Comparison of Finite Element and Photoelastic Stress Analysis Methods

Sonlu Elemanlar ile Fotoelastik Stres Analiz Metotlarının Karşılaştırılması

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ABSTRACT Objective: This study was intended to compare two different stress analysis methods. For this purpose stress distribution in supporting bone around an implant was evaluated by photoelastic method (PM) and finite element method (FEM). **Material and Methods:** A mandibular section of bone with a missing second premolar and an implant to receive a crown was developed. A solid 4.1 × 10-mm screw-type dental implant system and a metal-ceramic crown using Ni-Cr and feldsphatic porcelain and IPS Empress 2 crown designs were modeled. A load of 300 N was applied in a vertical direction to the buccal cusp of the crowns. The resultant stresses that developed in the supporting bone were evaluated using FEM and PM. **Results:** When the stress values and distributions on implant and cortical bone evaluated using FEM, maximum stress concentrated in the neck of implant and abutment (22 MPa and 35 MPa). Maximum stress on supporting bone concentrated at the level of cortical bone around the neck and apical region of the implant for each crown design (20.8 MPa and 35 MPa). In PM, stress located around the grooves and apex of the implant for each crown design. **Conclusion:** Both methods were gave information about stress distribution in supporting bone however more detailed information obtained about the location, type and mathematical value of stresses using FEM.

Key Words: Dental implantation, dental stress analysis, finite element analysis

ÖZET Amaç: Bu çalışma iki farklı stres analiz metodunu karşılaştırmak amacıyla yapıldı. Bu amaçla implant etrafındaki destek kemikte stres dağılımı fotoelastik metot (PM) ve sonlu elemanlar stres analiz metodu (FEM) ile değerlendirildi. **Gereç ve Yöntemler:** Kayıp bir ikinci premolar dişi içeren mandibular kemik kesitinde implant ve kron üst yapısı oluşturuldu. 4.1 mm çapında ve 10 mm uzunluğunda vida tipi dental implant sistemi ve üzerine Ni-Cr ve feldspatik porselen kullanılarak metal destekli bir kron ve IPS Empress 2 kron dizaynları modellendi. 300 N'luk bir kuvvet kronların bukkal kaspına vertikal yönde uygulandı. Destek kemikte oluşan stresler FEM ve PM kullanılarak değerlendirildi. **Bulgular:** FEM kullanılarak implant ve kortikal kemikteki stres değerleri ve dağılımı incelendiğinde, maksimum stresin implant ve abutment'ın boyun bölgesinde yoğun olduğu tespit edildi (22 MPa ve 35 MPa). Destek kemikteki maksimum stres her iki model de boyun bölgesi etrafındaki kortikal kemikte ve apikal bölgede konsantre olmuştur (20.8 MPa ve 35 MPa). PM'de, stres her iki model için de implantın yivleri etrafında ve apikalde lokalize olmuştur. **Sonuç:** Her iki metot da destek kemikteki stres dağılımı hakkında bilgi vermektedir fakat lokalizasyon, stres tipi ve matematiksel değer olarak FEM kullanıldığında daha detaylı bilgi elde edilebilmektedir.

Anahtar Kelimeler: Dental implantasyon, dental stres analizi, sonlu eleman analizi

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It's very difficult or impossible to make stress analysis in living tissues. For this reason, stress analysis studies are made in a model of living tissues. Moreover, in all analysis models, the ratio of the approximation of the model to the living tissue is important so the results are reliable.[1] Currently, in dentistry the following methods which are analysis functional strains in biological materials and treatment materials are drawn: (a) Brittle lacquer coating, (b) Photoelastic stress analysis, (c) Thermographic stress analysis, (d) Stress analysis by using strain gauges, (e) Holographic interferometer, (f) Finite element stress analysis.[1]

With the recent advances in prosthetic dentistry, it is imperative to understand the nature of stresses and strains acting on dental structures and materials. Such studies can provide better prognosis in clinical practice. Dental biomechanics is an interdisciplinary approach in which engineering principles are applied to dentistry. Studies of stress and strain are routinely done in vivo using stress analysis methods.[2] FEM and PM are the most widely used stress analysis methods to evaluate stresses in dental structures and materials.

The importance of experimental biomechanical models is to add information related to clinical situations. PM and FEM models have been used to determine bone response to external load on implants.[2-4] PM is based on the property that some transparent materials exhibit colorful patterns when submitted to loads and viewed with polarized light. This array of colored patterns is called isochromatic fringes.[1] Studies with photoelastic analysis have been thoroughly conducted to determine the stress distribution around natural teeth, abutments of removable partial prosthesis and fixed partial prosthesis around endoosseous implants under complete dentures or to determine stresses around endoosseous implants supporting fixed partial dentures (FPDs).[3,5-10]

With FEM models, the system geometry and mechanical properties of biologic tissues can be defined. The analysis provides type of stresses as well as strains.[6] The basic concept of this technique is the visualization of the actual structure, which is a continuum, as an assemblage of a finite number of discrete structural elements connected at a finite number of points. The FEs are formed by figuratively cutting the original structure into segments. [1]

Biomechanical considerations are recognized as amongst the most important factors for the long term success of the osseointegrated implant, because mechanical stresses and strains by functional loading inevitably by influence long-term peri-implant bone remodeling.[11-15] Among the methods for evaluation of implant biomechanics, two-dimensional (2D) FEM and PM have been widely used for the quantitative evaluation of such stresses and strains in the bone due to technical limitations of stress assessment in bone in vivo.[13-16] The purpose of this study was to compare two different stress analysis methods. For this purpose stress distribution in supporting bone around implant supported single unit crown was evaluated by PM and FEM.

MATERIAL AND METHODS

2-D FEM and 2-D PM simulating implant-supported single unit mandibular premolar crown was used in this study. A one-piece (ITI implant with an a solid abutment tightened on the implant) 4.1 x 10 mm screw shape dental implant system (solid implant) (ITI, Instut Straumann AG, Waldenburg, Switzerland) was selected. Two different occlusal materials used in implant supported FPDs were; IPS Empress 2 crown design, porcelain fused base metal (Ni-Cr) crown design (PFBM) (Table 1).

Metal substructure thickness was 0.8 mm and superstructure thickness was 2 mm for both crown designs. Cement thickness was ignored.[5] Based on a previous report pertaining to FPDs supported by implants, the avarage of maximum occlusal force was approximately 200 N for first premolar and molars, and 300 N for second premolars.[17,18] Therefore, an average biting force of 300 N was selected considering these values. A total vertical force of 300 N was applied on buccal cusp.[17] The geometry of the crown model has been sketched according to mesiodistal cross section of crown used at PM. The applied forces were static. In FEM, a mandibular bone model was selected; simulating type II bone, according to the classification system by Lekholm and Zarb.[19] The implant geometry was sketched according to dimension values acquired from manufacturer at computer environment.

All materials were presumed to be linear elastic, homogenous and isotropic.[20,21] The corresponding elastic properties such as Young's modulus and

TABLE 1: Occlusal surface materials used in implant supported fixed prosthesis.

Occlusal surface material	Framework material	Manufacturer
PFBM	Co-Cr	Wiron 99, Bego, Bremen, Germany
IPS Empress 2	Lithium disilicate glass ceramic core	Ivoclar Vivadent, Schaan, Lichtenstein

Poisson ratio were determined from a literature survey, and are summarized in Table 2.[22-25] In total, the model consisted of 2168 nodes and 2312 elements. The final element on x-axis for each design was assumed to be fixed which defined boundary condition.[26,27] Elastic modulus and Poisson's ratio of the materials, along with the coordinate and geometry of each node and element, were entered to a computer. The mesh view of the model was obtained (Figure 1B). By using SAP 2000 structural analysis program Nonlinear Version 7,12 (Computer and Structures Inc, Berkley, CA, USA) was used to solve the stress analysis problems.

Calculated numeric data were transformed into color graphics to better visualize mechanical phenomena in the models.[28,29] Stress values were evaluated for each design (IPS Empress 2, PFBM crown designs).

In PM, after the location for implant was selected, a hole which was suitable for ITI solid screw implant (4.1 mm in diameter, 10 mm in length) was prepared with the aid of a periscope (Bego, Bremer Goldschlägerei Wihl, Herbst GmbH and Company, Bremen, Germany). A screw shape implant was placed on this hole and fixed with wax (Polywax, Bilkim Chemical Company, İzmir, Turkey). A polysiloxane silicon–based impression material (Zetaplus, Zhermack, Italy) was used to make an impression of the mandibular model. PL-2 (Measurments Group, Inc. Raleigh, NC) epoxy resin and PLH-2 activator were used to simulate body of the mandible. Per product directions, the resins were weighed in different glasses and placed in the drying oven with the cast, which was made of elastomeric impression material and heated to 46°C to 52°C. This process reduced the viscosity of the resin and with the help of the activator resulted in a more homogeneous mixture.

TABLE 2: Material properties.

Crown Design	Material	E (MPa)	V	Reference
	Titanium	110000	0.35	17, 24
	Compact bone	13800	0.30	17,24, 26
	Trabeculer bone	1380	0.30	17,24,26
PFBM	Porcelain	82800	0.35	24, 25
	Framework	206000	0.33	24, 25
IPS Empress 2	Porcelain	60000	0.23	25
	Framework	96000	0.25	25

E= Young's modulus, v= Poisson ratio

During mixing, the heat expelled as a result of the exothermic chemical reaction was observed with use of a thermometer placed in the resin. When the heat of the resin reached 55°C, the resin was poured slowly into the cast, which had been prepared and heated to 46°C to 52°C. To complete polymerization, the resin was kept at room temperature for 18 hours. After polymerization, the model was removed from the cast, finished, and polished. Abutments were placed and tightened 35 Ncm with ratchet with torque control device (ITI, Instut Straumann AG, Waldenburg, Switzerland) and SCS screwdriver (ITI, Instut Straumann AG, Waldenburg, Switzerland). Conventional restorative techniques were used fabricate the FPDs at average size according to the Wheeler Specifications and remained uncemented (PFBM and IPS Empress 2 crown design).[22]

The model made of photoelastic resin had an 10 mm buccolingual width, 35 mm occlusal cervical height, 20 mm mesiodistal length (Figure 1A). The restorations were evaluated for passivity of fit on the model by placing the restorations on the photoelastic model and examining for stress in field of a polariscope (Measurments Group, Instruments Division Raleigh, NC).[1] The polariscope revealed the presence of any stress within the model. No stress was observed, confirming passivity. 300 N force was applied on buccal cusp. The model was immersed in a tank of mineral oil to minimize surface refraction and thereby facilitate photoelastic observation. As a result of these, the fringe order (stress lines) created on the model was watched in

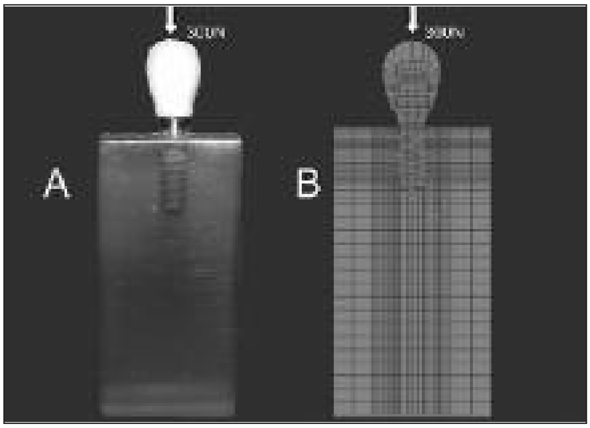

FIGURE 1: A, Photoelastic model. B, Mesh view of the FE model.

color by using white light in a polariscope machine. Color photographs were taken with a mounted camera (Nikon Coolpix E995, Japan) on to the polariscope with 30 cm standard distance and 90 degrees angle from the model.

Each fringe represented a stress level and for analysis, two factors were considered, According to French et al.[2,8,30]: (1) The larger the number of fringes, the higher the stress magnitude, (2) the closer the fringes were to each other, the higher the stress concentration.

RESULTS

RESULTS OF FEM

Stress values were evaluated on the main model and on the bone for each design:

A1) Stress distribution on the main model of IPS Empress 2 FPD design:

a) In IPS Empress 2 FPD design, when the stress values and distributions on porcelain structure were evaluated, maximum compressive stress was accumulated in buccal cusp. Maximum stress value was 22 MPa in this area. When the stress values and distributions on framework were evaluated, maximum tensile stress was localized in buccal tubercule. Maximum stress value was 35 MPa in this area. When the stress values and distributions in implant were evaluated, tensile stresses attract attention to decrease towards the 2/3 of the abutment's body and maximum tensile stress value was observed in the coronal 1/3 of the abutment and maximum stress value was 35 MPa in this area. Maximum compressive stress was accumulated in the neck of the implant and maximum stress value was 22 MPa in this area (Figure 2A). When the stress values and distributions on bone were evaluated, maximum tensile stress on supporting bone was concentrated around the grooves of the implant and maximum stress values were 20,8 MPa, and 35 MPa (Figure 3A).

b) Figure 4A shows the values and distributions of von Mises stresses.Von Mises stresses are most commonly reported in FE analysis studies to summarize the overall stress state at a point. Maximum von Misses stress was accumulated in the buccal cusp of the porcelain and framework. Also, in the neck of the implant von Misses stress values were increased. There were a homogeneous stress distribution in the supporting bone.

c) Figure 5A shows displacement in IPS Empress 2 FPD design. Ghost image is undeformed shape and colored image is deformed shape.

A2) Stress distribution on the bone of IPS Empress 2 crown design: When the stress distribution on the bone were evaluated, maximum compressive stresses were accumulated in the coronal part of the implant's socket and in the apical region of the implant. Maximum tensile stresses were noted on the lateral walls of the implant socket (Figure 3B).

B) Stress distribution of PFBM crown design: The localization and mathematical values of all stress types (compressive, tensile, shear) were sim-

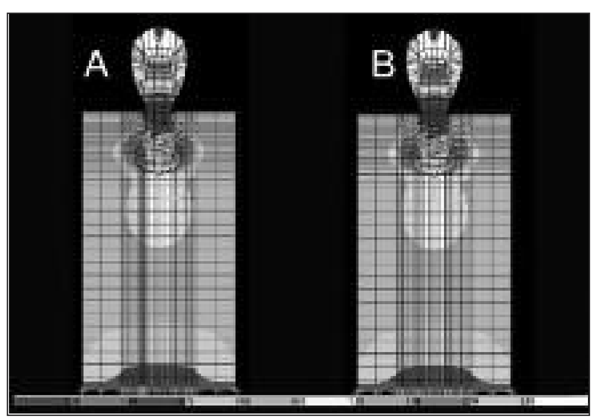

FIGURE 2: Distribution of tensile and compressive stresses. A, Witin the main model of IPS Empress 2. B, Within the main model of PFBM.

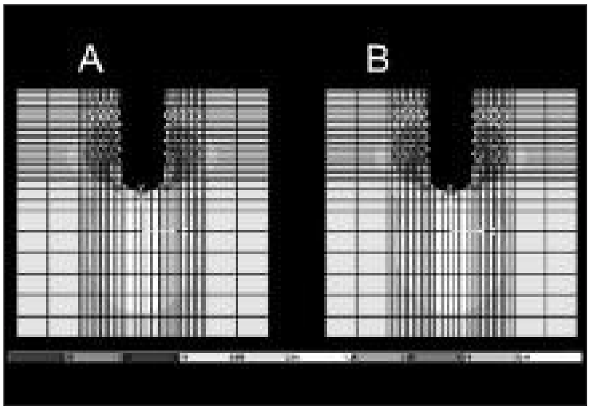

FIGURE 3: (A) Distribution of shear stresses within the main model of IPS Empress 2, (B) Distribution of shear stresses within the main model of PFBM.

ilar to IPS Empress crown design on implant and supporting bone (Figure 2B, 3B, 4B). When the stress localizations and values in abutment and porcelain crown structure were compared with IPS Empress 2 crown design, stresses were more spread in the abutment and the stress values were higher than IPS Empress 2 crown design (Figure 2, 3, and 4B). Figure 5B shows displacement in PFBM crown design.

RESULTS OF THE PM

Observing the photographic records of the models without load application, fringes were not observed in the photoelastic resin model, which indicates the absence of tension.[8,30]

In the presentation of the stress data below, the following terminology has been adopted: (a) low stress- 1 fringe or less; (b) moderate stress- between 1 and 3 fringes; and (c) high stress- more than 3 fringes (Figure 6).[31]

Due to the limitations of the technique, only the photoelastic material which simulates the supporting bone can be evaluated. The same vertical load was applied on the two different materials, and differences between observed stresses were noted. Moderate stresses (3 fringes) were observed around the grooves and apical region of the implant. Both PFBM and IPS Empress 2 crown designs, as a result of vertical loads, an equivalent amount of stress was observed in the bone (Figure 7A, B).

DISCUSSION

FEM and PM models have been used extensively to study the biomechanics of stress transfer in dentistry; however, both methods have some limitations inherently. In PM, the resin which is used to simulate bone has different homogeneity and isotropic characteristics than does actual boner The FEM program used in this investigation also has several limitations with respect to unrealistic simulation of material properties of the structure. The program assumes that the bone is homogeneous, linear-elastic and isotropic. Furthermore, both methods assume that the bonding of the bone and the implant is perfect and all static mastication forces applied to implant supported fixed partial denture was loaded axially in this study. However, the mastication forces are dynamic and oblique relative to

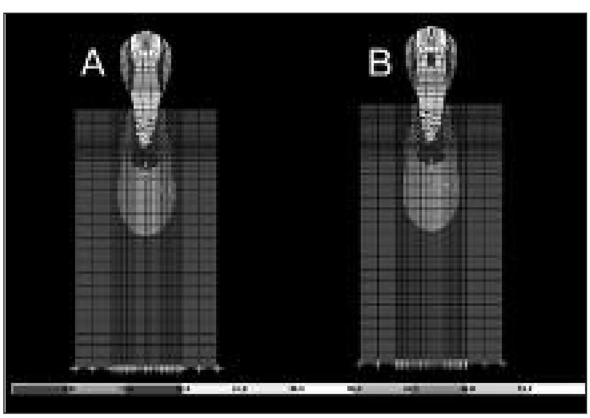

FIGURE 4: Distribution of tensile and compressive stresses: (A) Within the bone model of IPS Empress 2, (B) Within the bone model of PFBM.

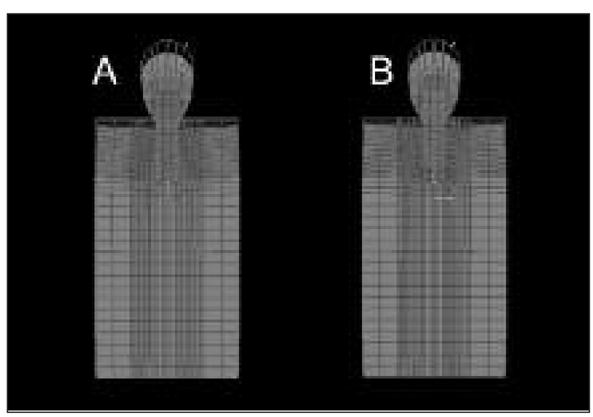

FIGURE 5: (A) Deplasmans within the main model of IPS Empress 2 (B) Deplasmans within the main model of PFBM.

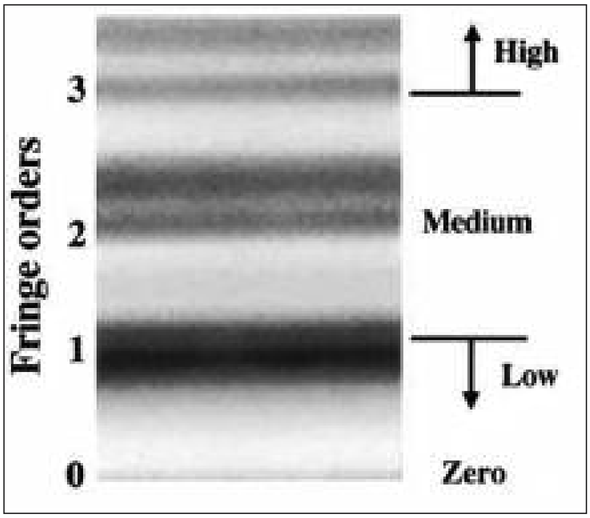

FIGURE 6: Relation between stress level and fringe order used to describe results.

the occlusal surface of the implant supported FPDs, and the interface between the implant and the bone is dynamic in reality. Consequently, it is usually impossible to reproduce all the details of natural behavior. Due to these limitations, the values obtained in this study may not resemble actual values but, at most, these may show the stress differences.[32]

In the 2D systems, it is assumed that out-of-plane deformations, strains, and stresses are negligible. This may reduce the cost of analysis, but it also introduces more error due to the assumed artificial boundary conditions.[33] Recently, 3D models have been preferred because more realistic results can be obtained.[33,34-39] To date, the 2D method has been used when numerous, varied models and designs are evaluated in the literature.[40-48] As one model and two crown designs were analyzed in this study, 2D models were decided to use for both methods.

In PM, it is not possible to model all the mechanical properties of a structural element. Photoelastic imitators were used in PM. Consequently a decision must be made as to which properties are most pertinent to the clinical problem at hand. In general, selecting of photoelastic materials for prostheses and tissue modeling is based on relative modulus values.[1] The ratio of moduli of bone imitator selected from available photoelastic materials, are not identical to the reported natural tissue ratio. Furthermore, use of these materials with corresponding moduli has been shown to be predictive of clinical behavior.[1] In FEM each element retains the mechanical characteristics of the original structure.[1] This is an advantage of the FEM over PM.

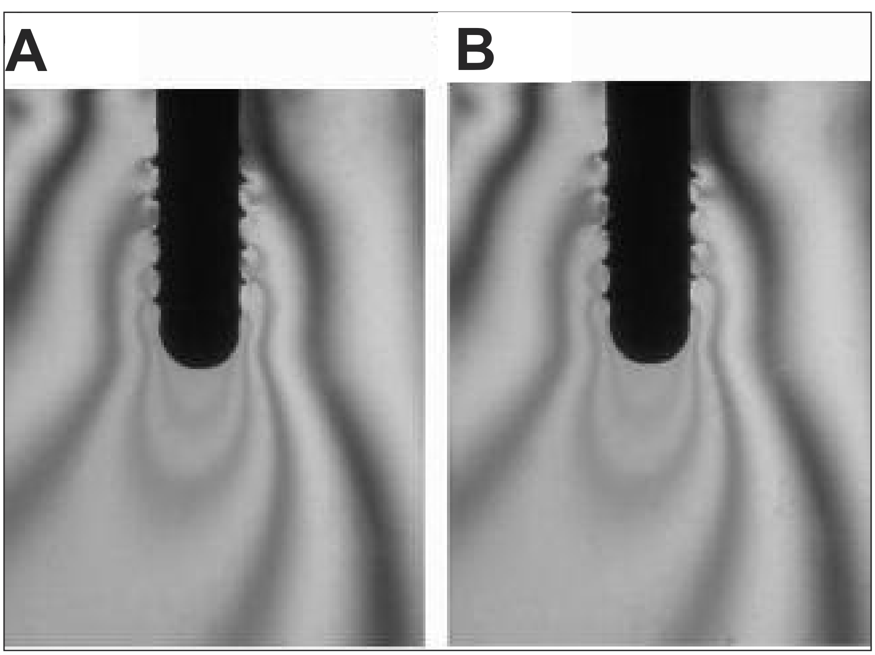

FIGURE 7: Distribution of stresses in photoelastic model (A) IPS Empress 2 crown design, (B) PFBM.

FEM provides type of stresses as well as strains. When FE models of screw type implants were studied, tensile, compressive stresses were shown to develop at different locations in the bone around the implant.[6] In PM, isochromatic fringes were gave information about the stresses develop at different locations in the bone around the implant. In the light of these knowledge, FEM can be concluded a more detailed stress analysis method than PM.

However 2D PM has many advantages. These; (1) it is easy to fabricate the models, (2) a wide variety of loading conditions can be applied to the model and (3) different appliances may be tested on the same model. The technique suffers the major disadvantage of imperfectly reproducing the three-dimensional geometry of the oral situation. Consequently, the full 3D stress distribution cannot be determined.

Qualitatively, a similar stress distribution was determined on the bone-implant interface from both techniques. In FEM, PFBM porcelain crown design showed the higher stress localization. The high stress value in porcelain was the result of the force applying structure. When the framework was investigated, stress localizations were different for each model. The reason of these differences may result from the different elasticity modulus of the occlusal materials. Structural differences in porcelain and frameworks affected the stress distribution in implant and bone structure. When the stress distribution in supporting bone was investigated, no differences were found among two different designs. It was concluded in several FEM studies, using more rigid or resilient material for the superstructure of an implant supported partial dentures did not have any effect on stress distribution and stress values at the bone tissue surrounding implant.[4,16,21] However, in the abutment and crown structure, stress distributions and localizations were affected by the material rigidity.[21] In this study, the reason of using two different occlusal materials was to strengthened our basis and decrease mistake ratio to minimum when comparing two different stress analysis methods.

In the present study, in IPS Empress 2 and PFBM, as a result of vertical loads, an equivalent amount of stress was observed in the bone for each stress analysis methods. When the stress distribution on the bone and implant were evaluated for both techniques, maximum stress localizations were accumulated in the neck and apical region of the implant, and in the coronal and apical part of implant's socket. Also stress localizations were noted in the bone around the implants' grooves. Because the round-end nature of ITI implant apex decreased magnitude and concentration of stresses in the apical region, higher stress gradients were observed in the vicinity of the threads.[18] Nevertheless, this situation has not been reported to lead to bone loss at the tips of its threads. On the contrary, this property may decrease the amount of force transferred to the apical part of the implant under axial loading.[16]

In both stress analysis methods, the high stress concentration found around the neck of implant in supporting bone should be considered. Clinical studies show that bone resorption occurs around the coronal zone of the implant.[21-24] Therefore; it can be assumed that this phenomenon is related to applied moments, influencing the bone crest. To avoid high stresses at that location, the implant should be planed to be subjected to vertical forces during function.[27] Moreover, since in clinical situations no optimal control of loading type can be achieved as in an in vitro study, the bending moments could be even higher.[26] This situation is more pronounced when the compact bone at the neck of the implant is considered compared with much less rigid bone in other areas. When more accurate mechanical properties, defining these differences in bone type were introduced to FE models, higher stresses were developed at the coronal zone.

Stress transfer at the bone–implant interface depends on the; occlusal relationship. type of loading; material properties of the implant and prosthesis; nature of the bone–implant interface; quality and quantity of the surrounding bone; implant geometry, length and diameter as well as shape; implant surface structure.[49,50] One can only understand the influence of these clinically relevant parameters when time-dependent bone reactions around oral implants are examined under well-controlled in vivo load experiments.

Current study showed that more accurate and realistic models can be provided with FEM when comparing to PM. Because computer programs are developing day by day and it is possible to form accurate models of living tissues. And currently FEM analysis techniques have been used extensively in dentistry. FE models are said to be an actual representation of stress behavior in supporting bone.[23] Also PM gave the location and intensity of stress concentrations. This information can indicate areas of structural weakness and potential failure due to either fracture or exceeding the yield strength of the material.

For long term success of the restorations, knowledge about stress distribution around dental materials or tissues under loading forces is necessary. FEM and PM were gave similar stress localizations in supporting bone. Therefore, the results of FEM and PM were supported each other.

However the limitations of the FEM and PM must be considered for this reason clinical trials and laboratory studies are still required to determine the stress distribution and localization in models.

CONCLUSION

Within the limitations of this study, the following conclusions were drawn;

1. Both methods gave information about stress distribution in supporting bone however more detailed information was obtained about the location, type and mathematical value of stresses using FE method.

2. In both of the techniques (FEM and PM) the stress distributions on cortical bone were concentrated at the level of cortical bone around the neck of the implant, and in the apical region of the implant for each designs (IPS Empress and PFBM).

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