as in the studies of Savignano et al and Won-kyung et al, no value exceeding the yield strength of the titanium alloy was obtained.[41,42] In a previous study, it was reported that the stress occurring in the region of the abutment-implant connection is likely to exceed the yield strength of titanium.[43] Previous FEA studies reported lower forces on the implant, abutment, and screws than those reported in the present study.[20,21,25,26] The reason for this may be the difference in the implant models investigated in the studies, whether the models are more complex, the difference in the number of nodes and elements, the loadings made under different conditions, and the use of different analysis methods.

Although this study attempted to simulate clinical conditions, finite element analysis has some limitations. Anatomical conditions, the level of osseointegration, and the quantity and direction of applied forces can all affect the results. Although the stress values obtained within these limitations provide a general picture of the implants used, clinical studies are required to investigate the long-term effects of these implants on prosthetic components and implants.

CONCLUSIONS

The use of different implant threads and angled abutments affects the stress transmitted to the surrounding bone and implant. In addition, decreased trabecular bone density and cortical bone thickness was associated with increased stress.

Both implant designs evaluated in this study showed a good distribution of applied force; the transmitted forces were concentrated in the crestal region of the bone-implant interface. BLT implants with angled or non-angled abutments have the most appropriate implant design and elements in terms of stress on all bone types.

CONFLICT OF INTEREST

Authors Ikbal Leblebicioglu Kurtulus, Kerem Kilic, Burak Bal, and Ahmet Kilavuz state that there are no conflicts of interest.

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REFERENCES

1. Ryu HS, Namgung C, Lee JH, et al. The influence of thread geometry on implant osseointegration under immediate loading: a literature review. J Adv Prosthodont 2014;6:547-554
2. Kordusky BA. Accuracy of BLX and BLT Guided Implants in the Edentulous Maxilla: An In Vivo. Ann Arbor: West Virginia University; 2020.
3. Haas R, Mensdorff-Pouilly N, Mailath G, et al. Brånemark single tooth implants: a preliminary report of 76 implants. J Prosthet Dent 1995;73:274-279
4. Goodacre CJ, Bernal G, Rungcharassaeng K, et al. Clinical complications with implants and implant prostheses. J Prosthet Dent 2003;90:121-132
5. Fugazzotto PA. Success and failure rates of osseointegrated implants in function in regenerated bone for 72 to 133 months. Int J Oral Maxillofac Implants 2005;20:77-83
6. Albrektsson T, Brånemark PI, Hansson HA, et al. Osseointegrated titanium implants. Requirements for ensuring a long-lasting, direct

bone-to-implant anchorage in man. Acta Orthop Scand 1981;52:155-170
7. Ellis R, Chen S, Davies H, et al. Primary stability and healing outcomes of apically tapered and straight implants placed into fresh extraction sockets. A pre-clinical in vivo study. Clin Oral Implants Res 2020;31:705-714
8. Ballini A, Cantore S, Scacco S, et al. Mesenchymal stem cells as promoters, enhancers, and playmakers of the translational regenerative medicine. Stem Cells Int 2018;2018:6927401
9. Ibrahim A, Heitzer M, Bock A, et al. Relationship between implant geometry and primary stability in different bony defects and variant bone densities: an in vitro study. Materials (Basel) 2020;13: 4349
10. Albrektsson T, Wennerberg A. On osseointegration in relation to implant surfaces. Clin Implant Dent Relat Res 2019;21:4-7
11. Bergkvist G. Immediate loading of implants in the edentulous maxilla. Swed Dent J Suppl 2008:10-75
12. Cooper L, De Kok IJ, Reside GJ, et al. Immediate fixed restoration of the edentulous maxilla after implant placement. J Oral Maxillofac Surg 2005;63:97-110
13. Meloni SM, De Riu G, Pisano M, et al. Implant treatment software planning and guided flapless surgery with immediate provisional prosthesis delivery in the fully edentulous maxilla. A retrospective analysis of 15 consecutively treated patients. Eur J Oral Implantol 2010;3:245-251
14. Papaspyridakos P, Chen CJ, Chuang SK, et al. Implant loading protocols for edentulous patients with fixed prostheses: a systematic review and meta-analysis. Int J Oral Maxillofac Implants 2014;29:256-270
15. Ibañez JC, Jalbout ZN. Immediate loading of osseotite implants: two-year results. Implant Dent 2002;11:128-136
16. Ostman PO, Hellman M, Sennerby L. Direct implant loading in the edentulous maxilla using a bone density-adapted surgical protocol and primary implant stability criteria for inclusion. Clin Implant Dent Relat Res 2005;7:S60-S69
17. Huang HL, Chang CH, Hsu JT, et al. Comparison of implant body designs and threaded designs of dental implants: a 3-dimensional finite element analysis. Int J Oral Maxillofac Implants 2007;22:551-562
18. Ríos-Santos JV, Menjívar-Galán AM, Herrero-Climent M, et al. Unravelling the effect of macro and microscopic design of dental implants on osseointegration: a randomised clinical study in minipigs. J Mater Sci Mater Med 2018;29:99
19. Elleuch S, Jrad H, Kessentini A, et al. Design optimization of implant geometrical characteristics enhancing primary stability using FEA of stress distribution around dental prosthesis. Comput Methods Biomech Biomed Eng 2021:1-17
20. Gupta Y, Iyer R, Dommeti VK, et al. Design of dental implant using design of experiment and topology optimization: a finite element analysis study. Proc Inst Mech Eng H 2021;235:157-166
21. Yalçın M, Kaya B, Laçin N, et al. Three-Dimensional finite element analysis of the effect of endosteal ımplants with different macro designs on stress distribution in different bone qualities. Int J Oral Maxillofac Implants 2019;34:e43-e50
22. Abuhussein H, Pagni G, Rebaudi A, et al. The effect of thread pattern upon implant osseointegration. Clin Oral Implants Res 2010;21:129-136
23. Fromovich O, Dada K, Pariente L, et al. BLX: a new generation of self-drilling implants. BLX Mag 2019:9-40
24. Abrahamsson I, Berglundh T. Effects of different implant surfaces and designs on marginal bone-level alterations: a review. Clin Oral Implants Res 2009;20:207-215
25. Eraslan O, Inan O. The effect of thread design on stress distribution in a solid screw implant: a 3D finite element analysis. Clin Oral Invest 2010;14:411-416
26. Oliveira H, Brizuela Velasco A, Ríos-Santos JV, et al. Effect of different ımplant designs on strain and stress distribution under non-axial loading: a three-dimensional finite element analysis. Int J Environ Res Public Health 2020;17: 4738
27. Chu CM, Huang HL, Hsu JT, et al. Influences of internal tapered abutment designs on bone stresses around a dental implant: three-dimensional finite element method with statistical evaluation. J Periodontol 2012;83:111-118
28. El-Anwar M, El-Zawahry M, El-Mofty M. Load transfer on dental implants and surrounding bones. Aust J Basic Appl Sci 2012;6:551-560
29. Misch CE. Bone classification, training keys to implant success. Dent Today 1989;8:39-44
30. Alsaadi G, Quirynen M, Michiels K, et al. A biomechanical assessment of the relation between the oral implant stability at insertion and subjective bone quality assessment. J Clin Periodontol 2007;34:359-366
31. Chun HJ, Cheong SY, Han JH, et al. Evaluation of design parameters of osseointegrated dental implants using finite element analysis. J Oral Rehabil 2002;29:565-574
32. Shigemitsu R, Yoda N, Ogawa T, et al. Biological-data-based finite-element stress analysis of mandibular bone with implant-supported overdenture. Comput Biol Med 2014;54:44-52
33. Sugiura T, Yamamoto K, Horita S, et al. The effects of bone density and crestal cortical bone thickness on micromotion and peri-implant bone strain distribution in an immediately loaded implant: a nonlinear finite element analysis. J Periodont Implant Sci 2016;46:152-165
34. Prendergast P, Huiskes R. The biomechanics of Wolff's law: recent advances. Ir J Med Sci 1995;164:152-154
35. Frost HM. Skeletal structural adaptations to mechanical usage (SATMU): 2. Redefining Wolff's law: the remodeling problem. Anat Rec 1990;226:414-422
36. Bhering CL, Mesquita MF, Kemmoku DT, et al. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: a prototyping guided 3D-FEA study. Mater Sci Eng C Mater Biol Appl 2016;69:715-725
37. Baggi L, Pastore S, Di Girolamo M, et al. Implant-bone load transfer mechanisms in complete-arch prostheses supported by four implants: a three-dimensional finite element approach. J Prosthet Dent 2013;109:9-21
38. Kao HC, Gung YW, Chung TF, et al. The influence of abutment angulation on micromotion level for immediately loaded dental implants: a 3-D finite element analysis. Int J Oral Maxillofac Implants 2008;23:623-630
39. Lin CL, Wang JC, Ramp LC, et al. Biomechanical response of implant systems placed in the maxillary posterior region under various conditions of angulation, bone density, and loading. Int J Oral Maxillofac Implants 2008;23:57-64
40. Lee H, Park S, Noh G. Biomechanical analysis of 4 types of short dental implants in a resorbed mandible. J Prosthet Dent 2019;121:659-670
41. Savignano R, Soltanzadeh P, Suprono MS. Computational Biomechanical Analysis of Engaging and Nonengaging Abutments for Implant Screw-Retained Fixed Dental Prostheses. J Prosthodont 2021;30:604-609
42. Jung WK, Lee WS, Kwon HB. Effects of abutment screw preload in two implant connection systems: a 3D finite element study. J Prosthet Dent 2019;122:474.e1-474.e8
43. Cho SY, Huh YH, Park CJ, et al. Three-Dimensional Finite Element Analysis on Stress Distribution of Internal Implant-Abutment Engagement Features. Int J Oral Maxillofac Implants 2018;33:319-327

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