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Scientific Paper

The sensitivity of contact stresses in the mandibular premolar region to the shape of Zirconia dental implant: A 3D finite element study

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Abstract

Background: Implant thread profile plays a vital role in magnitude and distribution of contact stresses at the implant--bone interface. The main goal of this study was to evaluate the biomechanical effects of four distinct thread profiles of a dental implant in the mandibular premolar region.
Methods: The dental implant represented the biocompatible Zirconia material and the bone block was modelled as transversely isotropic and elastic material. Three-dimensional finite element simulations were conducted for four distinct thread profiles of a dental implant at 50%, 75%, and 100% osseointegration. An axial static load of 500 N was applied on the abutment surface to estimate the stresses acting within the bones surrounding the implant.
Results: Regions of stress concentration were seen mostly along the mesiodistal direction compared to that in the buccolingual direction. The cortical bone close to the cervical region of the implant and the cortical bone next to the first thread of the implant experienced peak stress concentration. Increasing the degree of osseointegration resulted in increased von-Mises stresses on the implant-cortical transition region, the implant-cancellous transition region, the cortical bone, and the cancellous bone.
Conclusion: The results show that the application of distinct thread profiles at different degrees of osseointegration had significant effect on the stresses distribution contours in the surrounding bony structure. Comparing all four thread profiles, a dental implant with V-thread profile induced lower values of von-Mises stresses and shear stresses on the implant-cortical transition region, implant-cancellous transition region, cortical bone, and cancellous bone.

Key words: dental implant; finite element method; osseointegration; stress analysis; thread profile.

Introduction

Dental prostheses are retained and supported by endosseous implants for restoring fully or partially edentulous patients. Osseointegrated dental implant, similar to that of natural intact teeth, is subjected to static and dynamic loads. The presence of periodontal ligament tissue between the cementum and the alveolar bone in natural intact teeth acts as a cushioning element [1], while the applied occlusal forces are transmitted directly to the surrounding bone in patients treated with a dental implant [2]. Therefore, the magnitude and distribution of contact stresses induced on jaw bone will probably be different for a dental implant compared to the natural intact teeth. Contact stresses of a higher order of magnitude induced on the jaw bone can potentially lead to stress fracture within the bone, fractured implant, abutment screw loosening, and crestal bone resorption [3,4]. Therefore, it is crucial to comprehend the stress concentration on dental implants that is influenced by choice of material, shape, and size.

The implant thread profile plays a vital role in enhancing the biomechanical effectiveness of dental implants [2]. Various design parameters including, depth, pitch, and shape are required to define the implant thread profile [1]. The thread profile chosen for the dental implant should facilitate the dissipation of contact stresses at the transition region (implant-cortical & implant-cancellous) by maximizing the initial contact and stability [4]. The clinical success of a dental implant depends on the stability of the dental implant within the surrounding bone [5,6]. Existing numerical biomechanical studies of the dental implant have considered the stability of the dental implant as perfectly osseointegrated i.e. a 100% perfect contact exists between the implant and the surrounding bone [3,4,7-10]. However, clinical studies have proven that there are some regions where the contact between the implant and the bone does not occur and therefore, a perfect osseointegration is not possible [8]. Hence, the biomechanical efficacy of the dental implant at various degrees of osseointegration has to be investigated.

Previous numerical studies have modelled the cortical and the cancellous bones to behave as an isotropic [9,10]. However, the mechanical properties change with the direction along the bone and therefore, the bone should be modelled to behave as an anisotropic. Few studies which have modelled the bone to behave as an anisotropic have only estimated the von-Mises stresses [11,12], however, estimation of individual stress components is required to study the behaviour of an anisotropic material. In this study, the bones were modelled to behave as an anisotropic material so that a more precise analysis could be performed. Zirconia-based ceramics possess great characteristics as a dental biomaterial and currently the material of choice in restorative dentistry [11]. A very few biomechanical studies have investigated the influence of the Zirconia implant on the stresses and strains acting within the surrounding bones [11,12]. Finite element (FE) simulations are considered a valuable tool to numerically model and study the biomechanical effectiveness of medical implants [13-16]. The stresses and strains acting within the surrounding bones of the dental implant could be estimated using FE simulations and therefore, it is a valuable tool in offering physiological insights and assessing crucial design parameters of the dental implants.

Therefore, the primary objectives of this study were to (1) compare the contact stresses (von-Mises stresses, shear stresses, and compressive stresses) and their distributions on the bones surrounding the dental implant by varying the shape of the dental implant and (2) study the influence of various degrees of osseointegration on the contact stresses acting within the bones surrounding the dental implant, using a three-dimensional FE model of the dental implant and the surrounding bones.

Materials and methods

Geometry and finite element model

The FE simulations were performed in this study to evaluate the sensitivity of contact stresses in the mandibular premolar region to the shape of Zirconia dental implant. The 3D geometries of the jawbone and implants of distinct thread profiles were modelled using a computer aided design tool. Four commercially available thread profiles were considered in the present study including buttress thread, reverse buttress thread, V-thread, and square thread [17]. The abutment was considered to be an integrated part of the dental implant [16,18,19]. The outcomes were not affected by this consideration as the stresses and strains induced on the implant-bone is of major importance and that induced on the implant itself is not important. The detailed geometry of the dental implant is shown in **Figure 1**. To reduce the computational cost, a portion in the mandibular premolar region was modelled for this study. The chosen mandibular premolar region had the cortical bone of thickness 2 mm surrounded by a dense cancellous bone [20]. The implant-cortical transition region and the implant-cancellous transition region was modelled based on the guidelines proposed by Kurniawan *et al* [21]. The transition region, including implant-cortical transition region and implant-cancellous transition region, was modelled as a separate part and was set 0.5 mm from the inner diameter of the dental implant as shown in **Figure 2**. The geometries of the bone and the implant were meshed in HyperMesh (Altair Engineering, Troy, MI, USA), using first order four-node tetrahedral elements. All FE simulations were simulations were performed on a personal computer (AMD A10, 3 GHz processor, 8 GB RAM) using ANSYS Mechanical APDL 17.0 (ANSYS, Inc., Canonsburg, PA, USA).

Material properties

The bone was assumed to behave as an anisotropic because the mechanical properties change with the direction along the bone. However, in this study, the bone was modelled to behave as transversely isotropic as Young's modulus of cortical bone and cancellous bone in two directions (buccolingual direction and inferosuperior direction for cortical bone; buccolingual direction and mesiodistal direction for cancellous bone) are almost the same [21-23]. Generally, 21 elastic properties are required to model the anisotropic material, wherein the case of transversely isotropic material, only five elastic properties are required to model and these five properties can be calculated using the law of elasticity.

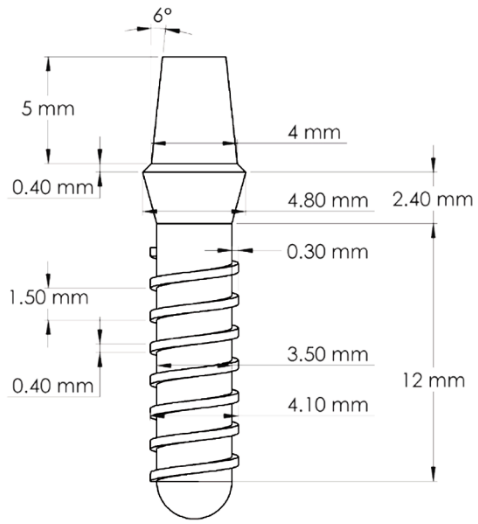

Figure 1. Schematic representation of design parameters used for modeling the dental implant and the abutment.

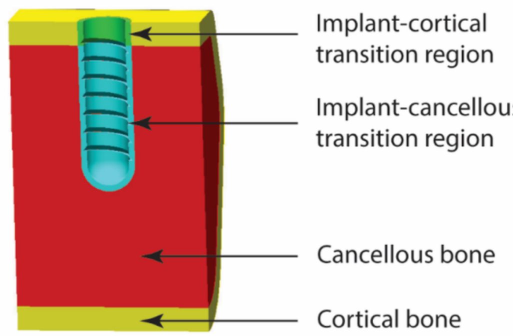

Figure 2. Cross-sectional view of the dental implant, the implant-cortical transition region, the implant-cancellous transition region, the cortical bone, and the cancellous bone.

Table 1. Mechanical properties of cortical and cancellous bone at different degrees of osseointegration.

Mechanical property		Cortical bone			Cancellous bone		
		50%	**75%**	**100%**	**50%**	**75%**	**100%**
Young's modulus (E) MPa	E_x	9700	14500	19400	574	861	1148
	E_y	6300	9450	12600	574	861	1148
	E_z	6300	9450	12600	105	157.5	210
Poisson ratio (ν)	ν_{xy}	0.253	0.253	0.253	0.32	0.32	0.32
	ν_{xz}	0.253	0.253	0.253	0.01	0.01	0.01
	ν_{yz}	0.3	0.3	0.3	0.05	0.05	0.05
Shear modulus (G) MPa	G_{xy}	2850	4275	5700	217	325.5	434
	G_{xz}	2850	4275	5700	34	51	68
	G_{yz}	2425	3637.5	4850	34	51	68

The mechanical properties of the cortical bone and the cancellous bone used in this study were taken from the experimentally measured values published by O'Mahony *et al* [21] and listed in **Table 1**. Various degree of osseointegration (50%, 75%, and 100%) was considered in this study. To model the partial osseointegration condition, a fraction of the bulk bone property was applied to the implant-cortical transition region and implant-cancellous transition region as shown in **Table 1** [8]. The Zirconia dental implant including the abutment was assumed to have an elastic modulus of 210 GPa and a Poisson ratio of 0.31 [24].

Boundary and loading conditions

The experimental data to model the implant-bone contact and to model other FE constraints is limited, therefore it remains a challenge to accurately determine the boundary conditions of the implant-bone interface [18,25]. The boundary conditions on the buccal inferior surface and the lingual inferior surface were completely constrained [4]. There is no direct contact between the implant and the bulk bone, therefore, there is no perfect osseointegration [8]. The contact between the implant and the transition region, the transition region and the bone, and the cortical-cancellous bone was tied using CEINTF command in ANSYS Mechanical APDL 17.0 by connecting the selected nodes of the one structure to the selected elements of the another structure [26,27]. The occlusal load, in this study, was assumed as a compressive stress [4,8] and applied on the top of the abutment surface. In intact conditions, the mean values of peak vertical bite forces were 469 N, 583 N, and 723 N in the canine region, second premolar region, and second molar region, respectively [27]. In the case of a dental implant, the peak vertical bite force was around 500 N in the mandibular molar region [28]. Therefore, in this study, an axial static occlusal load of 500 N was applied on the top of the implant surface as a 0.07 GPa compressive stress [29,30] as shown in **Figure 3**.

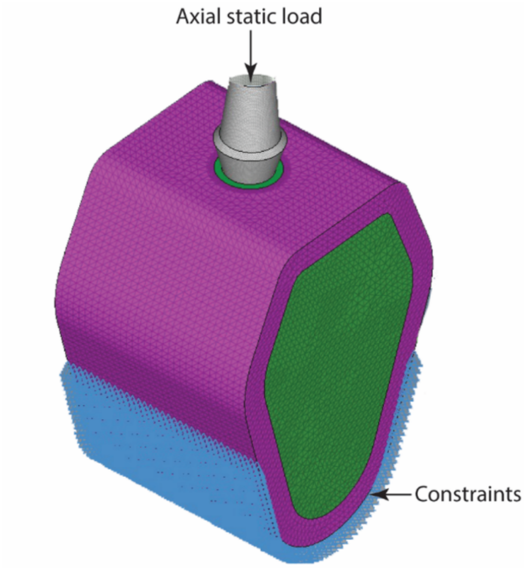

Figure 3. Representation of the boundary and the loading conditions on the three-dimensional finite element model of the dental implant and the surrounding bones.

Results

Regions of stress concentration were seen mostly along the mesiodistal direction compared to that in the buccolingual direction as shown in **Figure 4**. Only slight significant change in stress distribution was observed throughout the bony structures for all four thread profiles at different degrees of osseointegration. The cortical bone close to the cervical region of the implant and the cortical bone next to the first thread of the implant, for all four thread profiles at different degrees of osseointegration, experienced peak stress concentration as shown in **Figure 4**. The peak von-Mises induced on the implant-cortical transition region and cortical bone was several orders of magnitude higher than that induced on the implant--cancellous transition region and cancellous bone, respectively. (**Table 2**). For all four distinct thread profiles, increasing the degree of osseointegration resulted in increased von-Mises stresses on the implant-cortical transition region, implant-cancellous transition region, cortical bone, and cancellous bone. Comparing all four thread profiles, a dental implant with V-thread profile induced lower von-Mises stresses on the transition region and bulk bone.

Table 2. Peak von-Mises stresses induced on the implant-cortical transition region, implant-cancellous transition region, cortical bone, and cancellous bone when the dental implant was subjected to an axial static occlusal load of 500 N.

Thread profile type	Osseointegration (%)	Stress in transition region (MPa)		Stress in bulk bone (MPa)	
		Implant-cortical	Implant-cancellous	Cortical bone	Cancellous bone
Buttress	50	126.72	7.96	50.04	5.50
	75	132.11	10.78	51.14	5.52
	100	136	11.51	51.11	5.63
Reverse buttress	50	113.97	11.12	49.77	5.36
	75	120.72	12.49	50.90	5.42
	100	130.29	13.19	51.02	5.47
V-thread	50	108.17	7.85	40.76	4.10
	75	116.57	9.76	44.32	4.15
	100	124.94	9.91	46.79	4.36
Square	50	120.72	8.80	53.63	4.79
	75	125.17	9.54	53.21	4.95
	100	129.82	10.01	52.10	5.09

Table 3. Shear stresses induced on the implant-cortical transition region when the dental implant was subjected to an axial static occlusal load of 500 N.

Thread profile type	Osseointegration (%)	S_{xx} (MPa)		S_{yy} (MPa)		S_{zz} (MPa)		S_{xy} (MPa)		S_{xz} (MPa)		S_{yz} (MPa)	
		Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Buttress	50	73.99	-89.6	100.91	-128.08	66.31	-55.10	46.35	-31.02	25.80	-33.83	63.60	-43.84
	75	78.06	-96.5	109.01	-143.90	66.12	-62.84	48.67	-33.66	26.58	-34.37	63.31	-49.18
	100	80.48	-102.1	114.49	-155.53	65.30	-68.83	50.60	-36.02	28.17	-34.47	62.18	-53.31
Reverse buttress	50	72.98	-90.38	80.15	-133.07	50.51	-61.56	34.31	-42.28	25.39	-26.35	43.60	-44.07
	75	75.43	-96.59	88.83	-148.73	53.98	-69.28	38.35	-44.37	26.27	-28.10	48.78	-49.73
	100	77.00	-101.1	94.63	-159.98	56.03	-74.93	41.49	-45.18	27.12	-27.86	52.87	-54.18
V-thread	50	67.10	-93.12	111.46	-127.86	58.98	-74.07	42.27	-32.70	29.26	-31.34	52.73	-43.22
	75	69.10	-99.08	116.44	-142.72	66.45	-70.23	46.19	-36.05	32.1	-34.44	52.88	-48.67
	100	70.35	-103.5	118.48	-153.54	71.99	-66.75	48.81	-38.57	34.42	-36.84	52.26	-52.89
Square	50	69.51	-87.94	88.19	-124.52	53.75	-67.80	37.61	-31.51	29.74	-44.48	41.42	-41.49
	75	73.12	-94.45	96.09	-140.16	60.18	-68.33	40.69	-33.65	33.74	-44.39	46.31	-47.06
	100	75.16	-99.28	100.78	-151.43	65.10	-68.13	42.58	-35.13	36.90	-43.96	50.56	-51.36

Table 4. Peak compressive stresses induced on the bone surrounding the implant when subjected to an axial static occlusal load of 500 N.

Thread profile type	Osseointegration (%)	Compressive stress (MPa)
Buttress	50	85.96
	75	97.08
	100	105.40
Reverse buttress	50	84.03
	75	93.73
	100	100.56
V-thread	50	88.64
	75	90.62
	100	107.10
Square	50	82.27
	74	96.46
	100	99.69

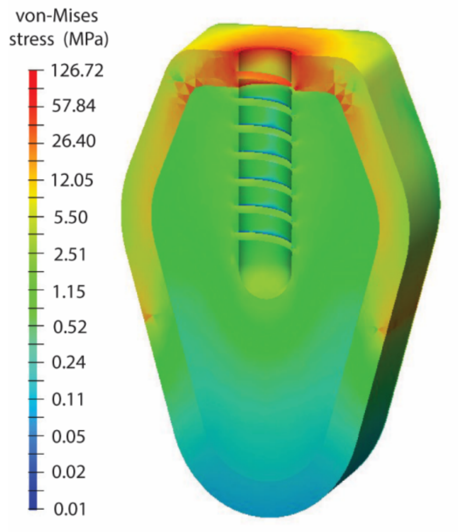

Figure 4. Distribution of von-Mises stresses within the surrounding bone of the buttress thread implant at 50% osseointegration with the application of axial static occlusal load of 500 N (buccolingual cross sectional view).

Shear stress distribution contours, like in the case of von-Mises stress distribution, had slight significant change in all four thread profiles at different degrees of osseointegration as shown in **Figure 5**. For all four distinct thread profiles, peak shear stresses were induced on the cortical bone close to the cervical region of the implant, the cortical bone next to the first thread of the implant, and the cortical-cancellous interface region. Increasing the degree of osseointegration resulted in increased peak shear stresses on the implant-cortical transition region (**Table 3**). For all four thread profiles, the cortical bone experienced high values of shear stresses when compared to that in the cancellous bone as shown in **Figure 5.**

Similar to von-Mises stress and shear stress distribution contours, compressive shear distribution contours had slight significant change for all four thread profiles at different degrees of osseointegration as shown in **Figure 6**. For all four thread profiles, peak compressive stresses were induced in the neck region of the dental implant. Increasing the degree of osseointegration resulted in increased compressive stresses on the implant-cortical transition region, implant-cancellous transition region, cortical bone, and cancellous bone (**Table 4**). The cortical bone, for all four thread profiles, experienced high values of compressive stresses when compared to that in the cancellous bone.

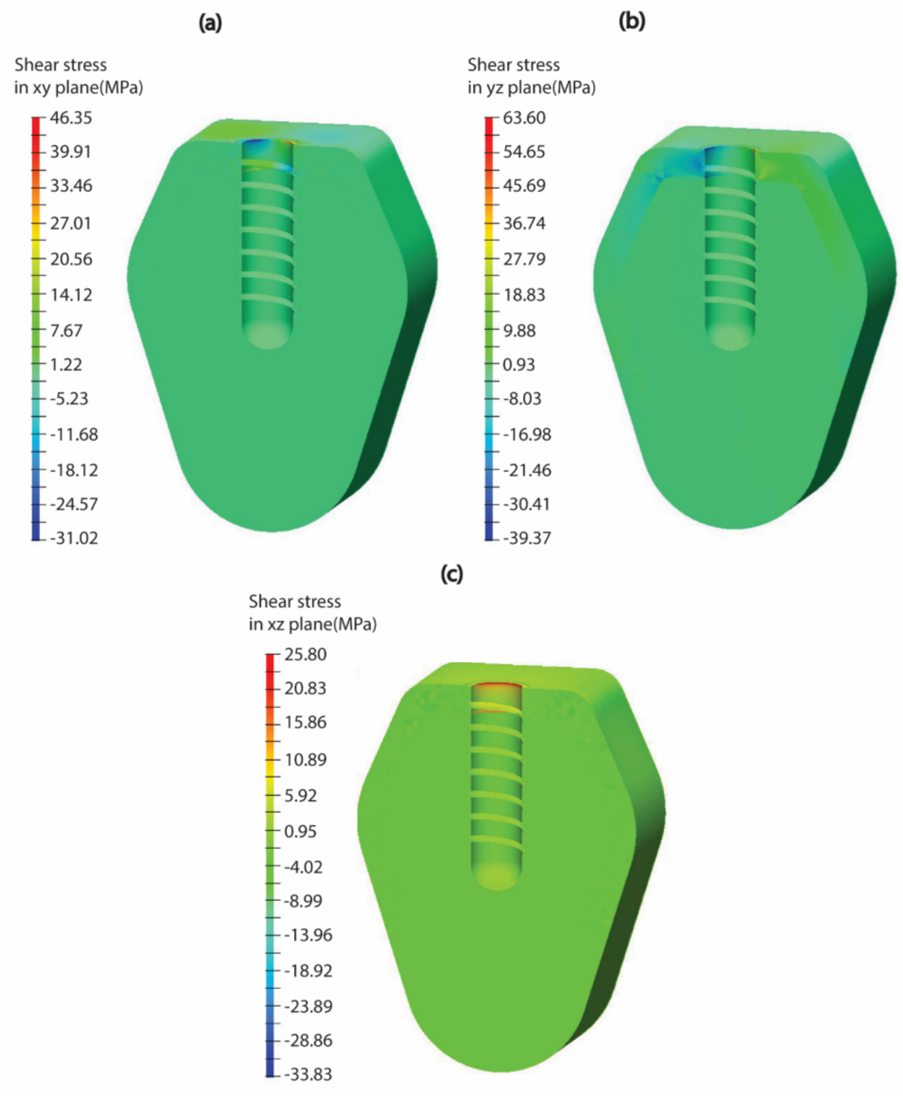

Figure 5. Distribution of shear stresses within the surrounding bone of the buttress thread implant at 50% osseointegration with the application of axial static occlusal load of 500 N (buccolingual cross sectional view). (a) Shear stress acting in the y-direction on the plane whose normal is x-axis (S_{xy}), (b) Shear stress acting in the z-direction on the plane whose normal is y-axis (S_{yz}), and (c) Shear stress acting in the z-direction on the plane whose normal is x-axis (S_{xz}).

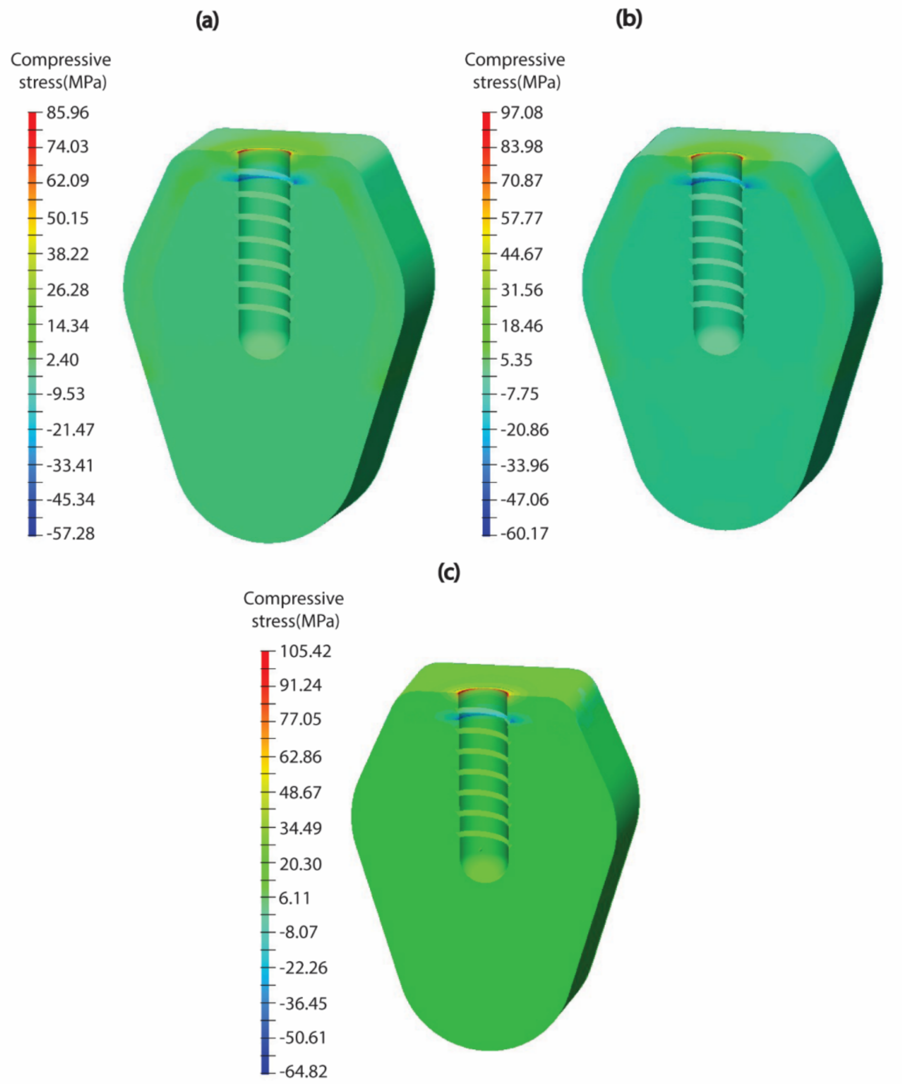

Figure 6. Distribution of compressive stresses within the surrounding bone of the buttress thread implant with the application of axial static occlusal load of 500 N (buccolingual cross sectional view). (a) 50% osseointegration, (b) 75% osseointegration, and (c) 100% osseointegration.

Discussion

Supplanting a damaged, chipped, or cracked tooth with a dental prosthesis is a promising treatment procedure for fully or partially edentulous patients. A dental implant of required thread profile could be reproduced using the existing design and manufacturing technologies to fit well within the corresponding bones. The optimal choice of the thread profile type for a dental implant plays a critical role in improving contact stresses (von-Mises stresses, shear stresses, and compressive stresses) experienced by the surrounding bones of the dental implant. The crucial findings of the current study were: (1) the regions of stress concentration were seen mostly along the mesiodistal direction compared to that in the buccolingual direction, (2) the cortical bone close to the cervical region of the implant and the cortical bone next to the first thread of the implant experienced peak stress concentration, and (3) increasing the degree of osseointegration resulted in increased von-Mises stresses on the implant-cortical transition region, the implant-cancellous transition region, the cortical bone, and the cancellous bone.

Increasing the degree of osseointegration from 50% to 100% resulted in 8% to 10% increase of peak von-Mises stresses induced on the implant-cortical transition region, implant-cancellous transition region, cortical bone, and cancellous bone (**Table 2**). This increase in peak von-Mises stresses is in line with the reported values in the literature [30]. The results suggest that the implant-bone setup which is partially osseointegrated is more prone to failure. For analysis of different thread profiles of the dental implant used in this study, the degree of osseointegration in the range of 75% to 90% can be taken into consideration [31,32].

To study the sensitivity of the contact stresses acting within the bones to the shape of the implant, the thread profile type of the dental implant was varied and the remaining parameters were kept constant for all FE simulations. This helps to compare the influence of the thread profile type of the dental implant. For all four thread profiles, the von-Mises stress distribution contours within the bones surrounding the dental implant were nearly identical. This result is in line with the results published by Geng *et al* [3]. They studied the effect of distinct thread profiles of a dental implant and reported that the contact stress distribution on the cortical bone was not sensitive to the thread profile type. The magnitude of contact stresses induced on the cortical bone was not sensitive to the thread profile type (**Tables 2-4**). This result is in line with the findings published by Mosavar *et al* [30] and Hansson and Werke [33].

The long-term implant survival and success in the clinical scenario depends on the way the stresses are transferred within the bone surrounding the implant [9]. The design of the implant thread must reduce the stresses induced on the implant-bone interface [34]. The compressive forces induced on the bony structures helps to improve the bone strength by increasing the density of the bone, while the shear, as well as tensile forces, and weaken the bony structures [34]. Increase in compressive forces to improve the bone strength can be achieved by reducing the shear and tensile forces.

The dental implant with a V-thread induced the lowest contact stresses at all distinct degrees of osseointegration on the implant-cortical transition region, implant-cancellous transition region, cortical bone, and cancellous bone. The buttress and the square thread showed less than 5% deviation when the degree of osseointegration was increased from 50% to 75% and 100%. This result is in contrast to the findings published by Mosavar *et al* [30]. They reported that the dental implant with a square thread induced lowest contact stresses induced at all distinct degrees of osseointegration. Hence, the outcomes of this study show that the material choice of the dental implant also plays a critical role on the stress induced within the bones surrounding the implant. This result is in line with the findings reported by Shriram *et al* [13] and Lih-Jyh Fuh *et al* [35]. Shriram *et al* studied the effects of material properties of an implant and reported that the contact stresses induced on the articulating surface are sensitive to the implant material stiffness [13].

The dental implant with a reverse buttress thread and the dental implant with a square thread induced similar shear stresses on the transition region and the bulk bone at all three degrees of osseointegration (Table 3). In this study, using three-dimensional FE simulations, we have demonstrated that the dental implant with a V-thread induced the lowest shear stresses on the transition region and the bulk bone at all three degrees of osseointegration. Misch *et al* reported in contrast to our result that the dental implant with a square thread is more favourable than the dental implant with a V-thread and the dental implant with a reverse buttress thread [34].

There was significant difference in compressive stresses induced within the bones surrounding the implant for all distinct thread profiles at different degrees of osseointegration (**Table 4**). The dental implant with a V-thread induced greater values of compressive stress on the transition region and the bulk bone. Higher compressive force in the implant-bone interface increases the bone density and increases the bone strength [4]. Therefore, the V-thread profile type is considered to be a favourable shape for the dental implant made of the biocompatible Zirconia material. The changes in compressive stress values between the dental implants with a reverse buttress thread, buttress thread, and square thread are not significant. This result is in line with the findings reported by Eraslan and Inan [4]. The outcomes of this study represent that the dental implant with a V-thread profile induced lower values of von-Mises stresses and shear stress, and induced higher values of compressive stresses on the transition region and the bulk bone at all three degrees of osseointegration.

The clinical dental implant models were numerically simulated in this study. Transversely isotropic and elastic material for the bone was implemented, therefore, the modelled bone behaves as a linearly elastic continuum. This limitation has to be considered while interpreting the results of a functioning clinical scenario, and further studies are required.

Conclusion

In conclusion, we have demonstrated that a solid-screw Zirconia dental implant of V-thread profile prevents higher magnitude contact stresses within the surrounding bones when compared to dental implants of buttress thread profile, reverse buttress thread profile, and square thread profile. The contact stresses (von-Mises stresses, shear stresses, and compressive stresses) are sensitive to the thread profile, type of the dental implant and the degree of osseointegration. Increasing the degree of osseointegration resulted in increased von-Mises stresses on the implant-cortical transition region, the implant-cancellous transition region, the cortical bone, and the cancellous bone. These crucial findings will be used to optimize the design parameters of the dental implants and eventually accomplish long-term implant survival and success in the clinical scenario.

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