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Effect of specific retention biomaterials for ball attachment on the biomechanical response of single implant-supported overdenture: A finite element analysis.

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Abstract:

Purpose: The purpose of this finite element analysis (FEA) was to evaluate the effect of specific retention biomaterials with different elastic modulus on the biomechanical response to the axial and off-axial biting loads of a mandibular midline single implant-supported overdenture (SIO) model.

Methods: Five 3-dimensional (3D) finite element models of an edentulous mandible with SIO were designed as follows: model M with a titanium retentive element for ball attachment, model P with PEEK retentive element, model S with silicone resilient liner retentive element, model T with a thermoplastic acrylic resin retentive element made from a CAD-CAM material, and model A with polyacetal resin retentive element. Posterior bilateral vertical load (PV) at the 1st molar areas and anterior oblique load (AO) at the incisal edge of the mandibular central incisors at a 30-degree angle of 100 N were applied. Stress values were recorded.

Results: Stress values were higher for all models under (AO) loading than under (PV) loading. Model M recorded the highest stress values on the implant, its components, cortical, and cancellous bone under both loading conditions. Under (AO) loading condition, the ball abutment von Mises stress value in model S was almost 7 times less than model M (19 and 130 MPa respectively) and the other 3 models (P, T, and A) (119, 121, 120 MPa respectively). However, model S recorded the highest value of denture base stress at the attachment area.

Conclusions: The elastic modulus of retention materials can affect stresses generated on the implant overdenture components and supporting structures.

1. Introduction

Osseointegrated implants have been used to enhance support, stability, and retention of complete dentures.[1,2] Although two to four implants are preferred, this option is not always the best alternative for some patients due to economic and anatomical constraints.[3] Alternatively, a mandibular overdenture retained by a single implant placed in the midline area of the edentulous mandible, which was suggested by Cordioli et al.[4] might be a feasible option. Previous studies[4–6]reported its favorable outcomes,

especially when compared to complete dentures. Moreover, it can be considered as a simple, less invasive, and straightforward prosthetic technique.[7]

The number of implants, their distribution, residual ridge shape, bone quality, prosthesis retention, patient dexterity, and the prosthesis design are among the factors which affect the attachment selection.[8] Ball attachment has been commonly used to retain single implant-supported overdentures (SIO) since they offer better stability and bracing effect when compared to shorter locator attachments.[9–11]

Despite the reliable outcomes reported for SIO, complications such as denture base midline fracture of SIO due to stress concentration at the weak area adjacent to the attachment can occur during functional loading.[12–16] A high rate of fracture incidence close to 50% was observed in 1 year.[15] Prosthetic adjustments such as the replacement or reactivation of the attachment due to retention loss was another complication.[17] In addition, SIO is biomechanically much more complex since the prosthesis's movement is three dimensional when compared to two implant-supported overdenture (TIO) which demonstrates a two-dimensional movement.[7]

Studies that investigated the biomechanics of SIO treatment approach showed some variations in their findings. Two previous studies[18,19]concluded that SIO tends to generate higher stress values on bone when compared to the TIO. On the other hand, Maeda et al,[3]found that the SIO retained with dome-type magnet or ball attachments is biomechanically similar to TIO in terms of lateral forces to the abutment and denture base movements under functional molar loading. Liu et al,[7] used a finite element analysis (FEA) to conclude that the peri-implant bone strains for SIO were low and did not exceed the physiological limits.

Different biomechanical factors play a role in force distribution around osseointegrated dental implants, including the type of loading, material properties of the implant and the prosthesis, attachment type, implant geometry, surface structure, quality, and quantity of the surrounding bone.[20–22] Unlike natural teeth, implants are unable to buffer occlusal forces. As a result, they may be more prone to occlusal overloading, which is frequently regarded as one of the potential causes of peri-implant bone loss and implant failure. Large cantilevers, parafunctional habits, improper occlusal designs, and premature contacts are examples of overloading factors that may have a negative impact on implant longevity. Frost's mechanostat theory[23] proposed that bone can make a biomechanical adaptation in response to an external loading condition. According to that theory, four microstrain zones that corresponded to mechanical adaptations were defined: (a) disuse atrophy, (b) steady-state, (c) physiological overload, and (d) pathological loading. Mechanical fatigue damage occurs between 2500 and 3500 microstrains, but bone modeling normally repairs the damage by depositing new bone, which is mostly woven bone. Pathological bone resorption begins when peak loading levels exceed 3500 microstains. The amount of strain is directly correlated to the applied stress such as occlusal loading and the mechanical properties of the bone.[24,25] Longitudinal studies[26] have shown that implants for overdentures can fail due to osseointegration loss even in the absence of bacterial infection; thus, occlusal forces play a critical role in long-term success. Denture base reinforcements in the form of metal[27,28] and fibers[29–32] have been used effectively for enhancing the denture base rigidity and providing even stress distribution to the supporting structures. Besides, the type of attachment may affect potential denture movement and stress distributions on bone and implants.[33,34]

A variety of materials with favorable physicochemical and mechanical properties have been tested as retentive attachment receptacles for ball abutment such as resilient denture liners[28,35,36] and thermoplastic polymers resins[37,38]. Polymers such as polyetheretherketone (PEEK) have been used as an alternative for titanium for fabricating esthetic metal-free implant/attachments.[39] PEEK abutments recorded lower biofilm values than those made of titanium.[40] Polyacetal copolymer is another type of thermoplastic resins that combines the strength of metal and the flexibility and comfort of plastic.[38] It has none or little porosity, which reduces biological substance accumulation such as plaque.[41] Besides the traditional forms, thermoplastic resin is also available in the form of computer-assisted design/computer-assisted manufacture (CAD/CAM) blocks with superior mechanical properties and better color stability.[42] Silicone resilient liners are wear-resistant, provide a cushion-like effect reducing the fracture incidence, and more comfortable to the patient.[35,36,43] Using resilient materials directly attached to the implant can provide better force distribution and reduce the stress transfer from the implants to the supporting structures.[22,44]

A successful treatment plan should consider the biomechanical behavior under masticatory loads along with overdenture retention and patient satisfaction.[3,18] The use of finite element analysis has been advocated by authors to study the transmission of stress to the implants and the surrounding bone.[45,46]

The authors are unaware of studies that investigated the impact of different retention biomaterials for a ball attachment on the biomechanical response of a mandibular midline SIO. Therefore, this FEA aimed to evaluate the effect of specific retention biomaterials with different elastic modulus on the biomechanical response to the axial and off-axial biting loads of a mandibular midline SIO model. The null hypothesis of the study was that different retention materials will not affect the biomechanics of SIO under different loading conditions.

2. Materials and methods

The current FEA was designed to simulate a clinical situation of an edentulous mandible rehabilitated with an SIO. A computer-aided design (CAD) 3D solid model was designed based on real dimensions followed by applying the proposed material properties for each part to start the analysis process.

The proposed 3D virtual CAD model of the edentulous jaw (2.2 cm height × 1.8 cm width × 13.5 cm length) and the SIO was established as shown in figure 1. The geometry was modeled using the CAD software[47,48] (Solidworks© 2017; Dassault Systems Solidworks Corp). A single conventional implant (3.75 mm in diameter × 11 mm in length) connected to a ball attachment (2.25 mm wide × 2 mm high) was centralized in the symphysis of the mandibular residual ridge crest. A space for the ball attachment was provided in the intaglio surface of the prosthesis. The model components including cortical bone, cancellous bone, implant, ball abutment, matrix, mucosa layer, and overdenture were designed and assembled in Solidworks© 2017 similar to a previous study[48]. Then, the model was imported to the analysis software (Ansys© 2019 R3; Ansys Inc). Then, the mechanical properties of the used materials were set in the software based on the literature[7,18,28,42,48–52] (Table 1). A meshing was generated for all parts using an automatic adaptive mesher and the required force vectors were applied to the desired positions.

Based on the actual position of the mandible and overdenture, the precise geometry of the mucosal area contacting the intaglio surface of the denture was deduced. The edentulous mandible was composed of a 2-mm constant cortical bone layer around a core of cancellous bone (19.2 mm) covered by a 2-mm-thick mucosa. The prosthetic acrylic overdenture base with a 2 mm thickness above the attachment was simulated. Denture teeth were simplified.[18]

Ten-noded tetrahedral elements were selected for model generation. The model had 37255 elements and 69696 nodes. The bone tissues were considered as isotropic, linear, homogeneous, and 100% osseointegrated to the implants. Similar to a clinical situation, bonded contacts were considered to exist among different components, which means that they were displaced as 1 unit and did not penetrate each other. However, a sliding friction contact at the overdenture-mucosa interface and between the ball abutment and matrix was considered.[32]

Five 3-dimensional (3D) finite element models were analyzed depending on the material used for retention element fabrication (Table 2) as follows: model M with a titanium retention element (socket) (3.7 mm in height × 5.5 mm in diameter) for ball attachment, model P with PEEK retention element, model S with silicone resilient liner retention element, model T with a thermoplastic acrylic resin retention element made from a CAD-CAM material which is used for fabricating long term provisional restoration (Multistratum flexible; Zirkonzahn), and finally model A with polyacetal resin retention element. These materials have been selected for testing since they presented positive results (fatigue, retention, and deformation) in previous studies[37,38] when used as a matrix with ball abutment for implant/mini-implant-supported overdentures. A previous photoelastic stress distribution study[53] concluded that no discernible differences were observed among the locator and different ball attachment systems with metallic female receptacle (with or without a nylon insert). Therefore, the female insert for model M was designed from titanium without a nylon insert.

A mesh was generated with an element size of 0.6 mm and submitted to convergence analysis before mechanical simulation. The stress behavior of the different retention materials was analyzed under 2 different loading conditions: bilateral posterior vertical (PV) loading condition where a 100-N axial load was applied bilaterally and simultaneously on the first molars[18] (simulating mandibular overdenture in balanced occlusion with the opposing maxillary denture) and anterior oblique (AO) loading condition where a 100-N load was applied to the incisal edge of the mandibular central incisors at a 30-degree angle[27] (simulating biting with incisor teeth). Stress distribution on the denture base, ball attachment, matrix, implants, mucosa, and peri-implant cortical and cancellous bone was investigated. von Mises stresses on the implant, matrix, and ball attachment were obtained. Maximum principal stresses (P_{max}) on the denture base and peri-implant bone were recorded, while minimum principal stresses (P_{min}) on the mucosa were recorded to investigate its ability to compress.[18] The stresses were numerically generated, color-coded (stress maps), and compared among all the models.

3. Results

Under the (PV) loading condition, model M recorded the highest values of P_{max} on the denture base and von Mises stresses on the matrix, abutment neck, and implant (Fig. 2A, 2B, 3, 4, 5). The anterior P_{max} on the denture base in model M were concentrated lingually above the ball as seen in Figure 3. The von Mises stress values on the ball abutment and the matrix of the other 4 models were lower than model M by almost 50% (Fig. 2B). The lowest values of implant stress were recorded in model T and model S. The P_{min} value on the mucosa for model M was higher than the rest of the models and stresses were compressive (Fig. 2C, 6). The values of P_{max} on cortical and cancellous bone were the highest in model M and those for cortical bone and were 2 times higher than the other models, however, it did not exceed 0.12 MPa (Fig. 2D, 7, 8). Model S recorded the lowest value of P_{max} on cortical bone. The P_{max} values on the cancellous bone for models P, S, T, and A were very close and the lowest value was recorded by model A.

Under (AO) loading condition, the P_{max} value on the denture base anteriorly at the matrix area was the highest for model S and the lowest for model A, while posteriorly the lowest P_{max} value was recorded in model M (Fig. 9A, 10). The von Mises stresses on the attachment components and implant were the lowest in model S and the highest in model M (Fig. 9B, 11, 12). Interestingly, the von Mises stress value on the abutment in model S was almost 7 times less than model M (19 and 130 MPa respectively) and the other 3 models (P, T, and A) (119, 121, and 120 MPa respectively). Model S recorded the lowest value of P_{min} on the mucosa (Fig. 9C, 13) and for P_{max} on the cortical bone which was nearly 50% less than the other 4 models. P_{max} on the cancellous bone were the lowest for models P and S (Fig. 9D). The P_{max} values on the cortical and cancellous bones were the highest for model M (Fig.

14, 15). For both loading conditions, von Mises stresses were concentrated around the neck of the ball abutment. Stress values were higher for all models under anterior oblique loading than under bilateral posterior vertical loading. In general, the recorded values for all of the models did not exceed the physiologic stress limits of cortical and cancellous bone in compression.[21,54]

4. Discussion

Our null hypothesis was rejected since different retention materials affected the biomechanics of SIO during FEA. Stress distribution to all of the structures of the implant-supported prosthesis can be evaluated using a numeric analysis made through finite element models, which helps to overcome some methodological and ethical restrictions of other experimental methods. It can give accurate information on how efficient the system is from the biomechanical aspect.[45] A 100 N was selected in this study since a study [55] reported that the maximum bite force for SIO was 146.6 ±56.2 N.

The biomechanical behavior of implant-supported overdentures is an important factor in treatment planning. An implant-supported overdenture is exposed to different types of axial and non-axial stresses, including the masticatory force. The sum of these forces is transmitted through the attachment superstructure to the implants and the supporting structures and may cause stress concentration in certain areas of the implants.[48] The peri-implant bone stresses, as well as the denture movement, can be modified by different approaches such as changing the material of the attachment system.[22,45,56,57]

Similar to previous investigations,[18,58] this FEA showed that ball abutment absorbed most of the applied stresses with a tendency toward stress concentration at the thin neck of the ball abutment. Although high attachments with a small diameter such as ball enhance bracing, however, they act as a lever arm and favor lateral forces and stress concentration in the weakest area of the implant/abutment complex (abutment neck) and the surrounding cortical bone.[59] Since the abutment neck absorbed most of the applied stresses, the amount of energy transferred to the implant is reduced.[60] Instead, those stresses at the ball abutment neck are transmitted to the nearby cortical bone at the crest. As a result, it recorded higher stress values when compard to the cancellous bone since the former has a higher young modulus and density.[18,60–63] This was evident in this study especially with the (AO) loading condition.

Matrix fabricated from silicone resilient liner reduced the stresses transmitted to the ball abutment, implant, mucosa, and supporting bone under both loading conditions. Therefore, they may reduce the incidence of technical complications such as abutment fracture. This may be attributed to its higher Poisson ratio (viscoelastic properties) and lower modulus of elasticity that can compensate for the difference in resiliency between the mucous membrane and the dental implants and transmit some of the occlusal loads to the residual ridge.[43] In other words, they provide vertical and rotational resiliency while acting as a stress breaker, absorbing more energy, and transmitting less stresses to the other structures.[18,28,64] Kanzawa et al.[65] reported that applying silicone resilient materials to the female part of ball attachment can significantly reduce stresses on the surrounding tissues with anterior loading. A previous FEA study [66] concluded that overdentures supported by conventional or mini-implants with a ball and flexible O-ring retention system demonstrated minimal stress within the bone and implants.

In addition, the other 3 tested polymer materials (models P, T, and A) reduced the amount of stress on the entire overdenture components and bone due to their lower elastic modulus and higher tendency toward deformation than titanium. Similarly, previous studies[45,56,57] concluded that plastic clips used with metal bar attachment for implant overdenture can reduce stresses on all of the structures when compared with metallic gold clips. It has been reported that crown materials with low modulus of elasticity, such as acrylic resin, act as a shock absorber for occlusal impact forces. As a result of their damping effect, the effect of occlusal forces on the bone-implant interface is significantly reduced.[22]

Since model M recorded the highest P_{max} value on denture base anteriorly around the attachment under the (PV) loading, this indicates that denture base fracture is more liable to occur in this area when a metal socket is used as reported previously.[67] Tensile stresses were recorded in denture bases at the area of the metal socket with bilateral posterior loading.[12,68] However, under the (AO) loading condition, the highest P_{max} value on the anterior denture base area was seen in model S which might be due to the severe compression and hence the reduced thickness of silicone resilient liner in this area during load application. The denture base P_{max} were lower for the other 3 models (especially model P) with polymer matrices which could have enhanced the denture base thickness in this area.

Maeda et al.[3] reported that the lateral load to the implant and the denture base movement decreased when the distance between the implant and the loading point increased. This explains why lower stress values were recorded with bilateral posterior axial loading than those recorded with anterior oblique loading. This finding was in agreement with previous studies[28,69,70] since oblique loading is analyzed into vertical and detrimental lateral loads.

When a load is applied anteriorly, overdenture starts to rotate over the implant and bend vertically rather than moving in a horizontal direction, increasing the lateral forces during function.[3] This analysis suggests that most of these lateral stresses were transmitted to the ball abutment especially when a titanium retentive matrix was used.

In this study, both cortical and cancellous bone stresses increased with anterior oblique loading. However, an FEA study conducted by Liu et al.[7] on the influence of the implant number on the biomechanical behavior of mandibular overdentures found that SIO rotated over the implant from side to side under vertical load on the lower incisors without increasing the peri-implant bone strains.

Finally, neither von Mises stresses on the attachment and the implant nor maximum principal stresses on the bone exceed the yield stress values of titanium and bone.[49,66,71] Therefore, the results of this study support the previously reported successful long-term clinical outcomes of SIO.[4,5] Moreover, they support the concept that, in SIO, the greatest part of the load is directed to the denture bearing mucosa. This study has the same previously reported limitations of FEA.[72] Therefore, further investigation with clinical studies is recommended.

5. Conclusion

Within the limitations of the study, the following can be concluded:

1. The elastic modulus of the retention (matrix) materials can affect stresses generated on the implant overdenture components and supporting structures.
2. For all the models under both loading conditions, maximum principal stresses were concentrated on the ball attachment neck. However, these stresses tend to decrease with retention materials of lower elastic modulus especially silicone resilient liner.
3. The investigated non-metallic retention materials especially silicone resilient liner can reduce stresses to the supporting bone, the implant, and attachment components. Hence, they can reduce the incidence of ball attachment’s complications and maintenance requirements for SIO.
4. All the tested materials can be considered as a suitable retention/receptacle material for the ball attachment from the biomechanical point of view.
5. Bilateral posterior occlusal contact is recommended for SIO in terms of stress distribution. Anterior oblique incisal contact should be avoided.

6. SIO retained with ball attachment can be considered a feasible treatment option as it doesn’t cause stress concentration on the bone around the implant.

Declaration of Competing Interest:

There are no conflicts of interest to declare

References

1. Emami E, Heydecke G, Rompré PH, de Grandmont P, Feine JS. Impact of implant support for mandibular dentures on satisfaction, oral and general health-related quality of life: a meta-analysis of randomized-controlled trials. *Clin Oral Implants Res*. 2009;20(6):533-544. doi:10.1111/j.1600-0501.2008.01693.x

2. Sadig W. A comparative in vitro study on the retention and stability of implant-supported overdentures. *Quintessence Int Berl Ger 1985*. 2009;40(4):313-319.

3. Maeda Y, Horisaka M, Yagi K. Biomechanical rationale for a single implant-retained mandibular overdenture: an in vitro study. *Clin Oral Implants Res*. 2008;19(3):271-275. doi:10.1111/j.1600-0501.2007.01425.x

4. Cordioli G, Majzoub Z, Castagna S. Mandibular overdentures anchored to single implants: a five-year prospective study. *J Prosthet Dent*. 1997;78(2):159-165. doi:10.1016/s0022-3913(97)70120-3

5. Krennmair G, Ulm C. The symphyseal single-tooth implant for anchorage of a mandibular complete denture in geriatric patients: a clinical report. *Int J Oral Maxillofac Implants*. 2001;16(1):98-104.

6. de Souza Batista VE, Vechiato-Filho AJ, Santiago JF, et al. Clinical viability of single implant-retained mandibular overdentures: a systematic review and meta-analysis. *Int J Oral Maxillofac Surg*. 2018;47(9):1166-1177. doi:10.1016/j.ijom.2018.01.021

7. Liu J, Pan S, Dong J, Mo Z, Fan Y, Feng H. Influence of implant number on the biomechanical behaviour of mandibular implant-retained/supported overdentures: A three-dimensional finite element analysis. *J Dent*. 2013;41(3):241-249. doi:10.1016/j.jdent.2012.11.008

8. Trakas T, Michalakis K, Kang K, Hirayama H. Attachment systems for implant retained overdentures: a literature review. *Implant Dent*. 2006;15(1):24-34. doi:10.1097/01.id.0000202419.21665.36

9. Sato H, Kobayashi T, Nomura T, et al. Oral mucosa pressure caused by mandibular implant overdenture with different types of attachments. *J Prosthodont Res*. 2020;64(2):145-151. doi:10.1016/j.jpor.2019.06.003

10. Alsabeeha NHM, Payne AGT, Silva RKD, Thomson WM. Mandibular single-implant overdentures: preliminary results of a randomised-control trial on early loading with different implant diameters and attachment systems. *Clin Oral Implants Res*. 2011;22(3):330-337. doi:10.1111/j.1600-0501.2010.02004.x

11. Matthys C, Vervaeke S, Besseler J, Doornewaard R, Dierens M, De Bruyn H. Five years follow-up of mandibular 2-implant overdentures on locator or ball abutments: Implant results, patient-

related outcome, and prosthetic aftercare. *Clin Implant Dent Relat Res*. 2019;21(5):835-844. doi:10.1111/cid.12840

12. Gonda T, Maeda Y, Walton JN, MacEntee MI. Fracture incidence in mandibular overdentures retained by one or two implants. *J Prosthet Dent*. 2010;103(3):178-181. doi:10.1016/S0022-3913(10)60026-1

13. Harder S, Wolfart S, Egert C, Kern M. Three-year clinical outcome of single implant-retained mandibular overdentures--results of preliminary prospective study. *J Dent*. 2011;39(10):656-661. doi:10.1016/j.jdent.2011.07.007

14. Liddelow GJ, Henry PJ. A prospective study of immediately loaded single implant-retained mandibular overdentures: preliminary one-year results. *J Prosthet Dent*. 2007;97(6 Suppl):S126-137. doi:10.1016/S0022-3913(07)60016-X

15. Nogueira TE, Aguiar FMO, de Barcelos BA, Leles CR. A 2-year prospective study of single-implant mandibular overdentures: Patient-reported outcomes and prosthodontic events. *Clin Oral Implants Res*. 2018;29(6):541-550. doi:10.1111/clr.13151

16. Passia N, Wolfart S, Kern M. Six-year clinical outcome of single implant-retained mandibular overdentures--a pilot study. *Clin Oral Implants Res*. 2015;26(10):1191-1194. doi:10.1111/clr.12427

17. Büttel AE, Lüthy H, Sendi P, Marinello CP. Wear of ceramic and titanium ball attachments in subjects with an implant-retained overdenture: a controlled clinical trial. *J Prosthet Dent*. 2012;107(2):109-113. doi:10.1016/S0022-3913(12)60035-3

18. Pisani MX, Presotto AGC, Mesquita MF, Barão VAR, Kemmoku DT, Del Bel Cury AA. Biomechanical behavior of 2-implant- and single-implant-retained mandibular overdentures with conventional or mini implants. *J Prosthet Dent*. 2018;120(3):421-430. doi:10.1016/j.prosdent.2017.12.012

19. Lahoti K, Pathrabe A, Gade J. Stress analysis at bone-implant interface of single- and two-implant-retained mandibular overdenture using three-dimensional finite element analysis. *Indian J Dent Res Off Publ Indian Soc Dent Res*. 2016;27(6):597-601. doi:10.4103/0970-9290.199587

20. Watzek G, ed. *Endosseous Implants: Scientific and Clinical Aspects*. 1 edition. Quintessence Pub Co; 1996.

21. Baggi L, Cappelloni I, Di Girolamo M, Maceri F, Vairo G. The influence of implant diameter and length on stress distribution of osseointegrated implants related to crestal bone geometry: a three-dimensional finite element analysis. *J Prosthet Dent*. 2008;100(6):422-431. doi:10.1016/S0022-3913(08)60259-0

22. El-Anwar MI, El-Mofty MS, Awad AH, El-Sheikh SA, El-Zawahry MM. The effect of using different crown and implant materials on bone stress distribution: a finite element study. *Egypt J Oral Maxillofac Surg*. 2014;5(2):58-64. doi:10.1097/01.OMX.0000444266.10130.4c

23. Frost HM. Bone's mechanostat: A 2003 update. *Anat Rec A Discov Mol Cell Evol Biol*. 2003;275A(2):1081-1101. doi:https://doi.org/10.1002/ar.a.10119

24. Frost HM. A 2003 update of bone physiology and Wolff's Law for clinicians. *Angle Orthod*. 2004;74(1):3-15. doi:10.1043/0003-3219(2004)074<0003:AUOBPA>2.0.CO;2

25. Chang M-C, Lin L-D, Chan C-P, et al. The effect of BisGMA on cyclooxygenase-2 expression, PGE2 production and cytotoxicity via reactive oxygen species- and MEK/ERK-dependent and -independent pathways. *Biomaterials*. 2009;30(25):4070-4077. doi:10.1016/j.biomaterials.2009.04.034

26. Ueda T, Kremer U, Katsoulis J, Mericske-Stern R. Long-term results of mandibular implants supporting an overdenture: implant survival, failures, and crestal bone level changes. *Int J Oral Maxillofac Implants*. 2011;26(2):365-372.

27. Amaral CF, Gomes RS, Rodrigues Garcia RCM, Del Bel Cury AA. Stress distribution of single-implant-retained overdenture reinforced with a framework: A finite element analysis study. *J Prosthet Dent*. 2018;119(5):791-796. doi:10.1016/j.prosdent.2017.07.016

28. Radi IA-E, Elmahrouky N. Effect of two different soft liners and thicknesses mediating stress transfer for immediately loaded 2-implant supported mandibular overdentures: A finite element analysis study. *J Prosthet Dent*. 2016;116(3):356-361. doi:10.1016/j.prosdent.2016.01.031

29. Vallittu PK. An overview of development and status of fiber-reinforced composites as dental and medical biomaterials. *Acta Biomater Odontol Scand*. 2018;4(1):44-55. doi:10.1080/23337931.2018.1457445

30. Vallittu PK. Flexural properties of acrylic resin polymers reinforced with unidirectional and woven glass fibers. *J Prosthet Dent*. 1999;81(3):318-326. doi:10.1016/s0022-3913(99)70276-3

31. Gibreel M, Lassila LVJ, Närhi TO, Perea-Lowery L, Vallittu PK. Load-bearing capacity of simulated Locator-retained overdenture system. *J Prosthet Dent*. 2018;120(4):558-564. doi:10.1016/j.prosdent.2018.04.009

32. Berger G, Pereira LF de O, Souza EM de, Rached RN. A 3D finite element analysis of glass fiber reinforcement designs on the stress of an implant-supported overdenture. *J Prosthet Dent*. 2019;121(5):865.e1-865.e7. doi:10.1016/j.prosdent.2019.02.010

33. Tokuhisa M, Matsushita Y, Koyano K. In vitro study of a mandibular implant overdenture retained with ball, magnet, or bar attachments: comparison of load transfer and denture stability. *Int J Prosthodont*. 2003;16(2):128-134.

34. Setz JM, Wright PS, Ferman AM. Effects of attachment type on the mobility of implant-stabilized overdentures--an in vitro study. *Int J Prosthodont*. 2000;13(6):494-499.

35. ELsyad MA. Prosthetic aspects and patient satisfaction with resilient liner and clip attachments for bar- and implant-retained mandibular overdentures: a 3-year randomized clinical study. *Int J Prosthodont*. 2012;25(2):148-156.

36. Koike T, Ueda T, Noda S, et al. Development of New Attachment System with Soft Lining Material for Implant-retained Complete Denture. Int J Prosthodont Restor Dent. 2013;3(1):21-24. doi:10.5005/JP-JOURNALS-10019-1070.

37. Valente MLC, Shimano MVW, Agnelli JAM, Dos Reis AC. Retention force and deformation of an innovative attachment model for mini-implant-retained overdentures. *J Prosthet Dent*. 2019;121(1):129-134. doi:10.1016/j.prosdent.2018.04.010

38. Galo Silva G, Valente ML da C, Bachmann L, dos Reis AC. Use of polyethylene terephthalate as a prosthetic component in the prosthesis on an overdenture implant. *Mater Sci Eng C*. 2019;99:1341-1349. doi:10.1016/j.msec.2019.01.136

39. Stock V, Wagner C, Merk S, et al. Retention force of differently fabricated telescopic PEEK crowns with different tapers. *Dent Mater J*. 2016;35(4):594-600. doi:10.4012/dmj.2015-249

40. Hahnel S, Wieser A, Lang R, Rosentritt M. Biofilm formation on the surface of modern implant abutment materials. *Clin Oral Implants Res*. 2015;26(11):1297-1301. doi:10.1111/clr.12454

41. Fitton JS, Davies EH, Howlett JA, Pearson GJ. The physical properties of a polyacetal denture resin. *Clin Mater*. 1994;17(3):125-129. doi:10.1016/0267-6605(94)90135-x

42. Perea-Lowery L, Gibreel M, Vallittu PK, Lassila L. Characterization of the mechanical properties of CAD/CAM polymers for interim fixed restorations. *Dent Mater J*. 2020;39(2):319-325. doi:10.4012/dmj.2019-042

43. Adrian ED, Krantz WA, Ivanhoe JR. The use of processed silicone to retain the implant-supported tissue-borne overdenture. *J Prosthet Dent*. 1992;67(2):219-222.

44. Federick DR, Caputo AA. Effects of overdenture retention designs and implant orientations on load transfer characteristics. *J Prosthet Dent*. 1996;76(6):624-632. doi:10.1016/s0022-3913(96)90441-2

45. dos Santos MBF, Bacchi A, Correr-Sobrinho L, Consani RLX. The influence of clip material and cross sections of the bar framework associated with vertical misfit on stress distribution in implant-retained overdentures. *Int J Prosthodont*. 2014;27(1):26-32. doi:10.11607/ijp.3627

46. Iplikçioğlu H, Akça K. Comparative evaluation of the effect of diameter, length and number of implants supporting three-unit fixed partial prostheses on stress distribution in the bone. *J Dent*. 2002;30(1):41-46. doi:10.1016/s0300-5712(01)00057-4

47. Tanino F, Hayakawa I, Hirano S, Minakuchi S. Finite element analysis of stress-breaking attachments on maxillary implant-retained overdentures. *Int J Prosthodont*. 2007;20(2):193-198.

48. Kasani R, Rama Sai Attili BK, Dommeti VK, Merdji A, Biswas JK, Roy S. Stress distribution of overdenture using odd number implants - A Finite Element Study. *J Mech Behav Biomed Mater*. 2019;98:369-382. doi:10.1016/j.jmbbm.2019.06.030

49. Kaleli N, Sarac D, Külünk S, Öztürk Ö. Effect of different restorative crown and customized abutment materials on stress distribution in single implants and peripheral bone: A three-dimensional finite element analysis study. *J Prosthet Dent*. 2018;119(3):437-445. doi:10.1016/j.prosdent.2017.03.008

50. Elsayyad AA, Abbas NA, AbdelNabi NM, Osman RB. Biomechanics of 3-implant-supported and 4-implant-supported mandibular screw-retained prostheses: A 3D finite element analysis study. *J Prosthet Dent*. 2020;124(1):68.e1-68.e10. doi:10.1016/j.prosdent.2020.01.015

51. Sćepanović M, Tihacek-Sojić L, Tasić M, Mitrović R, Todorović A, Trifković B. Finite element analysis in defining the optimal shape and safety factor of retentive clasp arms of a removable partial denture. *Vojnosanit Pregl*. 2013;70(11):999-1005. doi:10.2298/vsp110526021s

52. Reddy JC, Chintapatla SB, Srikakula NK, et al. Comparison of Retention of Clasps Made of Different Materials Using Three-Dimensional Finite Element Analysis. *J Clin Diagn Res JCDR*. 2016;10(5):ZC13-16. doi:10.7860/JCDR/2016/18405.7731

53. Nascimento JFM, Aguiar-Júnior FA, Nogueira TE, Rodrigues RCS, Leles CR. Photoelastic Stress Distribution Produced by Different Retention Systems for a Single-Implant Mandibular Overdenture. *J Prosthodont Off J Am Coll Prosthodont*. 2015;24(7):538-542. doi:10.1111/jopr.12269

54. Martin RB, Burr DB, Sharkey NA, Fyhrie DP. *Skeletal Tissue Mechanics*. 2nd ed. Springer-Verlag; 2015. doi:10.1007/978-1-4939-3002-9

55. Haraldson T, Carlsson GE. Bite force and oral function in patients with osseointegrated oral implants. *Eur J Oral Sci*. 1977;85(3):200-208. doi:10.1111/j.1600-0722.1977.tb00554.x

56. Dos Santos MBF, Zen BM, Bacchi A. Effect of vertical misfit and clip material on stress distribution of overdentures under masticatory loading. *Med Biol Eng Comput*. 2016;54(10):1515-1521. doi:10.1007/s11517-015-1426-0

57. Tanoue M, Kanazawa M, Takeshita S, Minakuchi S. Effects of clip materials on stress distribution to maxillary implant overdentures with bar attachments. *J Prosthet Dent*. 2016;115(3):283-289. doi:10.1016/j.prosdent.2015.07.017

58. Unsal GS, Erbasar GNH, Aykent F, Ozyilmaz OY, Ozdogan MS. Evaluation of Stress Distribution on Mandibular Implant-Supported Overdentures With Different Bone Heights and Attachment Types: A 3D Finite Element Analysis. *J Oral Implantol*. 2019;45(5):363-370. doi:10.1563/aaid-joi-D-19-00076

59. Ozan O, Ramoglu S. Effect of Implant Height Differences on Different Attachment Types and Peri-Implant Bone in Mandibular Two-Implant Overdentures: 3D Finite Element Study. *J Oral Implantol*. 2015;41(3):e50-59. doi:10.1563/AAID-JOI-D-13-00239

60. El-Anwar MI, Yousief SA, Soliman TA, Saleh MM, Omar WS. A finite element study on stress distribution of two different attachment designs under implant supported overdenture. *Saudi Dent J*. 2015;27(4):201-207. doi:10.1016/j.sdentj.2015.03.001

61. Daas M, Dubois G, Bonnet AS, Lipinski P, Rignon-Bret C. A complete finite element model of a mandibular implant-retained overdenture with two implants: comparison between rigid and resilient attachment configurations. *Med Eng Phys*. 2008;30(2):218-225. doi:10.1016/j.medengphy.2007.02.005

62. Khurana N, Rodrigues S, Shenoy S, et al. A Comparative Evaluation of Stress Distribution with Two Attachment Systems of Varying Heights in a Mandibular Implant-Supported Overdenture: A Three-Dimensional Finite Element Analysis. *J Prosthodont Off J Am Coll Prosthodont*. 2019;28(2):e795-e805. doi:10.1111/jopr.12966

63. 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. doi:10.1016/j.compbiomed.2014.08.018

64. Waters M, Jagger R, Williams K, Jerolimov V. Dynamic mechanical thermal analysis of denture soft lining materials. *Biomaterials*. 1996;17(16):1627-1630. doi:10.1016/0142-9612(95)00330-4

65. Kanazawa M, Minakuchi S, Hayakawa I, Hirano S, Uchida T. In vitro study of reduction of stress transferred onto tissues around implants using a resilient material in maxillary implant overdentures. *J Med Dent Sci*. 2007;54(1):17-23.

66. Solberg K, Heinemann F, Pellikaan P, et al. Finite element analysis of different loading conditions for implant-supported overdentures supported by conventional or mini implants. *Comput Methods Biomech Biomed Engin*. 2017;20(7):770-782. doi:10.1080/10255842.2017.1302432

67. Kern M, Att W, Fritzer E, et al. Survival and Complications of Single Dental Implants in the Edentulous Mandible Following Immediate or Delayed Loading: A Randomized Controlled Clinical Trial. *J Dent Res*. 2018;97(2):163-170. doi:10.1177/0022034517736063

68. ELsyad MA, Errabti HM, Mustafa AZ. Mandibular Denture Base Deformation with Locator and Ball Attachments of Implant-Retained Overdentures. *J Prosthodont Off J Am Coll Prosthodont*. 2016;25(8):656-664. doi:10.1111/jopr.12356

69. Chun H-J, Park D-N, Han C-H, Heo S-J, Heo M-S, Koak J-Y. Stress distributions in maxillary bone surrounding overdenture implants with different overdenture attachments. *J Oral Rehabil*. 2005;32(3):193-205. doi:10.1111/j.1365-2842.2004.01407.x

70. Barão V a. R, Delben JA, Lima J, Cabral T, Assunção WG. Comparison of different designs of implant-retained overdentures and fixed full-arch implant-supported prosthesis on stress distribution in edentulous mandible--a computed tomography-based three-dimensional finite element analysis. *J Biomech*. 2013;46(7):1312-1320. doi:10.1016/j.jbiomech.2013.02.008

71. Akça K, Iplikçioğlu H. Finite element stress analysis of the effect of short implant usage in place of cantilever extensions in mandibular posterior edentulism. *J Oral Rehabil*. 2002;29(4):350-356. doi:10.1046/j.1365-2842.2002.00872.x

72. Petrie CS, Williams JL. Probabilistic analysis of peri-implant strain predictions as influenced by uncertainties in bone properties and occlusal forces. *Clin Oral Implants Res*. 2007;18(5):611-619. doi:10.1111/j.1600-0501.2007.01384.x

Tables

Table 1. Properties of materials used for finite element analysis models

Material	**Density (kg/m^3)**	**Young's modulus (MPa)**	**Poisson's ratio**	**Tensile yield strength (Mpa)**	**Reference**
Titanium	4400	1.10E+05	0.35	834	49,50
Cortical bone	1990	13700	0.3	114	7,50
Cancellous bone	1847	1370	0.3	52	18,50
Acrylic resin teeth	1190	2940	0.3	61	28,50
Acrylic resin denture base	1190	2700	0.3	61	48,50
Mucosa	1400	0.34	0.45	4	28
Silicone resilient liner	1150	21	0.44	2,24	28
Polyether ether ketone (PEEK)	1320	3500	0.36	72	49
CAD-CAM thermoplastic resin (Multistratum flexible; Zirkonzahn)	1200	2400	0.3	125	42, manufacturer
Polyacetal resin	1420	2900	0.44	70	51,52

Table 2. Materials used for retention element fabrication

Model	**Material of retention element (matrix)**
Model M	Titanium
Model P	PEEK
Model S	Silicone resilient liner
Model T	Thermoplastic resin
Model A	Polyacetal resin

Figures

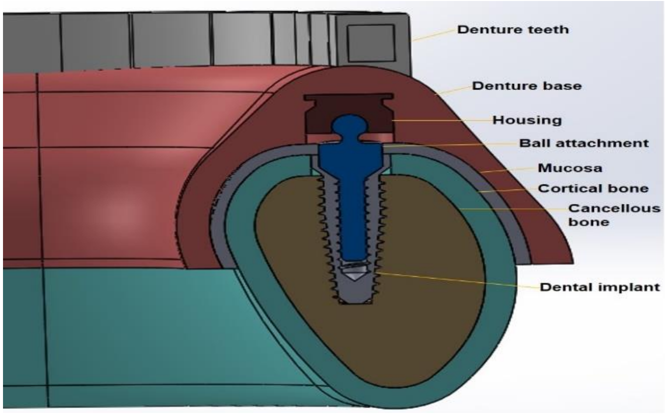
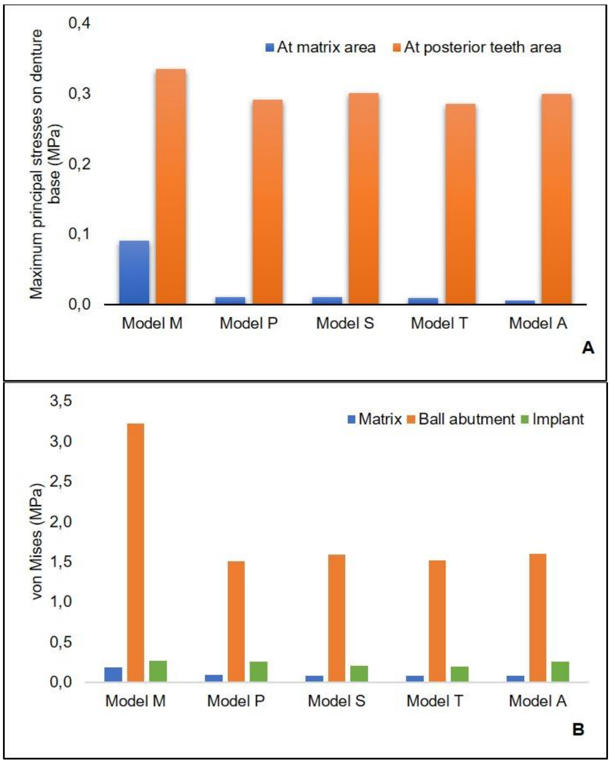


Fig. 1. Sagittal view of virtual overdenture model.



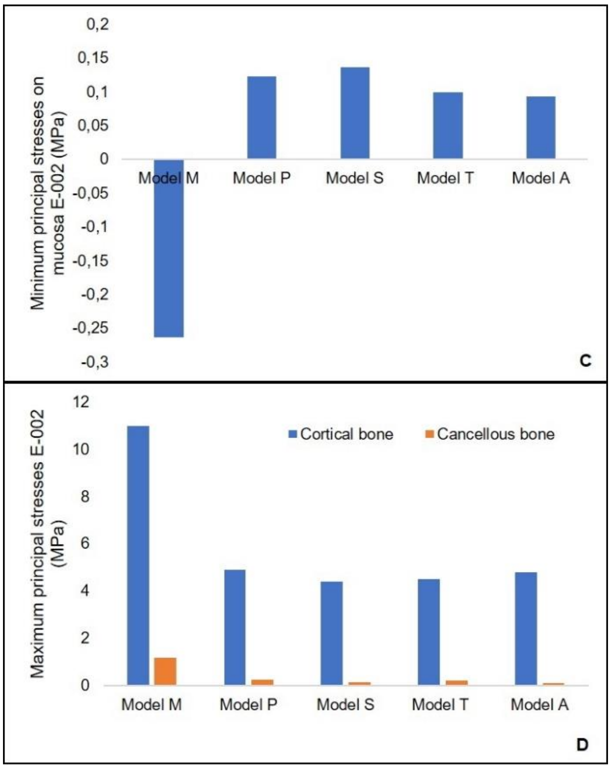


Fig. 2. Overdenture stresses during bilateral posterior vertical loading (PV). A, Maximum principal stresses (MPa) on denture base. B, von Mises maximum stresses (MPa) on matrix, ball abutment, and implant. C, minimum principal stresses (MPa) on mucosa. D, Maximum principal stresses (MPa) on peri-implant cortical and cancellous bone.

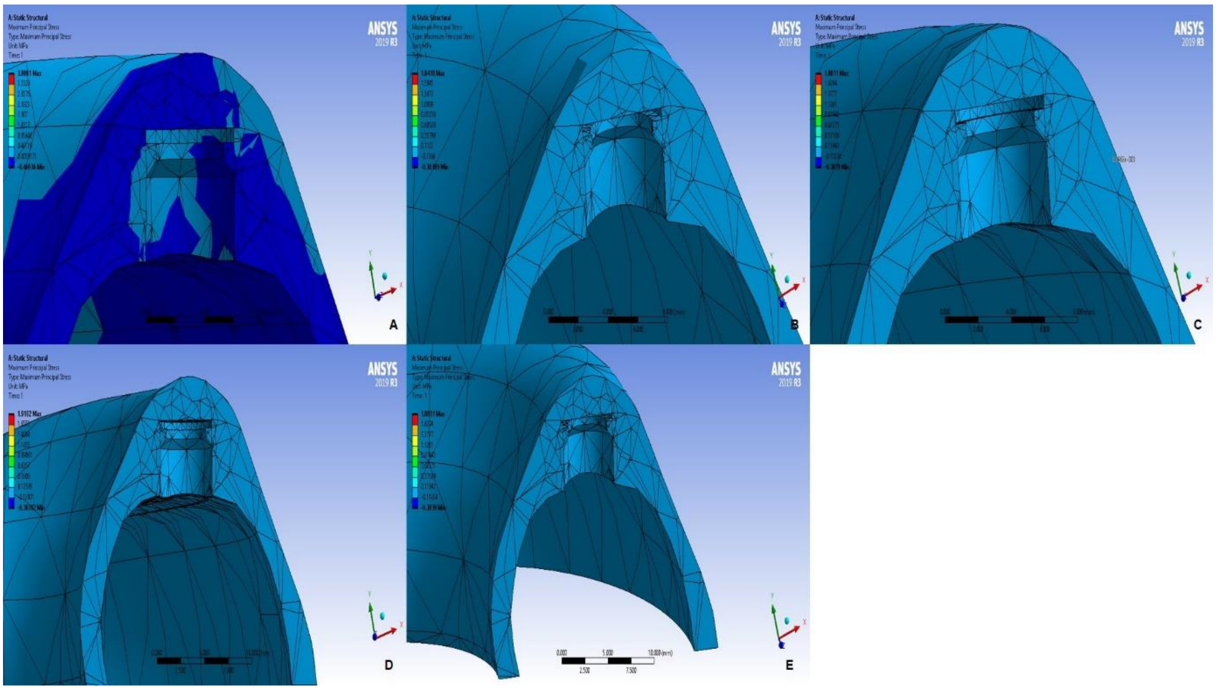


Fig. 3. Stress maps (maximum principal stresses) on denture base at the matrix area (PV loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A).

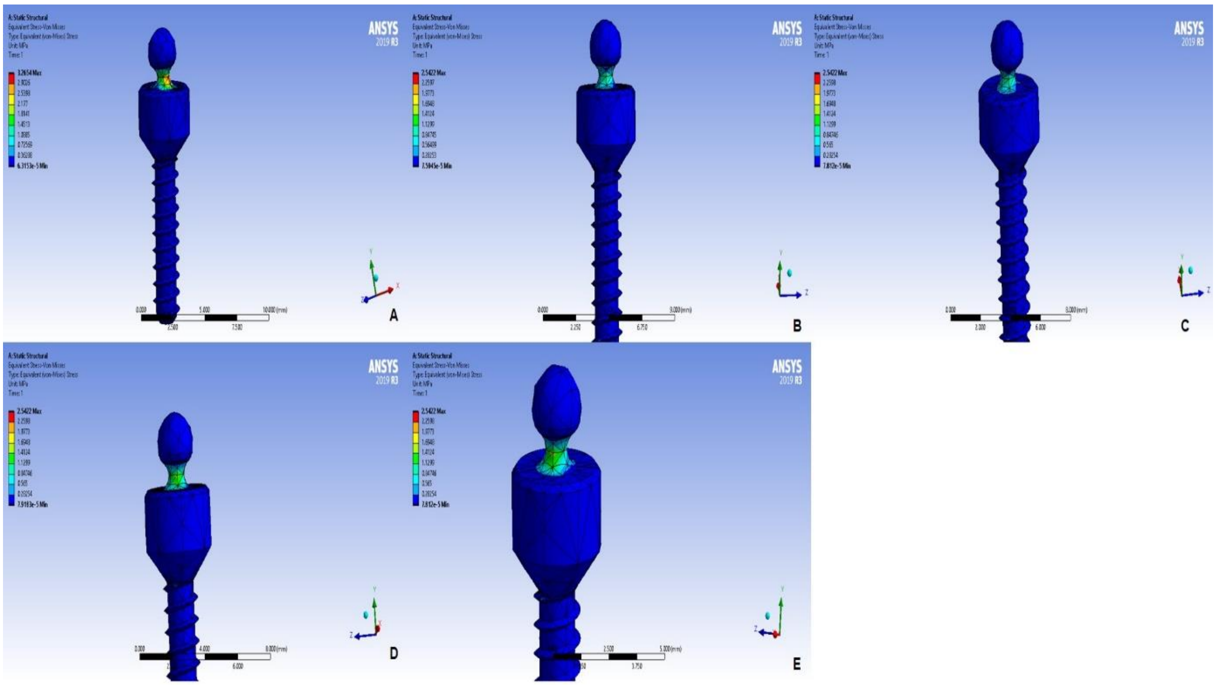


Fig. 4. Stress maps (von Mises stresses) on ball abutment (PV loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A)

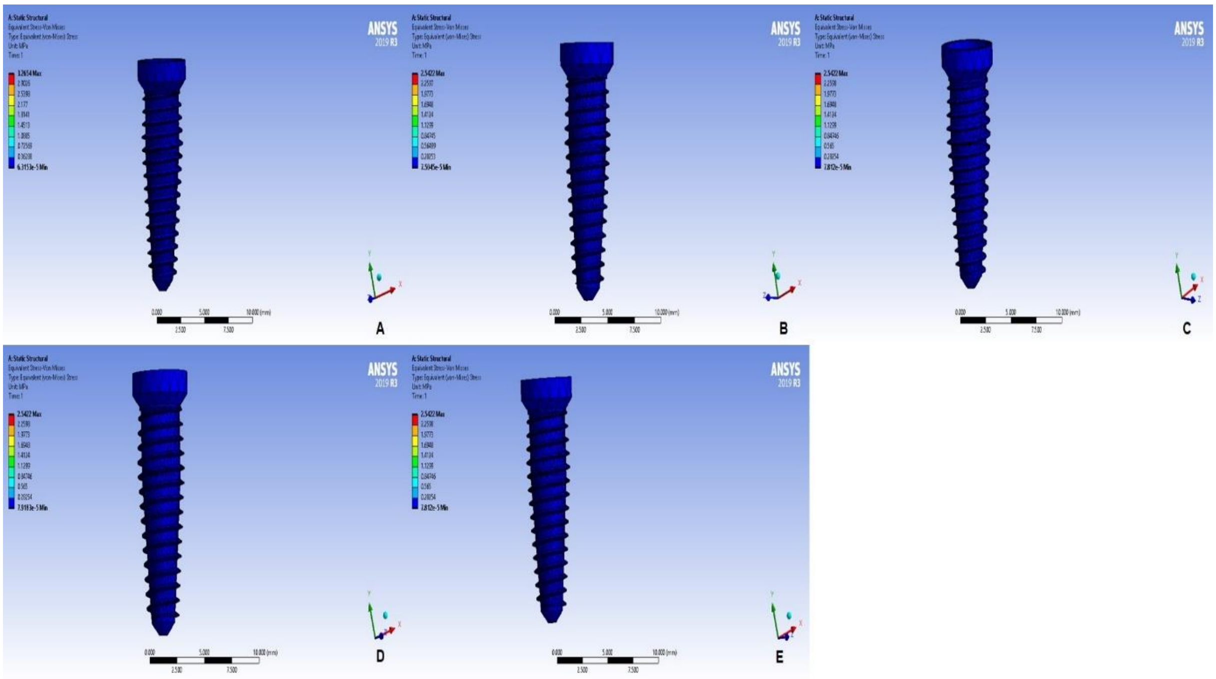


Fig. 5. Stress maps (von Mises stresses) of dental implant (PV loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A)

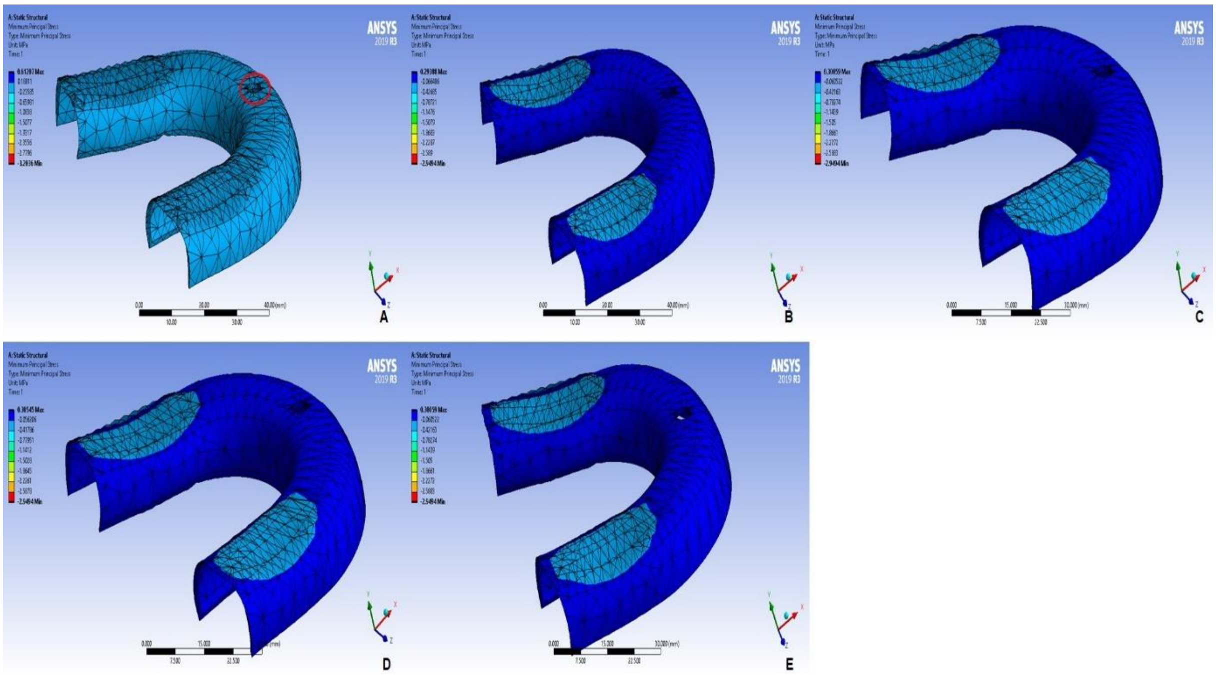


Fig. 6. Stress maps (minimum principal stresses) on mucosa (PV loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A) (red circle represents location of measurement).

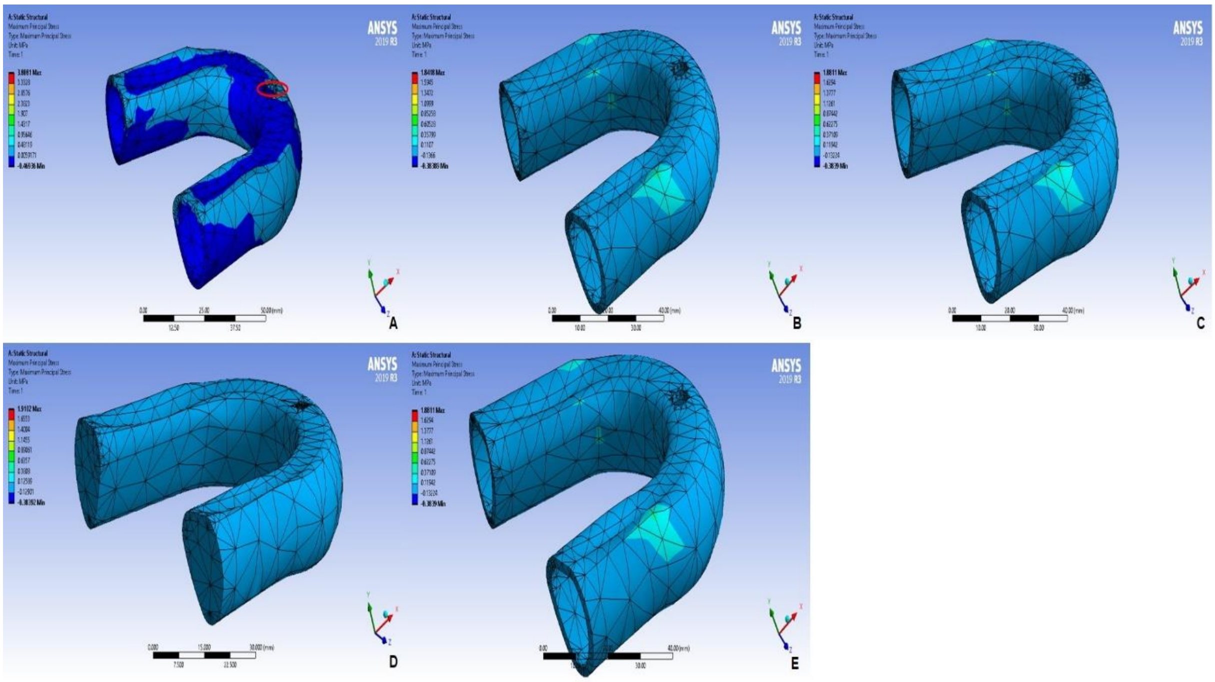


Fig. 7. Stress maps (maximum principal stresses) on cortical bone (PV loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A)(red circle represents location of measurement).

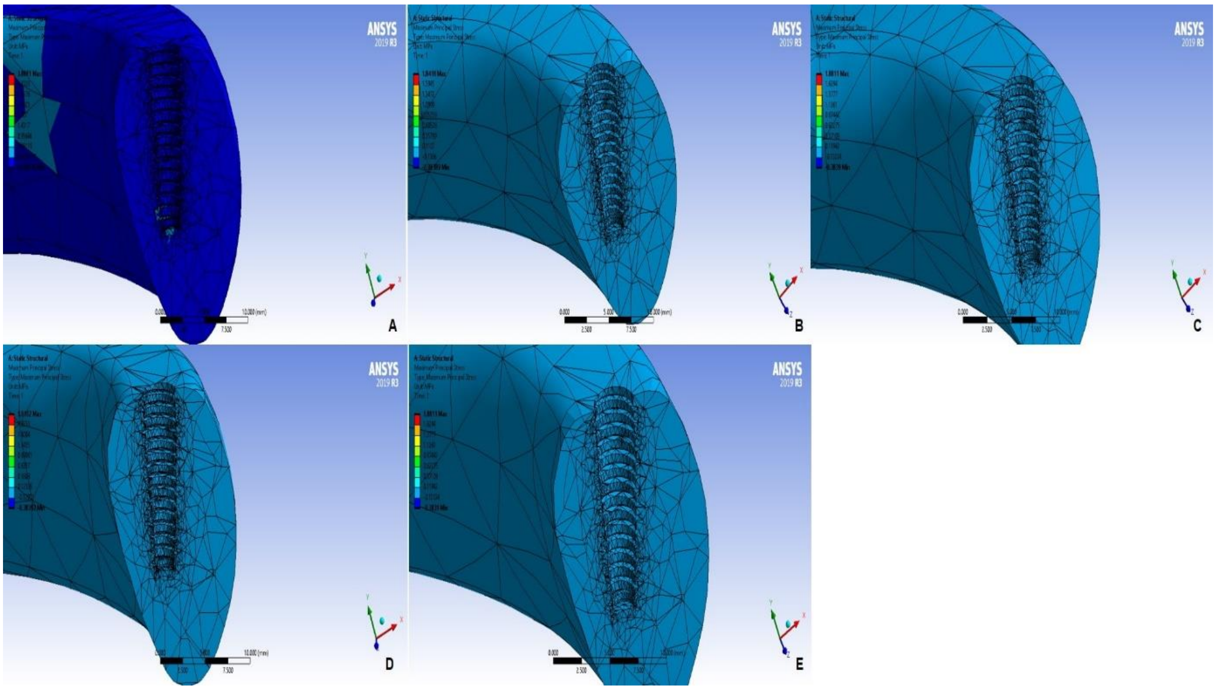
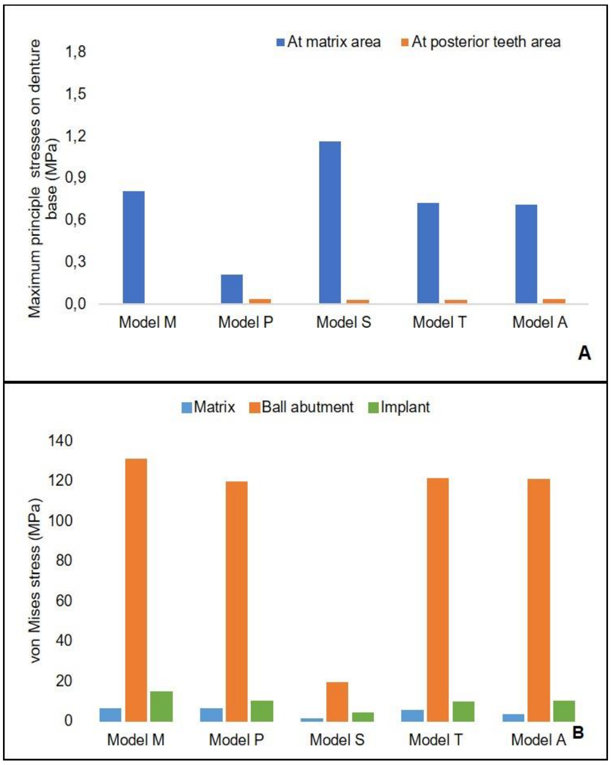


Fig. 8. Stress maps (maximum principal stresses) on cancellous bone (PV loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A).



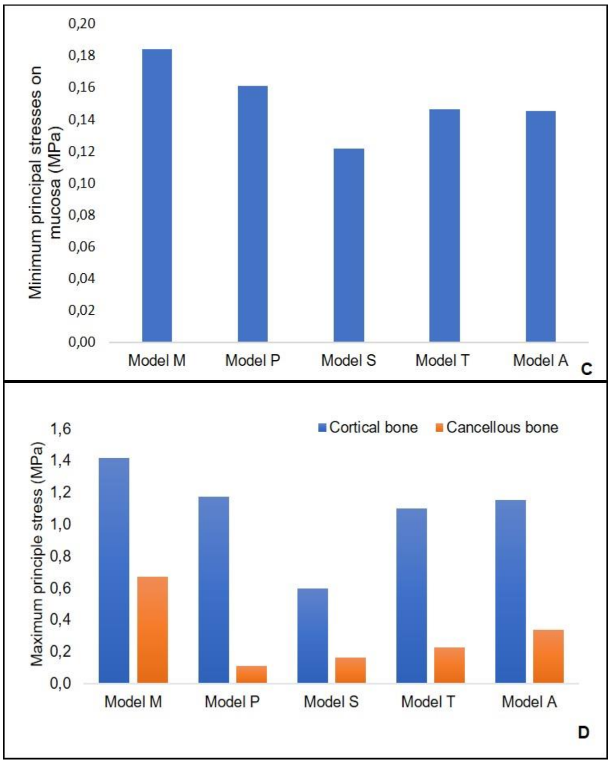


Fig. 9. Overdenture stresses during anterior oblique loading (AO). A, Maximum principal stresses (MPa) on denture base. B, von Mises maximum stresses (MPa) on matrix, ball abutment, and implant. C, minimum principal stresses (MPa) on mucosa. D, Maximum principal stresses (MPa) on peri-implant cortical and cancellous bone.

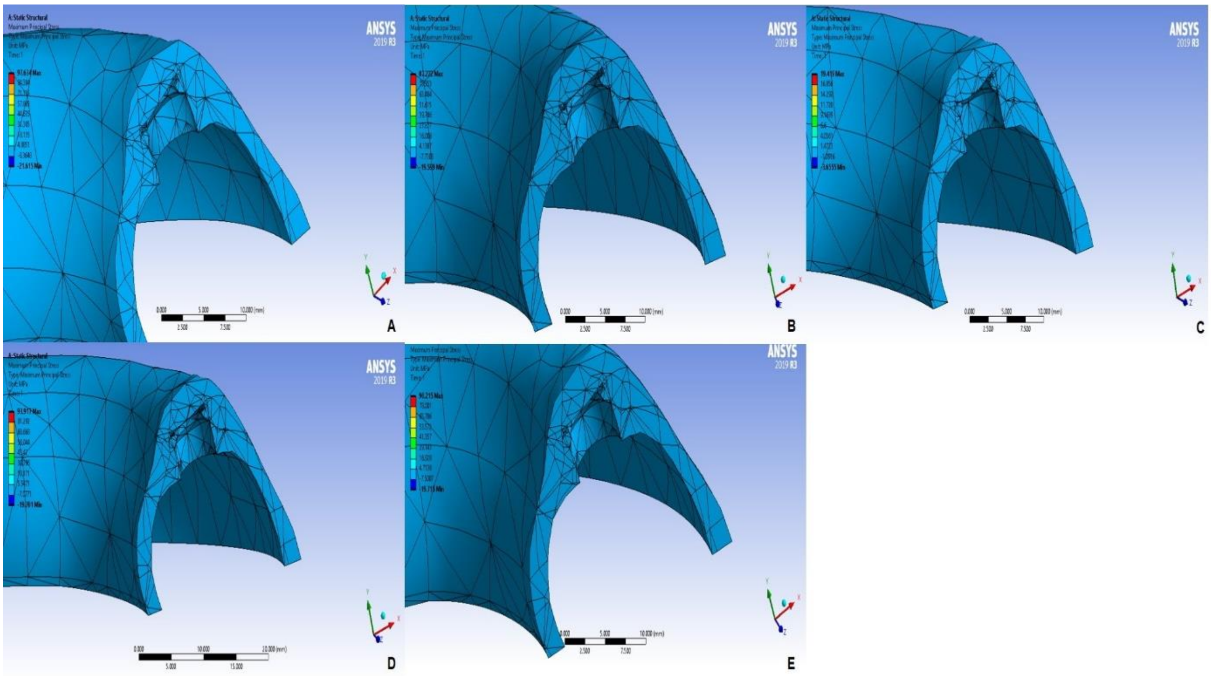


Fig. 10. Stress maps (maximum principal stresses) on denture base at the matrix area (AO loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A).

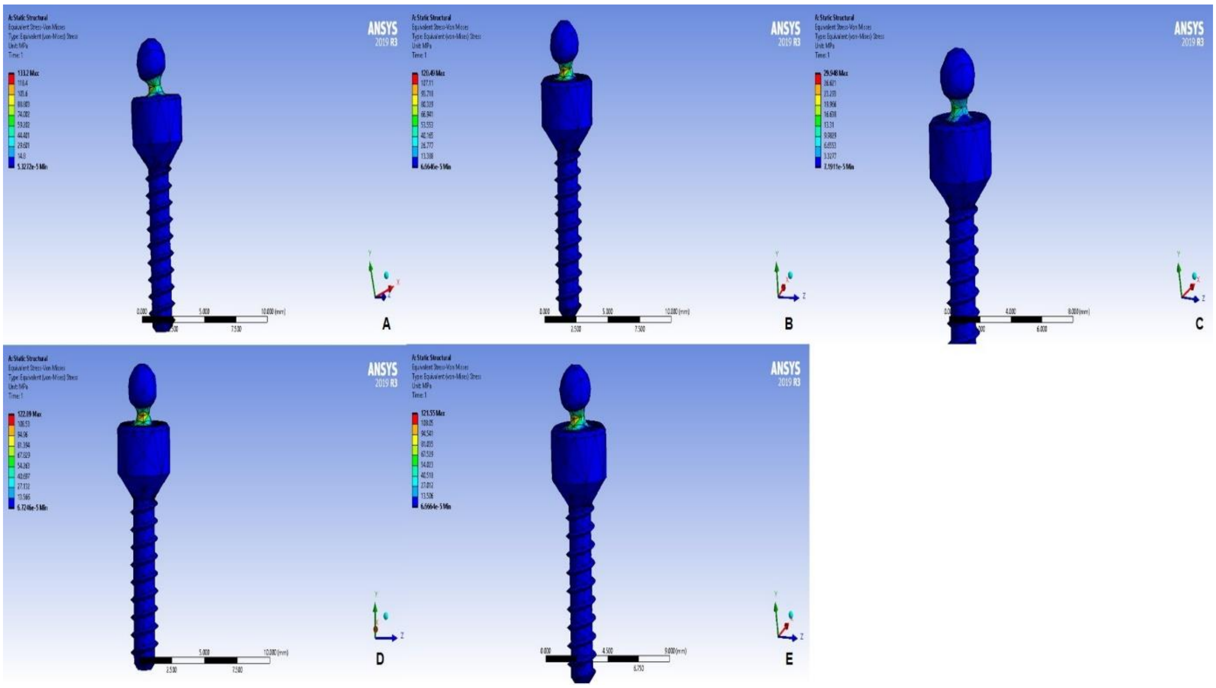


Fig. 11. Stress maps (von Mises stresses) on ball abutment (AO loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A).

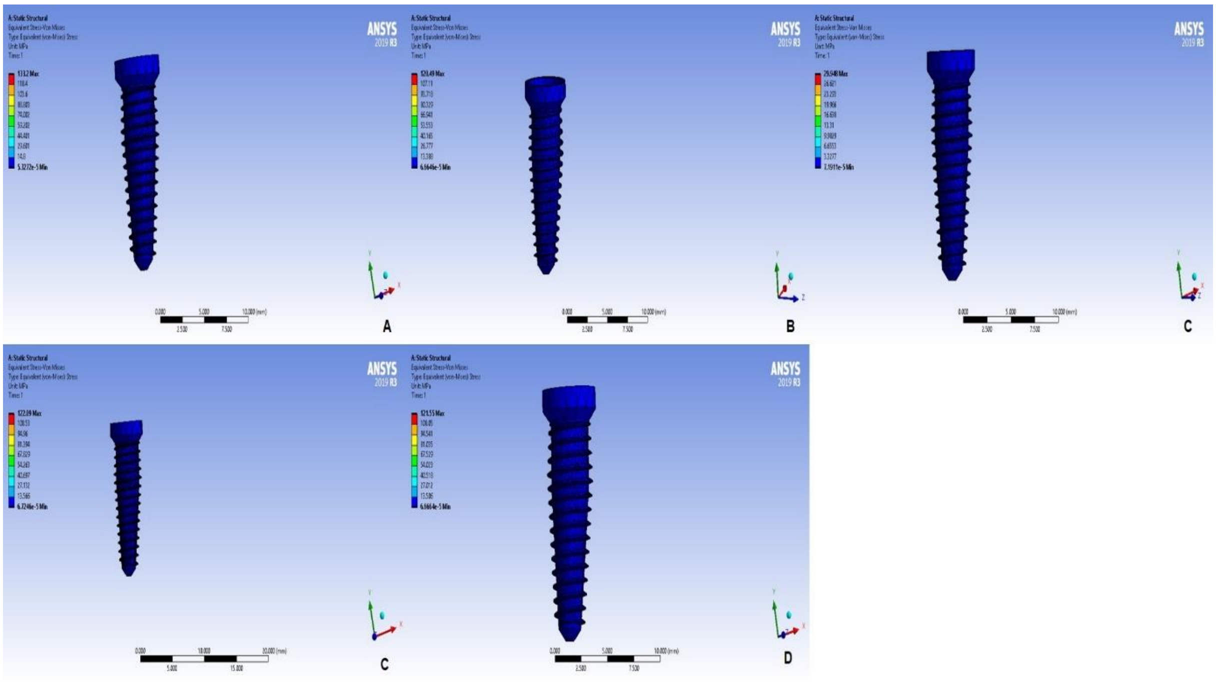


Fig. 12. Stress maps (von Mises stresses) on dental implant (AO loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A).

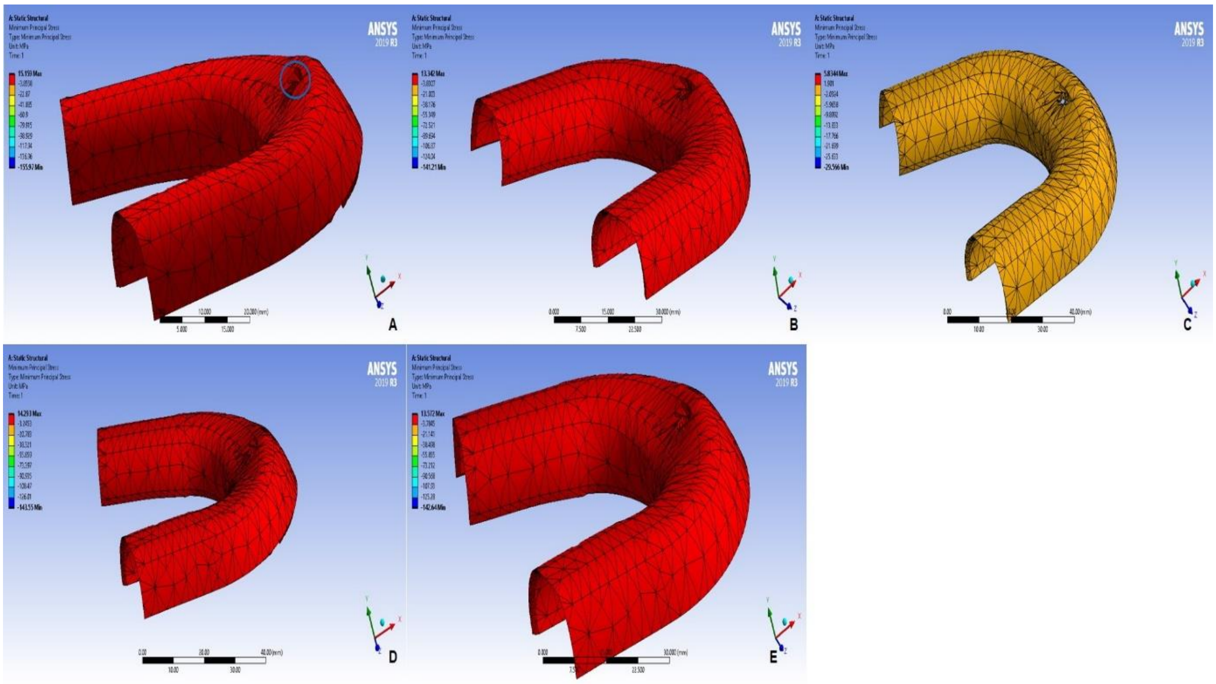


Fig. 13. Stress maps (minimum principal stresses) on mucosa (AO loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A) (blue circle represents location of measurement).

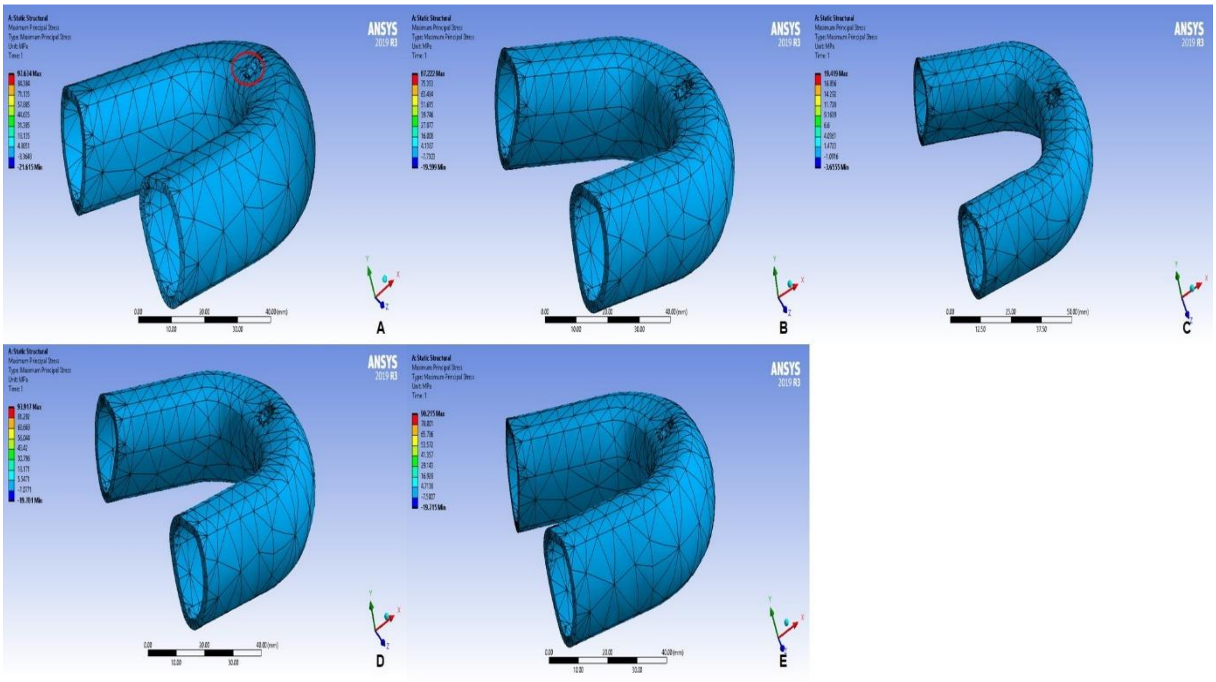


Fig. 14. Stress maps (maximum principal stresses) on cortical bone (AO loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A)(red circle represents location of measurement).

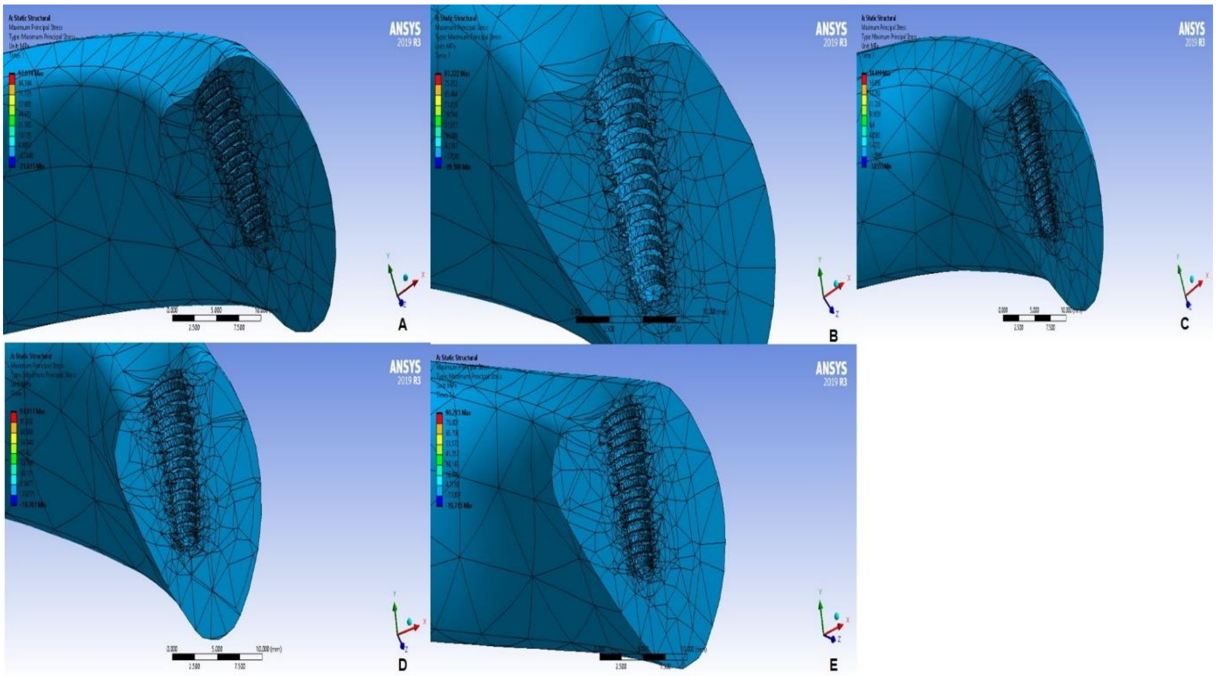


Fig. 15. Stress maps (maximum principal stresses) on cancellous bone (AO loading). A, with titanium (model M). B, with PEEK (model P). C, with silicone resilient liner (model S). D, with thermoplastic resin (model T). E, with polyacetal resin (model A).