Effect of bone quality and osseointegration on stress distribution in the bone tissue surrounding dental implant: a finite element analysis

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ABSTRACT

Aims Dental implant surgeries are considered to be a stable cure-all to restore a missed tooth as a distinct prosthetic reconstructing method. FEA was employed to find the stress distribution in the area of the implant-bone and bone separately in different bone qualities and four different bone-implant contact rates. The aim of this study was to investigate the effect of bone quality and osseointegration rate on the bone region stress distribution.
Materials and methods In this study, using periapical radiography (PA) images, osseointegrated patterns in the bone-implant interface were diagnosed via image processing software. Four rates of 100, 70, 50 and 30 percent of bone-implant contact were modeled. Applying Lekholm's classification of bone quality on the above-mentioned geometries, final models were achieved. Afterward, finite element analysis was implemented to investigate the stress distribution at the bone-implant interface during occlusal loading.
Results The von-mises stress distribution represented the effect of the osseointegration in all bone types of the implant-bone domain. Also, the comparison of incomplete osseointegration (i.e., 30%, 50%, and 70%) with the ideal case of complete osseointegrated implant indicated the importance of higher osseointegration on the final stability. Lower bone qualities showed higher stress in the crest area of cortical bone which leads to de-osseointegration.
Conclusions The contribution of bone quality to the stability of the implant was greater than the osseointegration rate but the rate of osseointegration can play an important role in the rate of stress that progresses to the apical and creates corrosion around the implant-bone contact.

KEYWORDS Bone quality, dental implant, finite element analysis, osseointegration, stress distribution

INTRODUCTION

Dental implants are one of the most common treatments in dentistry to replace the missing tooth root (1, 2). In this treatment, the fabricated crown is usually cemented or screwed on the abutment which is fixed with a screw to the implant which is placed in the jaw bone (3). Therefore, the masticatory forces lead to the distribution of stress in the implant and the bone tissue surrounding the implant. The stress transmission between implant and bone happens on the connecting surface. This force is applied immediately after attaching the crown to the abutment and loading the implant. Generally, after surgery and implant placement, there are two strategies for attaching the prosthesis and completing the treatment; one is immediate loading and the other is delayed loading after the healing period. In the delayed strategy, the diversity of the osseointegration process during the healing period for each patient causes the bone contact with the implant to be different. In this way, direct contact between bone and implant is the result of osseointegration process and the percentage of this bone formation in contact with the implant surface indicates the osseointegration quality (1, 4-6). Since an implant never achieves 100% osseointegration, several percentages are reported for dental implants from 30% to 80%, approximately. In almost all the previous studies investigating the stress distribution related to dental implant, the bone to implant contact is assumed as 100% osseointegration. Therefore, the significance of the percentage of osseointegration has not yet been investigated in computer simulation studies. Besides, dental implant osseointegration patterns (which describe the actual surface of the implant involved in the integration) are also important in the stress distribution. Therefore, the conditions of the simulated model of dental implant and bone are considered as an important part of investigating the stress distribution in the jawbone (7-9).

Stress filed is being calculated using constitutive model and finite elasticity equations. Then investigating the stress distribution throughout the geometry makes it possible to find the stress-concentrated regions. Stress concentration at the critical locations of the surgery site leads to micro-fracture and bone resorption, while it originates from the non-uniform material property distribution throughout the surgery environment. Bone quality and osseointegration have high importance in tolerating the transferred load from crown to the implant environment (10, 11). Some researchers believe that through decrement in the bone density, the prevailing stress on the bone would be lower, where this is estimated to be due to the inadequate applied stress on bone tissue (2, 12, 13). The mandible or maxilla quality around the implant is another characteristic that affects the stress distribution and consequently contributes to the enhanced bone remodeling that is important for the performance of implantation surgery. Due to the difference in spongy bone density between the four types of jawbones, this issue can highlight the effect of reducing the percentage of contact on the stress distribution (14, 15). The quality of osseointegration in lower bone densities is more important than in higher bone densities since the weak bone raises the need for more contact to support the implant across the masticatory forces (16, 17). Higher levels of bone density would help the stability of the implant that is surgically placed in the jawbone. Four bone types that are typically classified by Lekholm based on bone qualities are presented in (Fig. 1), which could be considered as a norm for assessing the patients. Researchers suggest that the bone quality within its current classification directly affects the stability of the placed implant in the jawbone (18).

Since the implant's mechanical and biological behavior is different from the natural teeth, simulation models are developed to investigate the stability of the implant (19). It is valuable to have tools to easily and immediately investigate the aspects of dental implant performance. Finite element analysis as a powerful tool in modeling and simulation has supported a wide range of mechanical and biological studies in this field to investigate a variety of features in dental implants (3, 20-24). In most of the studies investigating the mechanical stability of the implant, the ideal case of 100% osseointegration has been considered (4, 19). A very limited number of researchers have addressed this issue that the ideal case of complete osseointegration might not be always the right assumption in modeling. Although most dental implant models and FEA studies have assumed that bone to implant contact is 100%, osseointegration should also be considered as one of the interventions to the results in the context of bone remodeling examination and micro-displacement evaluation.

The purpose of the current study was to investigate the simultaneous effect of osseointegration and bone quality on the implant-bone stress distribution through a two-dimensional (2D) finite element analysis. In this way, a dental implant system was used to investigate the stress distribution under an oblique force in cases of completely or partially osseointegrated implants in four classical bones types.

MATERIALS AND METHODS

At first, two-dimensional model of the Avita dental implant was designed in SolidWorks. Then, four bone types were considered and their material properties were devoted according to Lekholm's classification (25). In most dental implant analyses, implant-bone contact is considered to be bonded. Therefore, the idea of examining osseointegration in each bone quality was put on the agenda from another aspect (11, 25). Since the osseointegration is referred to the contact of bone cells to the implant, the PA images of patients were used to model the osseointegration. In this way, the pattern of osseointegration in the first layer of implant contact with bone was determined (26) which is shown in (Fig. 2). Then, according to the pattern of osseointegration, four different values of 30%, 50%, 70%, and, 100% of implant contact interface with bone were considered, and according to four bone qualities, the 16 final models were used in finite element analyses.

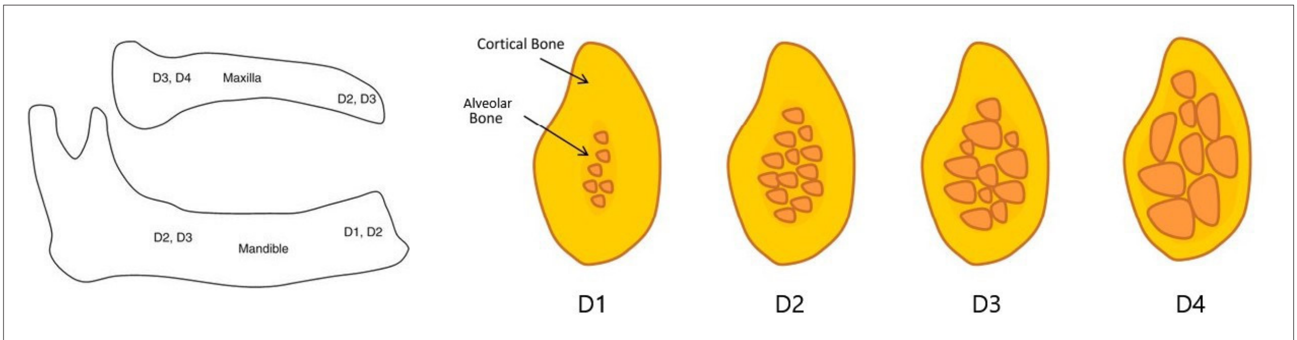

FIG. 1 Jaw bone classification; on the left, the schematic model of the jawbone and the different bone qualities in each area are shown, on the right, D1 to D4 bone qualities are presented. In D1 about 90% of the bone includes cortical bone, while the ratio of cortical to alveolar bone gradually decreases in D2 and D3, and finally, a thin layer of cortical bone is around the alveolar bone in D4.

Domain		E, Module of Elasticity (GPa)	ν, Poisson Ratio	Density (Kg/m^3)	Reference
Dental Implant		110	0.34	4510	[9, 26, 28]
Implant Crown		69	0.28	2500	[8, 27]
Cortical Bone		13.7	0.3	1800	[13, 15]
Alveolar Bone	D1	1.37	0.3	1200	[15]
	D2	0.8	0.3	900	[9, 26, 28]
	D3	0.5	0.3	450	[27]
	D4	0.38	0.3	300	[13]

TABLE 1 Material properties assigned to the models.

The acquired PA images were converted into Drawing Exchange Format (DXF) and subsequently used in the finite element analysis (FEA). Image processing was performed using ImageJ software to acquire osseointegration pattern. One DXF model of an AVITA dental implant was used in this study (diameter 4.0 mm and length 14.0 mm). The implant geometry was created in SolidWorks (Dassault Systems, France) and was subsequently virtually placed into the DXF models of the scanned bone blocks. Bone cases were modeled according to the cortical to alveolar ratio that includes: I) 90%-10%, II) 60%-40%, III) 40%-60%, and IV) 10%-90%. These models were then exported to COMSOL commercial software and stress distribution was computed under an oblique load of 100 N applied on the crown (27).

The data was collected from the clinical investigation of the Avita dental implant system conducted at the Dental Implants Research Center at Tehran University of Medical Science. As osseointegration is one of the most important characteristics in the stability of the implants, and as a well-defined representative for the success of surgery, follow-up PA of the patients was used to monitor these parameters. From PA images, partial osseointegration of 70%, 50%, and 30% were extracted to make DXF models and were compared to the ideal case of full osseointegration (26).

Four bone types were used in this simulation and each bone type was assigned specific material properties Table 1. For different bone types, different Young modulus and density with the assumption of isotropic were defined. According to the literature, the most common bite force applied to the crown is between 100 N and 250 N, where 100 N was usually applied with an angle of 30 degrees (24, 28, 29). Then, in this study an oblique force of 100 N was applied to the crown (Fig. 3). The cortical bone is considered to be fixed at the apical side. Three contacts were defined in this model; the first was the contact between the bones, the second was the contact between the implant-abutment-screw, and the last was the implant and bone interface. All the mentioned contacts were considered to be bonded or frictionless (8, 27).

To mesh the prepared geometry of the developed models, triangular elements with a standard setup were used in COMSOL. The number of elements depended on the percent of the osseointegration and was about 130,000 in the 100% and 90,000 in the 30%. The average number of elements in all the 16 developed models was about 106,000. Then, the finite element method was used to analyze the models of this study, using deformation, strain, and stress tensors.

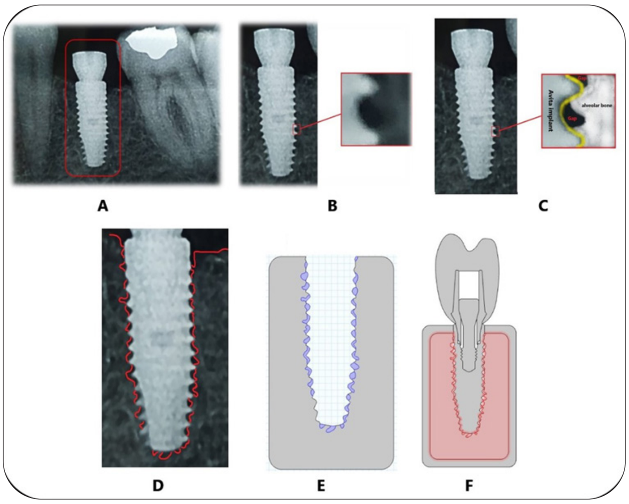

FIG. 2 The procedure of extracting the osseointegration pattern from the PA images; A: implant placed in the mandible, B: the magnification of periapical radiography, C: expected results of segmentation, D: the osseointegration pattern, E and F: simulated geometry that was modeled in SolidWorks.

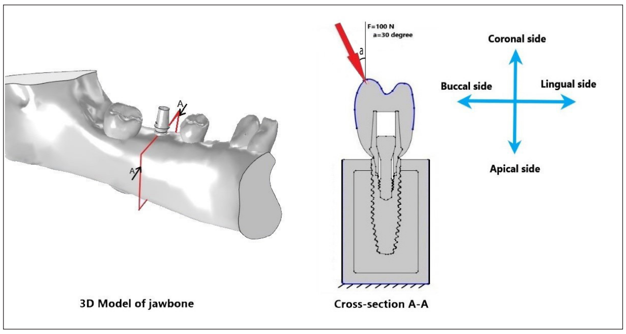

FIG. 3 Loading and boundary conditions of the 2D model at A-A cross-section from 3D jawbone.

RESULTS

The results of stress distribution in all the developed models are provided in Figure 4 and 5. The von Mises stress and stress distribution plots are compared between the 16 differ-

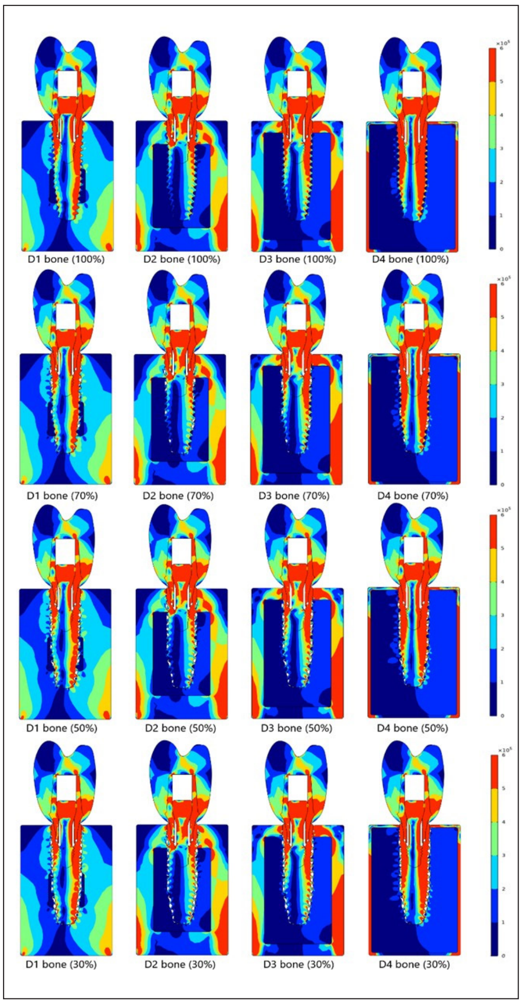

FIG. 4 Stress distribution in the jaw bone and the implant for 16 developed models including D1-D4 bone qualities and 30%, 50%, 70%, and 100% bone to implant contact as the quality of the osseointegration.

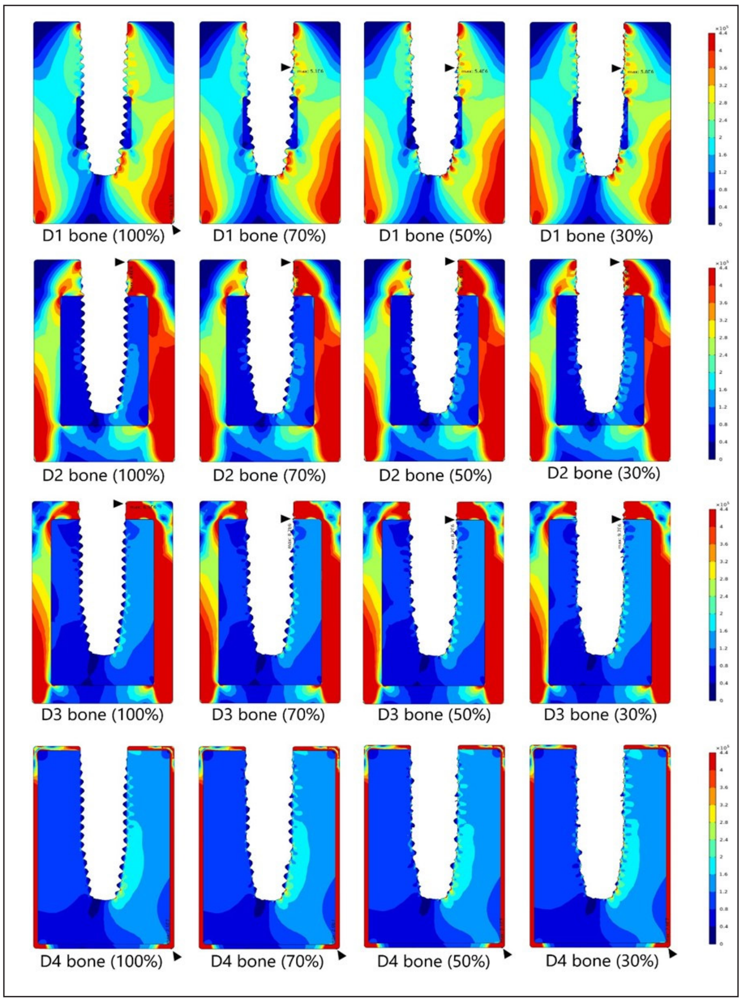

FIG. 5 Stress distribution in the cortical and alveolar bone for 16 developed models including D1-D4 bone qualities and 30%, 50%, 70%, and 100% bone to implant contact as the quality of the osseointegration. The black arrows indicate the maximum von Mises stress in each model.

ent models. The 2D von Mises stress distributions in different bone types are presented for 100, 70, 50, and, 30 percentages of osseointegration (Fig. 4). According to the effect of the stress scale bar of the plots presented in the (Fig. 4) on the visualization of stress distribution, the maximum stress was set to 440 KPa in the (Fig. 5) to see the stress distribution pattern in alveolar bone.

As the bone quality differs from D1 to D4, at all osseointegration percentages, the area indicating stress value over 500 KPa was increased and progressed along the coronal-apical axis of the implant towards the implant apex (Fig. 4). Besides, the cortical bone contact to implant in D1 was different from other bone qualities that resulted in greater stress applied to the bone around the apical threads of the implant (Fig. 5). Therefore, bone quality affected the stress distribution in both the implant and the surrounding bone and consequently could have an impact on the mechanical stability and micro movement of dental implants.

The results of this study indicated that in D1 bone quality, the stress in implant-bone interface was concentrated in the crestal bone (Fig. 5). In D2, D3, and D4 bone quality as the cortical bone is thinner than D1, the maximum stress was increased by about 48%, 122%, and 577% respectively in full osseointegration case.

The distribution of von Mises stress in the top line of the cortical bone of the four jaw bone qualities is presented in (Fig. 6). The maximum value of von Mises stress was observed around the implant neck in all the models. In addition, the maximum stress in D4 was obviously greater than other bone qualities. In each bone quality, the maximum stress was higher in the 30% osseointegration (16 MPa) compared to the ideal condition of 100% osseointegration (14 MPa).

DISCUSSION

The success of dental implant placement is related to stress distribution in the supporting bone. Finite element analysis

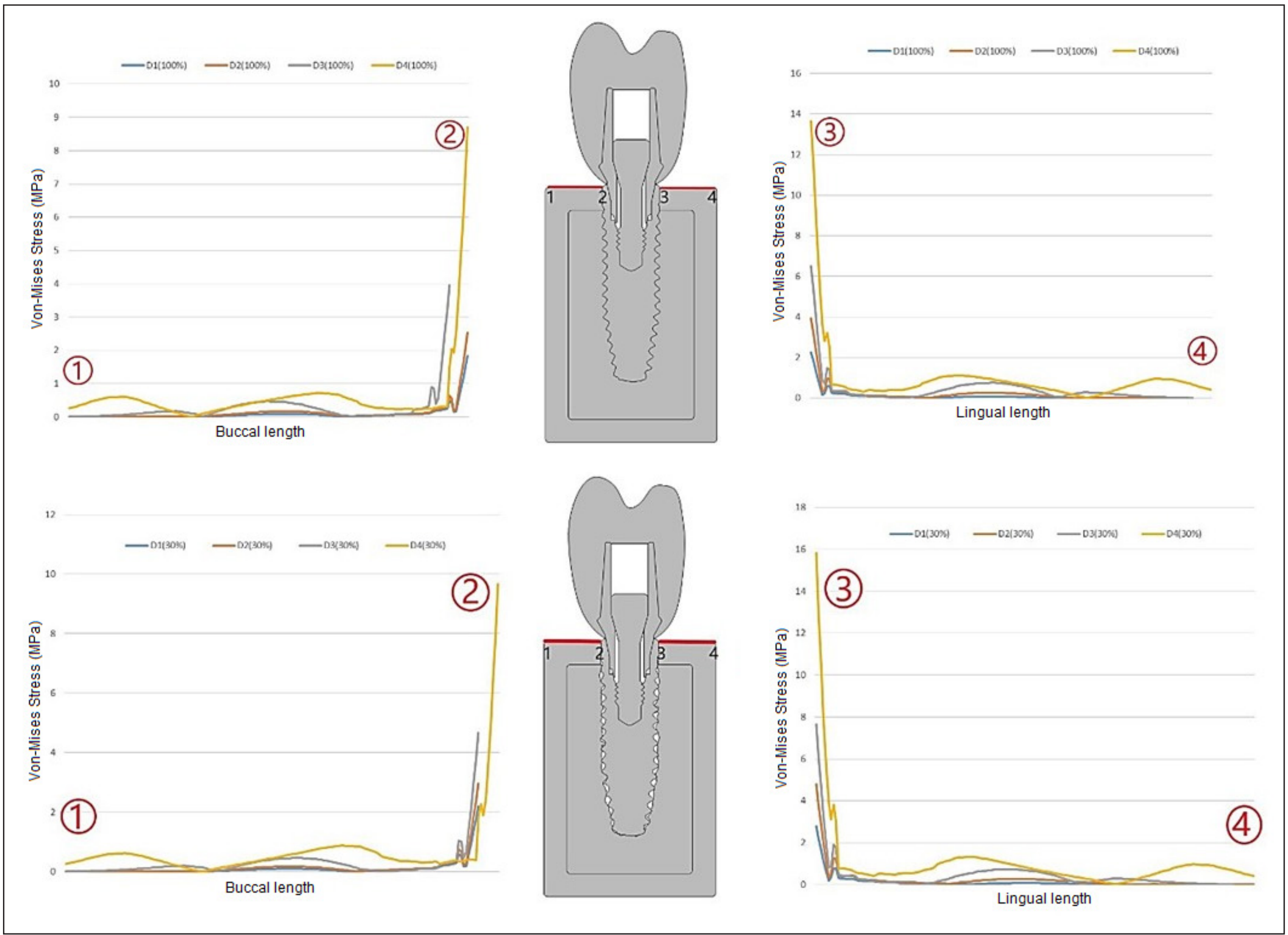

FIG. 6 The von Mises stress on cortical bone in different bone qualities for 100% osseointegration (top) and 30% osseointegration (bottom).

is a well-known method for investigation of the stress distribution in jaw bone and dental implant. The assumptions of the modeling procedure can highly affect the simulation results. Therefore, model geometry, material properties, loading conditions, quality of bone, and bone to implant contact are considered as affecting variables to achieve reliable FEA results. However, in most of the previous studies, the bone quality and bone to implant contact known as BIC were not thoroughly considered in the analysis, and thus the effects of these variables were not studied well in the FEA simulations (13, 30). In this study, the contact between jaw bone and dental implant was extracted from periapical images to investigate the effect of osseointegration on the stress distribution. In addition, the effect of bone quality, i.e. the ratio of cortical bone to alveolar bone, was considered in the developed models for the finite element analysis as well. The purpose of the current study was to investigate the simultaneous effect of osseointegration and bone quality on the stress distribution in bone and implant via a 2D-FEA.

In this study, for D1-D3 models the highest stress concentration was observed in the cortical bone around the neck of implant which is in agreement with previous studies Hingsammer et al. while for D4 bone type the highest stress concentration was found in the apical side of the cortical bone (31). The maximum stress values for D1, D2, and D3 bone types were between 2 MPa to 9 MPa, while for D4 bone type it was greater than 13 MPa. Besides, the stress distributions were different between the four bone types that indicated the effect of bone type on the results of FEA that is in agreement with the findings of Sunil & Dhatrak. (5). However, in most of the previous dental implant FEA studies, the bone type was not separately defined and independent analysis on one specific bone type can be rarely found (31). Therefore, we strongly suggest for future studies to consider the bone type in their simulations. When bone quality varies from D1 to D4, the cortical bone becomes thinner and the risk of cortical bone fracture in the crest zone increases due to stress concentration (19). The fracture or even the crack propagation in the crestal bone leads to greater stress values in the alveolar bone which could ultimately results in implant failure. An intensified stress concentration in the alveolar bone region increases the probability of micro-cracks formation and the risk of fracture would increase. The schematic geometry of cortical and alveolar bone was a limitation of this study. Since in reality, the material properties and bone density change in gradient direction, and there is no sudden change or definite boundary between these two materials to define their properties (10, 14, 18). Although the strain

is considered to be a continuous field, this discontinuity in stress distribution at the boundary between the cortical bone and the alveolar bone originated from the difference in material properties assigned to the schematic geometries. In addition, the results of this study indicated that the stress near the lingual apical region of the implant was increased due to reduction of bone to implant contact in each bone quality. This concentrated von Mises stress was generally about 2 MPa that is lower than the findings of Dhatrak et al. that indicated 6 MPa for shear stress in a reverse buttress threaded implant that is similar to the model implemented in this study (27). This difference could be a result of different loading (oblique force of 100 N vs. vertical 300 N) and boundary conditions (frictionless bonded vs. frictional contact) in these studies. Besides, in the current study, the stress near the buccal apical region was about 1 MPa that is in agreement with results of Dhatrak et al. that showed about 1 MPa stress distribution in the alveolar bone (27).
Besides, creating a 3D pattern for bone to implant contact increased the time of calculations in the finite element analysis because of a meshing the models and the number of elements were significantly greater than the 2D model. Indeed, analysis of the 3D models was stopped due to the heavy calculations in some cases. Therefore, investigating the stress distribution via a 2D FEA was a limitation of this study although it was not a problem according to the purpose of the study. Poiate et al. showed that stress distributions in 2D and 3D FEAs were almost similar, however the stress value was greater in the 3D analysis (32). It was concluded that a simplified 2D model could be used for qualitative investigation of biomechanical behavior of tooth and supporting bone; although a quantitative stress analysis was less reliable in a 2D FEA.
In addition, the results of this study indicated that the bone to implant contact known as osseointegration quality affected the stress distribution and the maximum von Mises stress. For instance, in D3 bone type the maximum stress observed in 100% and 30% contact were 7 MPa and 9.7 MPa, respectively.
Due to greater modulus of elasticity of the cortical bone compared to the alveolar bone, the von Mises stress in the cortical bone was higher than the alveolar bone that is in agreement with other studies (30). Therefore, spongy bone tissue may gradually degenerate based on the stress shielding theory. In addition, the stress value in the region between implant threads is low and the possibility of stress shielding would be higher. In this regard, the smaller pitch of the implant threads leads to the lower stress shielding area and the possibility of bone resorption could be reduced (23). On the other hand, smaller thread pitch results in the higher stress concentration and increases the possibility of crack propagation.
Considering the approximate mapping of the quality classification throughout the 3D geometry according to the left part of the (Fig. 1), modelling in three dimensions and true definition of material properties would provide an ideal stress distribution. Ignoring the effects of symmetricity and having an approximate assumption on the material properties for the bone quality classification helped us to perform the FE analysis and achieve stress pattern.
From the biomechanical point of the view, stress concentrations differs for short implants compared with the standard length implants, as well as in different diameters. Therefore, a different length and diameter of the implant will provide another pattern of the stress distribution. Ultimately, for future studies it is suggested to investigate the effect of diameter and length of implant on stress distribution in none-ideal osseointegration cases and in different bone qualities.

CONCLUSION

In this work, using real patients' PA images, four different osseointegration models were simulated. To this point, mechanical design SOLIDWORKS commercial software version 2020 was used to create the 2D geometry of the AVITA dental implant. Afterward, using ImageJ image processing software the three osseointegration models were created on the body of the bone. Ultimately using COMSOL multi-physics commercial software version 5.6, the osseointegration static models were simulated. In the conclusion, some points are elaborated:
1-Bone quality has a greater effect than osseointegration rate on stress distribution and the maximum amount of stress. It is commonly accepted that one of the reasons of an inappropriate osseointegration rate can be considered as a result of implant placement in weak bone. We concluded that if this happens, it will worsen the stability, and therefore in the first stage paying attention to bone quality will have a great impact on the final stability of the implant.
2-Decreased osseointegration leads to an increase in the progression of stress in the apical direction, and also greater stress occurs in the apical region of implant in contact with the bone. Indeed, this creates an intensified stress concentration in the threaded area, which causes small fractures and further reduction in osseointegration as a result.
3-Greater osseointegration could prevent stress concentration and result in uniform distribution of the von Mises stress. Due to the difference in the Young modulus of the bone and the implant, if the implant tolerates most of the load of the applied force on the crown, we can see the stress-shielding phenomenon in the alveolar bone supporting the implant.
Considering the results of this study, knowing the effect of bone to implant contact on the stress distribution, a dentist should load the implant after a healing period that implant is sufficiently osseointegrated. In this way, methods like resonance frequency analysis for measurement of osseointegration indicating the implant stability quotient (ISQ) are used as a measure of BIC. Finally, it is suggested to study the micro-motion of implant in the condition of nonideal osseointegration in future studies. Besides, investigating the effect of osseointegration and the related stress distribution on the bone remodeling process would be a valuable endeavor in future studies.

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