Comparison of the periimplant bone stress distribution on three fixed partial supported prosthesis designs under different loading. A 3D finite element analysis

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Introduction

The use of finite element analysis (FEA) is becoming a really important tool in biomechanical analyses and more in particular in odontology. FEA allows modelling complex structures and analysing their mechanical properties. As it is a non-invasive tool, it has been found to be really useful in order to study the biomechanics and the influence of mechanical forces on the biological systems. A finite element model is a geometrical model with certain material properties and boundary conditions that can be employed in order to analyse stress and deformations in any geometry.

It must be noticed that the use of any FEA model, means that some simplified assumptions are performed about geometry, load, boundary conditions and material properties (Álvarez-Arenal et al., 2017). In general, these assumptions do not affect the result as the model is configured in order to mimic the phenomenon under study.

Replacement of missing periodontal and dental tissues has been carried out since ancient times. Nowadays, the first therapy choice is generally an implant-supported prosthesis, due to the predictable long term results (Center et al., 2012).

In the case of posterior partial edentulism, some questions need to be answered about, for example, the number, location and position of the implants and also the best bridge design. For restoring three consecutive missing teeth, from the biomechanical point of view, the ideal situation is to place an implant for each missing tooth (Buser, Belser, & Lang, 1998) with a tripod configuration (Ferlay et al., 2013). However, two implants seem to be a valid option (Di Sebastiano & Mourtzakis, 2014).

Focusing on the latter option, the highest success and survival rates were achieved by two parallel implants on the sides and an intermediate pontic (Allott, Masko, & Freedland, 2013). Sometimes, due to certain anatomical circumstances such as proximity to maxillary sinus, mental nerve emergence or alveolar edge resorption, it is not possible to place the implants in an optimal position. In these circumstances, a cantilever prosthesis or tilted implants could be used (Del Fabbro & Ceresoli, 2014).

In the past four decades, in order to improve success and survival rates in implant therapy, factors that could produce mechanical, technical and biological complications have been studied. These have included periimplant bone loss produced by bacteria (periimplantitis), mechanical stress, or both (Kreissl, Gerds, Muche, Heydecke, & Strub, 2007). With regards to mechanical factors, The Frost Mechanostat Theory states that bone stress over 3000 microstrains or 60 MegaPascals is needed for bone resorption (Liu et al., 2011). Moreover, different factors may have influenced the quantity of stress/deformation transferred to periimplant bone and implant, including direction, intensity and distribution of the occlusal load, bone support density, prosthesis design and mechanical properties and number, size and disposition of the major axis of implants (Yokoyama, Wakabayashi, Shiota, & Ohyama, 2004).

Currently, there is controversy over whether tilted implants, with their possible resultant increase in implant therapy failure rates and periimplant bone loss, are a valid option compared with straight implants (Maló, De, & Nobre, 2011; Zurdo, Romão, & Wennström, 2009). For example, FEA have demonstrated higher periimplant stress levels in three separate studies: single crowns with tilted implants, straight implants under non-axial loads and splinted implant crowns with different implant inclinations, although it should be noted that normally there is a decrease in the periimpant bone stress in the splinted implants. However, other FEA studies carried out with full arch rehabilitations concluded that increasing implant inclination, thus reducing the cantilever extension, was biomechanically more favourable than using a straight implant, which increases cantilever length (Baggi, Pastore, Di Girolamo, & Vairo, 2013). With regards to the three-unit implant supported bridge, this question, therefore, remains unresolved.

The aim of this study was to provide theoretical guidance about which bridge design is biomechanically more favourable for periimplant bone and implants, in a three-unit rehabilitation supported by two implants. At the same time, the influence of factors such as direction and distribution of the occlusal loads along with the supporting bone quality were evaluated.

Material and methods

Finite element model design

Three specimens of three-unit posterior partial prostheses, supported by two implants simulating an upper right rehabilitation of the first and second premolar and the first molar, were modelled using Pro/Engineer Wildfire 5.0 design software. Each specimen was duplicated for the assessment of two different bone densities (D3 y D4) of the bone block (Sevimay, Turhan, Kiliçarslan, & Eskitascioglu, 2005).

The implants were placed in the middle of the mesio-distal and buco-lingual point of each crown. Model 1, the Straight Implants Model (SIM), represented in Figure 1 had parallel implants and were perpendicular to the occlusal plane. These were positioned at the first premolar and molar with a pontic in-between. Model 2, the Tilted Implant Model (TIM) represented in Figure 2, presented the same configuration as Model 1 but with the distal implant tilted 45º distally. In Model 3, the Cantilever Model (CM) Figure 3, implants were parallel, located at the premolar area with a distal cantilever.

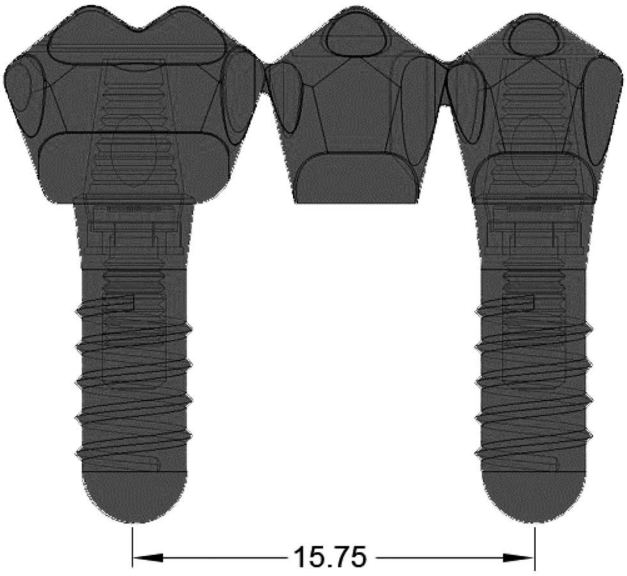

Figure 1. Straight Implant Model (SIR).

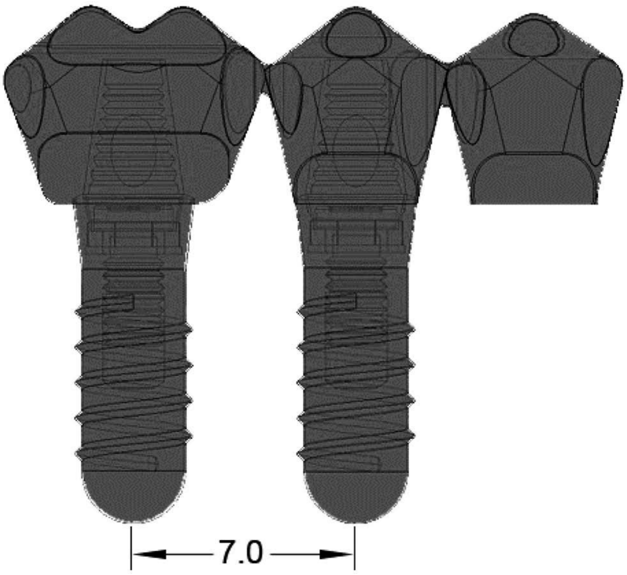

Figure 2. Cantilever Model (CM).

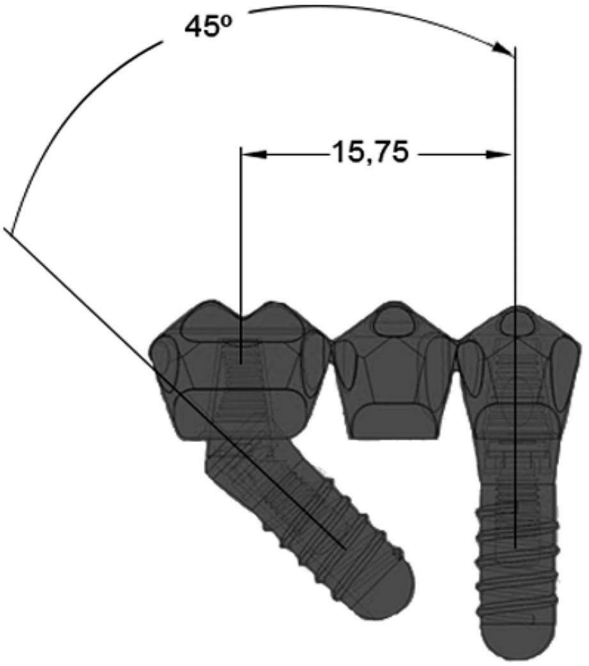

Figure 3. Tilted Implant Model (TIM).

The implants used were similar to the Standard Plus from the Straumann® Dental Implant System (Waldenburg, Basel, Switzerland). The size was 4.1 × 10 mm bone length plus 1.8 mm neck height. The distance between the major axes of the implants was 15.75 mm in the inter- mediate pontic bridge designs and 7 mm in the cantilever model.

Straight abutments 5.5 mm high were used except for the distal implant in Model 2. A 45° angulated abutment was designed ad hoc for the tilted implant. All the abutments were screw- retained.

All models presented a supra-structure simulating roughly the anatomy of first and second premolars and first molar of the upper jaw following the data of (Woelfel & Scheid, 1997). The crown-implant ratio was 1:1, that is, a 10 mm supra-osseous height, in which 8.2 mm was the supra-structure. The mesio-distal length was 24.5 mm, 7 mm for each premolar and 10.5 mm for the molar. In the cantilever model, the total length of the pontic was 12 mm from the distal wall, and 6.75 mm to the occlusal contact point. The bucco-palatal width of the supra-structure was 9 mm and 11.5 mm for the premolars and molar, respectively. The supra-structure was friction- retained. The occlusal surface was flat and parallel to the platform of the straight implants on the loading areas.

Material properties and interface conditions

According to the available FEA studies, few assumptions were made. All the materials used in these models were considered linearly elastic, homogeneous and isotropic. Elastic properties of the employed materials were obtained from the literature (Young Modulus 'E' and Poisson Modulus 'ν') (de Cos Juez, Sánchez Lasheras, Ordóñez Galán, & García Nieto, 2009; Pérez-Pevida et al., 2016) and are represented in Table 1. Contact between surfaces was 100%. Some anatomical structures were not designed, for instance soft tissues, cement and porcelain. Also, it must be noticed that any system as the one presented in this research, formed by more than one element, is homogeneous only when its properties are identical in all its parts (Alvarez-Arenal, Sánchez Lasheras, Martín Fernández, & González, 2009). Please note that as it was already stated before that as the system is considered to be isotropic, the reliability of the system is limited to those stress values that cause a linear deformation in the assembly. Although bone is not isotropic, this consideration is usually performed in the biomechanical FEA and does not affect the results.

Table 1. Material properties ascribed of the materials used.

Structure	Material	Young's Modulus (E) (GPa)	Poisson's ratio (ν)
Cortical bone		13.7	0.3
Cancellous bone D3		1.37	0.3
Cancellous bone D4		1.10	0.3
Implant	Ti6 Al4 V	110	0.33
Retention screw	Ti6 Al4 V	110	0.33
Abutment	Ti6 Al4 V	110	0.33
Framework-Bridge	Co-Cr	218	0.33

Loading and boundary conditions

Software ANSYS 14.0 de ANSYS Inc. (Canonsburg, Pennsylvania, EEUU) was used for the FEA. Table 2 shows the number of elements created for each model. Stress was expressed in MegaPascals following the Von Mises criterion. As results obtained by FEA do not vary, statistical analysis was not needed.

Four different occlusal loading combinations of varying direction and distribution were carried out on each model. A 450N total load was spread in three different application points over the occlusal centre of each crown. Distribution of the load was 'uniform', when 150N was equally applied over each crown, or non-uniform, when 175 N was applied onto the abutments and 100 N to the pontic. Additionally, the occlusal load direction was considered axial when it was the same as the major axis of straight implants, or non-axial, when the load was applied with 30° disto-mesial tilt to the 'axial load'. Tables 3 and 4 summarise the occlusal load applied over each model.

Table 2. Number of mesh elements in each model.

Component/Model	SIM	CC	TIM
Total nodes	86,894	117,187	77,389
Total elements	54,036	78,697	47,877
Total bodies	44,693	60,908	39,808
Elements in touch	9,343	17,789	8,069

Table 3. Occlusal loads applied to Straight Implant Model (SIM) and Tilted Implant Model (TIM).

Nomenclature	1º premolar	2º premolar	1º molar	Total	Direction
Uniform – axial	150 N	150 N	150 N	450 N	Vertical 0º
Non-uniform – axial	175 N	100 N	175 N	450 N	Vertical 0º
Uniform – non-axial	150 N	150 N	150 N	450 N	Oblique 30º
Non-uniform – non-axial	175 N	100 N	175 N	450 N	Oblique 30º

Table 4. Occlusal loads applied to Cantilever Model (CM).

Nomenclature	1º premolar	2º premolar	1º molar	Total	Direction
Uniform – axial	150 N	150 N	150 N	450 N	Vertical 0º
Non-uniform – axial	175 N	175 N	100 N	450 N	Vertical 0º
Uniform – non-axial	150 N	150 N	150 N	450 N	Oblique 30º
Non-uniform – non-axial	175 N	175 N	100 N	450 N	Oblique 30º

Results

Table 5 shows the stress transferred to implants and periimplant bone for the SIM in relation to the intensity and direction of the occlusal load in two different supporting bone density scenarios. The highest stress level (18.8 MPa) was located in the periimplant bone adjacent to the tilted implant under non-axial and non-uniform loading conditions with bone quality D3. The implant which suffered the greatest amount of stress was the tilted implant under non-axial load conditions with bone type D4. The lowest stress value was found in the periimplant bone in contact with the mesial implant of the cantilever model under non-axial and non-uniform loading conditions and bone D4. The implant that showed less strain was the distal of Model 1 under non-axial and non-uniform loads in both bone densities. The periimplant bone of the tilted implant experienced 3 to 5 times more stress than the bone of the other two models, and 30% more than the surrounding bone of the other implant in the same model. Additionally, implants of the tilted implant model experi- enced two to three times more stress than the implants of the cantilever model and up to seven times more than those of the straight implant model.

The quality of the supporting bone affected the transferred stress to the periimplant bone in the tilted implant model with less stress under bone type D4 than in D3, between 0.4 y 0.8 MPa lower. The same trend, but with slight differences (0.01 to 0.05 MPa), was noticed in the cantilever model. The opposite results, but also with minimum alterations, appeared in the straight implant model. With regards to the implants, when the supporting bone was less dense (D4), the implants experienced more stress in the tilted implant model and almost insignificant stress in the other two specimens.

In relation to the position in the arch, the distal periimplant bone in Models 2 and 3 suffered more stress than the mesial in all experiments, while in Model 1 the opposite occurred. The mesial implant experienced more strain under the axial load except in the case of the cantilever model when the distal suffered 20–40% more. Under non-axial loads, the difference between implants increased in straight implant and cantilever models, while in the tilted implant model, the distal implant experienced higher stress than the mesial implant.

Axial loads generated less stress in periimplant bone and implants in the tilted implant model and mesial implant and distal periimplant bone in the straight implant model than for non-axial loads. These were more favourable in the distal implant and mesial periimplant bone of the straight implant model and in all the structures of the cantilever model.

Uniform distribution of the occlusal load increased the strain in implants and periimplant bone of the straight implant and cantilever models. No differences were found in the mesial implant and distal periimplant bone of the tilted implant model, while in the distal implant and mesial periimplant bone, the opposite occurred.

Generally, stress was located in the first millimetres of the bone-implant contact. However, in a few situations, important strain was in the apical area, as it can be observed in Figures 4–7.

Discussion

Bridge design

Implant position and bridge design have an impact on the transferred stress to periimplant bone and implants in an implant supported partial prosthesis. The data of the current study coincide with the information available in the literature, namely that the lowest stress in periimplant bone implant results from a bridge design with an intermediate pontic and parallel straight implant on the sides compared with a cantilever configuration or with a tilted implant with a convergent apex placement.

Table 5. Stress in the implants and periimplant bone for all the models under different loading directions and magnitudes, and placed in different bone types, bone D3 (upper) and bone D4 (lower). Results showed in MegaPascals.

Model	Straight implant: SIM				Cantilever: CM				Tilted implant: TIM			
	Axial		Non-axial		Axial		Non-axial		Axial		Non-axial	
Force → Component ↓	Unif	No U	Unif	No U	Unif	No U	Unif	No U	Unif	No U	Unif	No U
Distal Implant (DI)	266	239	207	170	906	725	778	602	1,500	1,520	2,070	2,090
	289	240	191	168	1,020	717	769	597	1,760	1,780	2,360	2,380
Mesial Implant (MI)	300	262	411	372	779	497	462	275	1,840	1,840	1,910	1,920
	301	262	415	377	959	613	575	282	2,150	2,150	2,250	2,260
Distal Implant Periimplant bone (DPB)	3.99	3.70	4.71	4.33	5.18	4.45	4.23	3.55	17.7	17.7	18.7	18.8
	4.03	3.74	4.74	4.37	5.13	4.42	4.20	3.54	17.1	17.1	17.9	18
Mesial Implant Periimplant bone (MPB)	4.63	4.62	5.47	5.40	3.23	2.73	2.68	2.16	12.3	13.0	12.8	13.9
	4.68	4.67	5.51	5.45	3.20	2.71	2.66	2.15	11.9	12.5	12.2	13.3

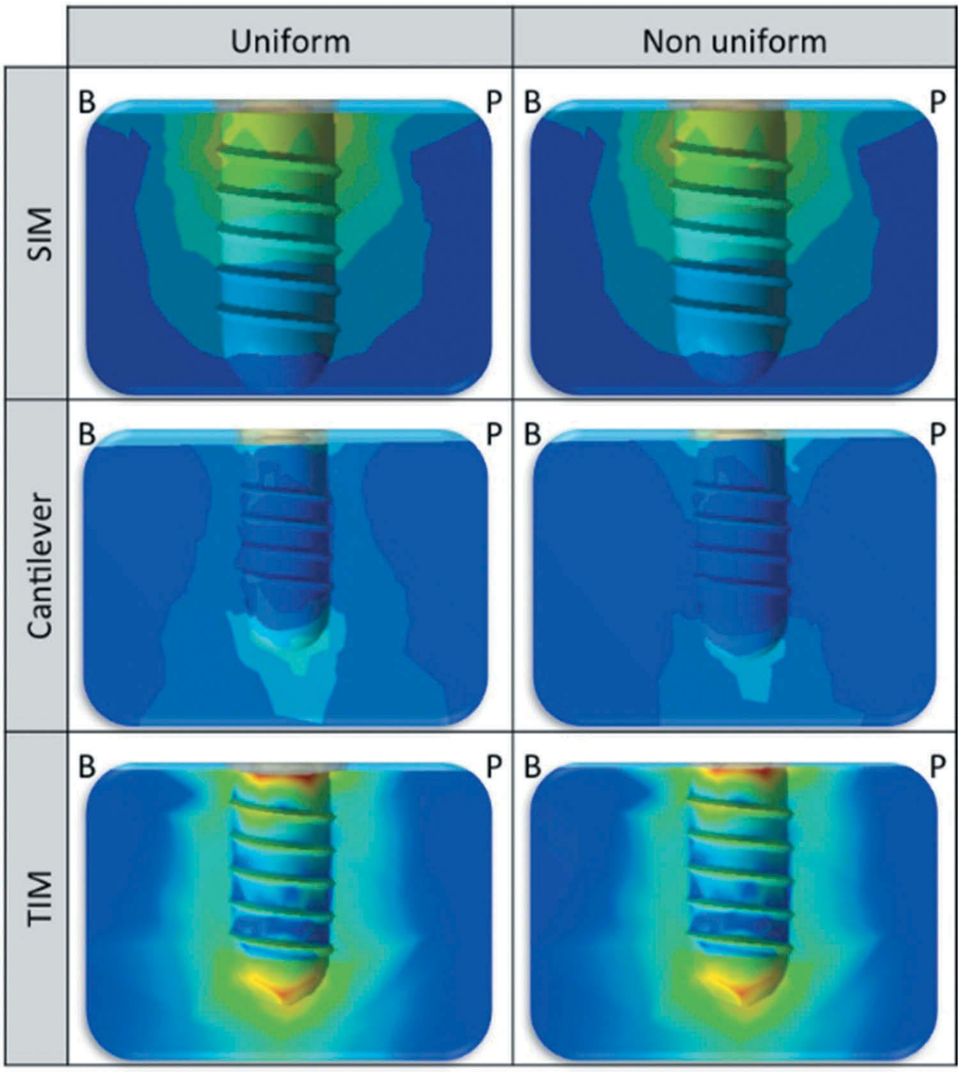

Figure 4. Stress distribution in the periimplant bone (D3) of mesial implant for every model under axial loading, uniform and non-uniform. Distal view.

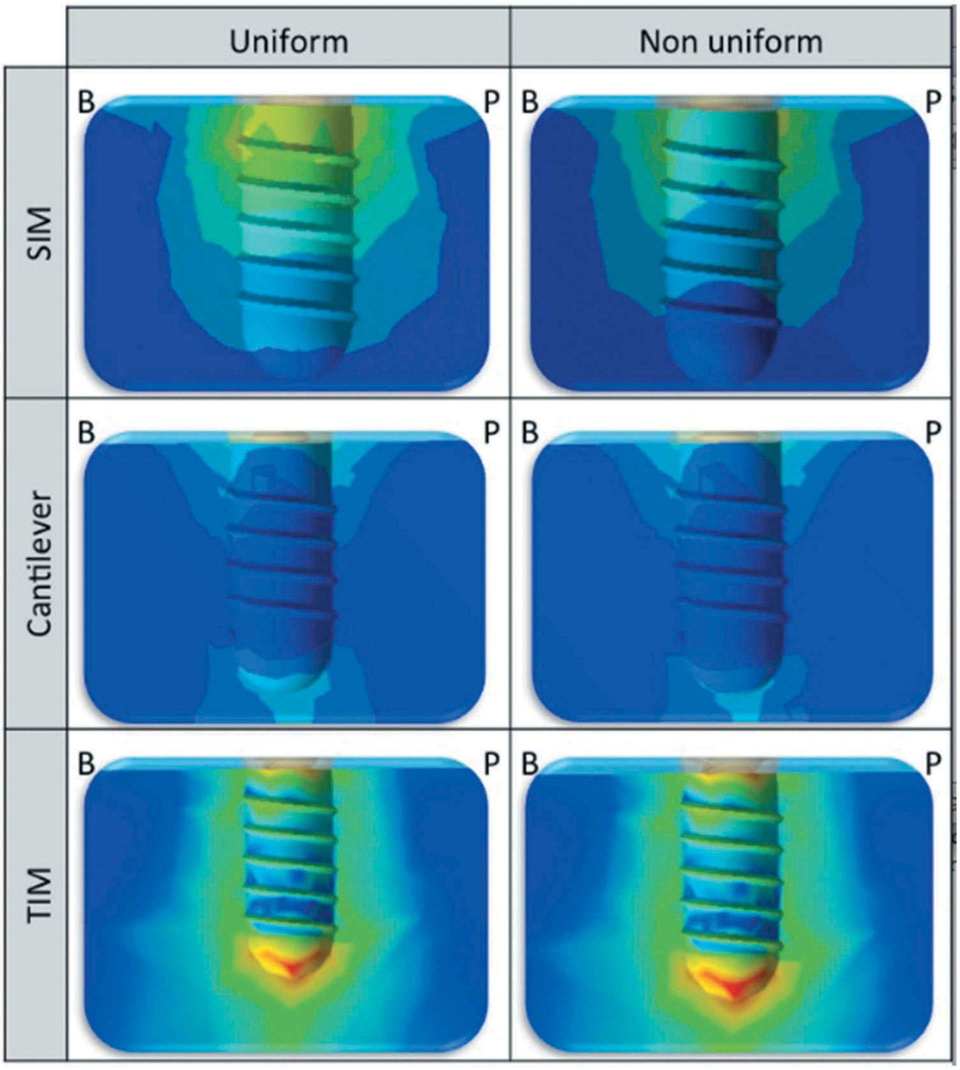

Figure 5. Stress distribution in the periimplant bone (D3) of mesial implant for every model under non-axial loading, uniform and non-uniform. Distal view.

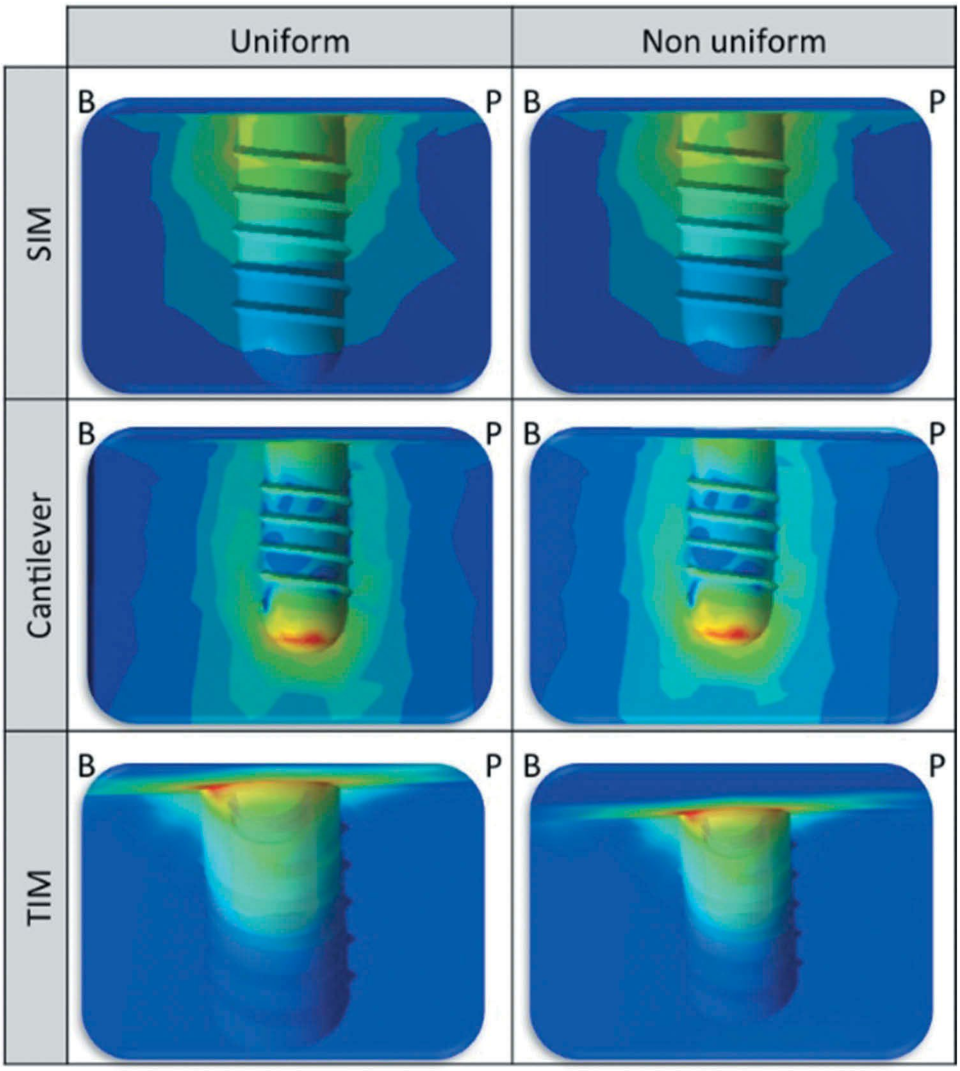

Figure 6. Stress distribution in the periimplant bone (D4) of distal implant for every model under axial loading, uniform and non-uniform. Distal view.

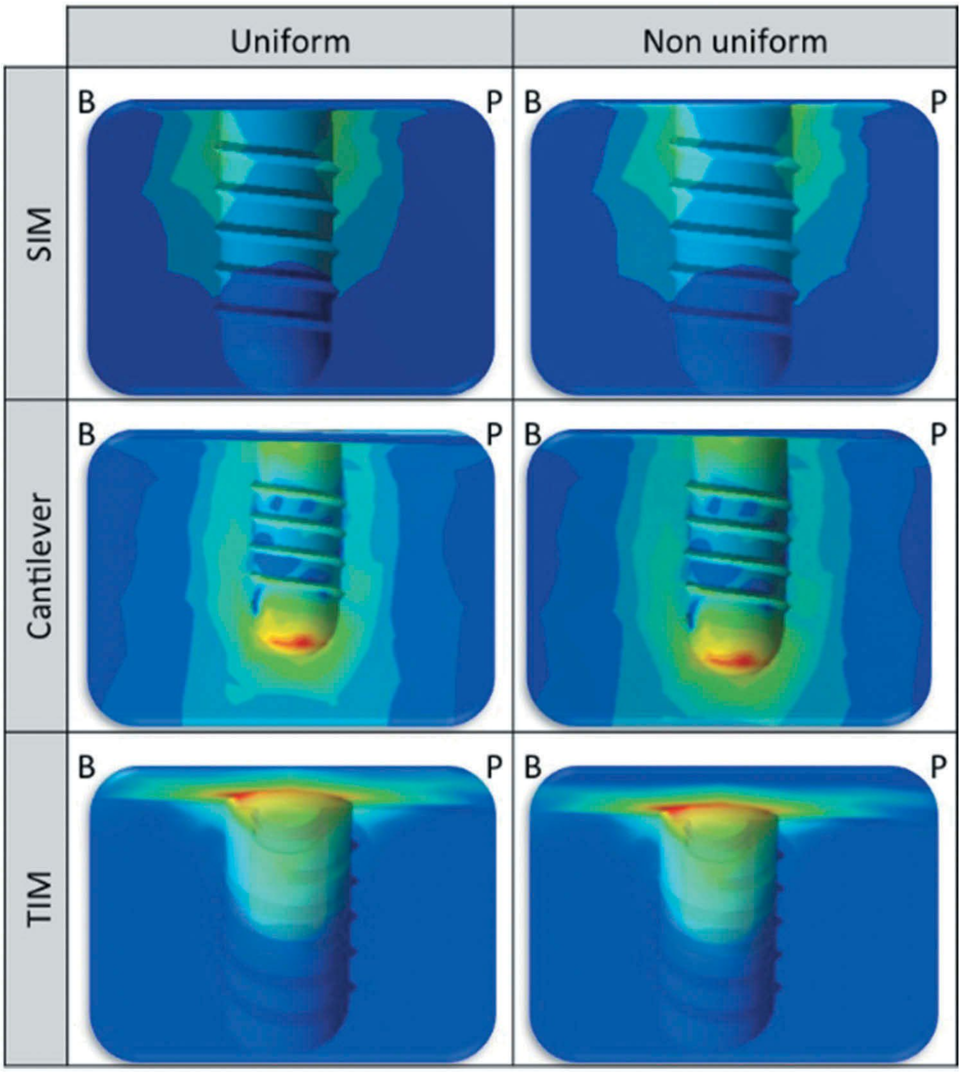

Figure 7. Stress distribution in the periimplant bone (D4) of distal implant for every model under non-axial loading, uniform and non-uniform. Distal view.

Nevertheless, a discrepancy was found with regards to the results between cantilever and tilted implant configurations. Current studies shown that placing a tilted implant, reducing cantilever length, leads to a biomechanical improvement, contrary to the data obtained in this work. This discrepancy could be arisen from several factors such as different occlusal loads, cantilever lengths and degree of tilting of the implants.

Firstly, regarding the occlusal loads, several studies like (Zampelis, Rangert, & Heijl, 2007) or (Bevilacqua et al., 2011) applied a single load on the end side of the cantilever, generating an important lever arm. In contrast, in this study, as in the (Yokoyama et al., 2004) study, occlusal forces were distributed among the three crowns, decreasing the injury effect of the bending moment of cantilevers.

Secondly, and related to the former, the cantilever sizes were different: as is well known, the bigger the cantilever, the higher the stress (Yokoyama et al., 2004). This cantilever model had a total non-supported pontic length of 12 mm but only 6.75 mm acted as the power arm, with a resistance arm of 11 mm, creating a mechanical advantage of 0.634.

Thirdly, the degree and direction of implant inclination play an important role. While (Zampelis et al., 2007) stated that the transferred stress to periimplant bone and implant was not increased by the alteration of the major axis of the distal implant from 0°, 10°, 20°, 30°, 45° in a 3-unit prostheses supported by two implants, and other authors have reached contrary conclusions, all of them have concluded that increasing the tilt of an implant led to an increase in the stress (CardelCardelli et al., 2009). Likewise, the tilted direction had an influence on the generated strain, when the apex were divergent 15°, a decrease of periimplant and implant stress occurs and vice versa in comparison with two parallel implants (Lan, Pan, Lee, Huang, & Wang, 2010), as it happened in these essays.

With regards to position in the arch, following the determination of the occlusal load distribu- tion proposed by (Watanabe, Hattori, & Satoh, 2005) the highest stress values should be achieved in the distal areas in all cases. However, due to the occlusal load was exactly the same independent of the arch position, results showed a similar trend to the other studies. These indicated that periimplant bone and implant stress is higher in the adjacent abutment to the cantilever (Baggi et al., 2013) and to the tilted implant (CardelCardelli et al., 2009). In the case of the straight implants model, the reason for the highest stress being located in the implant and periimplant bone of the first premolar is probably due to two reasons; firstly, the distance between the load application point and the second premolar/pontic, which is closer to the major axis of the mesial implant (7 mm) than the distal implant (9,5 mm), and secondly, the load intensity, which is identical in both abutments without taking into account the arch position.

Occlusal loading direction

Following our results and according to the literature, non-axial occlusal forces increased the stress in periimplant bone and implants in models with intermediate pontic in comparison to axial loads (Lin, Lin, & Chang, 2010). There is a correlation between the discrepancy of load direction and the major axis of the implant: the greater the discrepancy, the more stress is generated. This could be because of the forces resulting from the angle of incidence in respect to the occlusal plane or because of the increase in the implant inclination. In these situations, a bending moment is created, generating stress in the cervical area of the implant in contact with the cortical bone (Li et al., 2009).

Nevertheless, some particularities happened in this study due to the disto-mesial direction of the non-axial forces. For example, in the tilted implant model there was an increase in stress over both implants due to the fact that the occlusal load was favourable to the intrusion of the distal implant, increasing the deformation of the supra-structure and the generating more stress on the mesial implant. In the straight implant model, a reduction in stress occurred in the distal implant under uniform and non-axial forces due to the resultant direction being closer to the mesial implant.On the other hand and in contrast to the other models, non-axial forces reduced stress in cantilever implants and periimplant bone compared to axial loading, due again to the disto-mesial direction, which resulted in a decrease in the load to the cantilever pontic. This fact modified the cantilever behaviour creating a ‘balance effect’, which means that a mesial cantilever was created, reducing the distal lever arm and moving the fulcrum in both implants. The fact is that the studies obtained different results due to the fact that they only used bucco-lingual or linguo-buccal forces. Furthermore, in this model, periimplant bone and implants suffered more stress under axial loads than non-axial loads because the cantilever received more loading up to 20% less under axial and non-uniform load and non-axial uniform loads, resulting in almost 35% less in the distal implant and approximately 65% in the mesial implant under non-axial and non-uniform loads, similar to the reported in full arch processes by (Baggi et al., 2013).

Occlusal load distribution

In agreement with other authors (Sahin, Cehreli, & Yalçin, 2002), stress generated in the different prosthesis components is determined by the occlusal load applied. In these studies, reducing the occlusal load to the unsupported crowns led to a decrease in the stress transmission to periimplant bone and implants.

Regarding cantilevered bridges, occlusal load distribution and cantilever length had an enor- mous effect on the stress distribution over periimplant bone and implants. When the load was applied exclusively to the cantilever, stress experienced by the periimplant bone adjacent to the extension was twice that of the one further away (Stegaroiu, Sato, Kusakari, & Miyakawa, 1998). However, when the forces were spread over the three crowns, the stress suffered by the periim- plant bone closest to the cantilever was 50% higher than the homonymous of the straight implants model (Yokoyama et al., 2004).

With regards to a partial prosthesis with tilted implants, there were no studies that assessed the influence of different occlusal forces’ distributions to compare with these results. Focusing on the results of this study, the influence of the occlusal load distribution to the stress transferred to the distal periimplant bone and tilted implant was minimal while in the mesial periimplant bone, stress was slightly higher under a non-uniform load. It could be explained due to the fact that the highest load intensity (175 N) was applied further away from the mesial implant/fulcrum despite the total force applied to the lever arm was lower (275 N and 300 N).

Conclusions

According to our results and the limitations of this kind of study, it could be deduced that. Stress transmission in three-unit fixed prosthesis supported by two implants is influenced by bridge configuration, support bone quality and the direction and distribution of the occlusal loads (Fishwick & Zeigler, 1991; Shalin & Bertram, 1996).

From the biomechanical perspective, the first treatment option is to place parallel implants on each side of the bridge with an intermediate pontic, followed by two adjacent and parallel implants with a distal cantilever, and finally, a 45° tilted implant with its apex close to the other implant. The most favourable load condition is one where axial occlusal forces are applied mainly over the abutments to lighten the pontic. As there is less bone density, it is more important to control other biomechanical factors, such as occlusion distribution and bridge configuration, to reduce the strain on the periimplant bone and implants.

Disclosure statement

No potential conflict of interest was reported by the authors.

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