STRESS ANALYSIS OF THE PROSTHESES/IMPLANT/RETENTION SCREW SET WITHOUT PASSIVE FIT USING MEF-2D

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Abstract. *The aim of this study was to evaluate the displacement and stress inner distribution of surrounding bone and prostheses/implant/retention screw system with different levels of unilateral angular misfit through 2D-FEA. Four groups were characterized by mathematic models representing a metallic prosthesis connected with retention screw to an implant inside bone tissue. In Group 1 (control) the prosthesis fitted accurately to the implant while in Groups 2, 3 and 4, the prostheses presented unilateral angular misfit of 50µm, 100µm and 200µm, respectively. A load of 133N with 30^o angulation and off-axis at 2mm of the implant long axis was applied on the models in opposite direction of misfit, through a finite element program named Ansys. According to stress maps, the increase of misfit produced more stress in prostheses (1056N/mm^2 at 2326N/mm^2) and uniform stress distribution in implant and trabecular bone. Regarding the displacement, the set exhibited inclination from 0.3101mm in control group until 0.3179mm in group 4 due to loading and misfit. The reduction of the unilateral contact between prostheses and implant led to set displacement and alterations in stress distribution and magnitude, mainly in prostheses and retention screw region. As a general rule, the unilateral angular misfit of 100µm and 200µm produced higher stress values in comparison to the control group. The difficulties concerning validation and accuracy of 2D finite element model are shown in analyses.*

Keywords: *finite element analysis, biomechanics, misfit, dental prosthesis, dental implantation.*

1. INTRODUCTION

Since the preliminary studies on osseointegration, dental implants have been extensively used for the rehabilitation of completely and partially edentulous patients over the last three decades (Branemark et al., 1969; Branemark et al., 1977; Adell et al., 1990). Despite the high success rate reported by a vast number of clinical studies, early or late implant failures are still unavoidable (Esposito et al., 1998).

According to the biomechanical point of view, an accurate fit in prosthesis/implant/retention screw system is very important once the osseointegration is not reached by a resilient way at the alveolar bone (Weinberg, 1993). So, it must be emphasized the need of passivity between prostheses and implants in order to avoid harmful stress among the superstructure, implant components (Millington and Leung, 1995; Duyck et al., 2001; Kunavisarut et al., 2002), and surrounding bone (Skalak, 1983). Passive fit between prosthesis and implants is obtained when the screw is joined to the structures only by an interlocking force, implying no bone strain in the absence of an occlusal load (Mulcahy et al., 2000). The misfit can cause an asymmetrical contact among the various components of the system, but an acceptable misfit level that did not produce any mechanical or biological problem (Kallus and Bessig, 1994; Ma et al., 1997; Jemt et al., 2000) is not well defined.

Nowadays, it is possible to assess dental implants mechanical properties with the finite element analysis (FEA) which is a very reliable method (Baiamonte et al., 1996). FEA allows researchers to evaluate stress distribution in the contact area of the implants with cortical bone and around the implants apex in trabecular bone (Rieger et al., 1990; O'Mahony et al., 2000; Kunavisarut et al., 2002; Sutpideler et al., 2004). It also enables to predict problems in prostheses-implant connection mainly concerning the cause of failures in retaining screw and surrounding bone (Patterson and Johns, 1992; Sakaguchi and Borgersen, 1995; Haack et al., 1995; Sertgoz, 1997; Byrne et al., 1998; Alkan et al., 2004; Kitagawa et al., 2005; Huang et al., 2005; Kano et al., 2006).

The misfit between prostheses and implants is a consequence of clinical and laboratorial practice and results in long-term complications for osseointegrated implants.

Modelling biological structures of irregular shape and different materials is difficult, notably when the structure includes interfaces and thin layers (Romeed et al., 2006). Developing accurate FE models of complex structures can be challenging, and it may not be possible to generate a good-quality mesh in complicated models (Lin et al., 1999). The accuracy of the solution being sensitive to the aspect ratio of the elements and mesh density. Two-dimensional FEA has been extensively used in different areas of dental research. However, it is known that 2D-FEA has limitations which may compromise reliability in determining the mechanical behaviour of dental restorations with different designs (Yang et al., 2001; Yang et al., 1999). On the contrary, 3D-FEA may offer acceptable reliability but remains an emerging rather than a widely established methodology in dental research.

Implant biomechanics is a growing field of research since many factors of implant treatment are based on biomechanical principles. Some evidence exists about the bone reaction in front of loaded implants but the information is still scarse (Sahin et al., 2002). Therefore, the aim of this study was to use the 2D-FEA to assess the displacement and stress inner distribution in the prosthesis/implant/retention screw system and surrounding bone of a metallic crown passively fitted to an implant (control group) and presenting different levels of unilateral angular misfit of 50µm, 100µm, and 200µm.

2. MATERIAL AND METHODS

Two-dimensional finite elements models reproducing a frontal section of edentulous mandibular posterior bone was constructed using a standard model: 1 implant-supported fixed partial denture (FPD).

To evaluate the effect of misfit, variations of the standard finite element model were made. The misfit level between the superstructure and the implant varied in the models (Isa & Hobkirk 1995, Cheshire & Hobkirk 1996, Jemt 1996, Byrne et al. 1998) to determine four groups. In Group 1 (control) the prosthesis fitted accurately to the implant while in Groups 2 (gap 50µm), 3 (gap 100µm) and 4 (gap 200µm) the prostheses presented a unilateral angular gap of 50 µm, 100µm and 200µm respectively.

The implant components were represented by a 3.75mm X 15.0mm standard external hexagonal Branemark system implant (SIN, Implant Systems, Sao Paulo, SP, Brazil), a UCLA-type Co-Cr abutment (SIN, Implant Systems, Sao Paulo, SP, Brazil) and a titanium retaining screw (SIN, Implant Systems, Sao Paulo, SP, Brazil). A model of cobalt-chromium superstructure (CNG Prosthetic Solutions, Sao Paulo, SP, Brazil) with 8mm in height and 8mm in the major diameter was created (Binon 1996). The surrounding bone model assumed 22mm in height, 21.7mm in width, cortical bone at the crestal region with 1mm in thickness, inferior cortical bone with 2mm in thickness (Kunavisarut et al. 2002) and trabecular bone with 19mm in height.

The prosthesis/implant/retention screw system was longitudinally sectioned using a saw machine (Isomet 1000 Precision Saw, Buehler, Lake Bluff, II, USA) and then scanned (HP scanjet 2400, Hewlett-Packard Company, Palo Alto, CA, USA) to produce digitalized images. The images were imported into image analysis software (AutoCAD 2005, AutoDesk Inc., San Rafael, CA, USA) and placed within the supporting tissue.

The outline of the models images was manually quoted and each point converted into *x* and *y* coordinates. The coordinates were finally imported into the finite element software (Ansys 7, Swanson Anlysis System, Houston, Pa, USA) as keypoints of definitive images (Fig. 1).

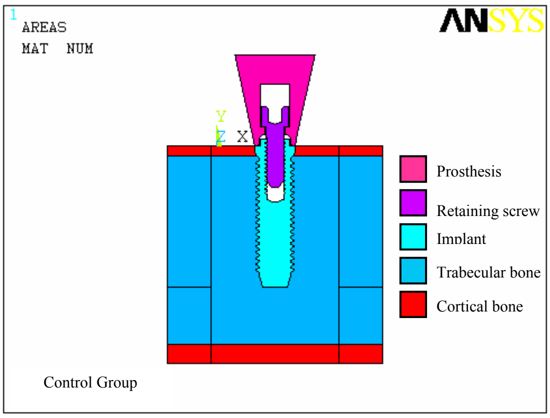

Figure 1: Model created in the finite element software representing prosthesis/implant/retention screw system in trabecular and cortical bone.

The geometric model was meshed with 2-D six-node triangular plain stress element (plane 2). The final models had a total number of 16.820 nodes and 8.275 elements for the model A, 16.868 nodes and 8.297 elements for the model B, 16.828 nodes and 8.277 elements for the model C and, 16.896 nodes and 8.309 elements for the model D (Fig. 2).

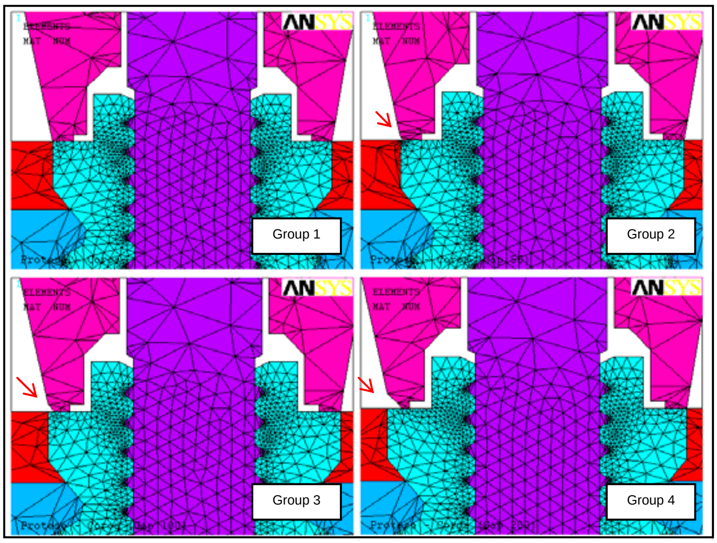

Figure 2: Approximate view of mesh elements in the region of contact between the prosthesis and the implant of groups 1, 2, 3 and 4, representing accurate fit and unilateral angular gaps of 50µm, 100µm and 200µm between the prosthesis and the implant, respectively.

When a model is assumed to be 2-D, the *z* axis (third dimension) must be specified to have either a plane-stress or a plane-strain condition. Plane stress assumes the model to be thin enough that no stress occurs in the *z* direction, but it has some strain in the *z* direction. Plane strain assumes the model to be infinitely thick, so that no strain occurs in the *z* direction, but some stress will develop in the *z* direction. In this study, a plane-stress condition ($\varepsilon_z \neq 0$ and $\sigma_z = 0$) was given to models because there was no constrain for *z* axis (buccal-lingual direction). Thus in third dimension (*z* axis) the models can deform and no stresses occurred.

All interfaces between bone and implant were considered as completely osseointegrated. All materials were assumed to be homogeneous and isotropic. Materials mechanical properties were taken from literature and manufacturer data (Tab. 1). In the four models, the boundaries conditions of the supporting tissue were constrained in the *x* axis and symmetric prescribed in the *y* axis to simulate the physiological conditions in a clinical situation.

Table 1. Structures and materials properties used in the models.

Materials	Young's modulus (GPa)	Poisson's ratio	References
Cortical bone	13.70	0.30	Barbier et al. (1998)
Trabecular bone	1.37	0.30	Barbier et al. (1998)
Implant (pure Ti)(1)	117.00	0.30	Sakaguichi and Borgersen (1995)
Co-Cr alloy	218.00	0.33	Craig (1989)
Titanium screw (Ti-6Al-4V)(1)	103.40	0.35	Sertgoz and Gunever (1996)

(1):The implant and retaining screw compositions were supplied by the manufacturer (SIN – Implant System).

In groups 2, 3 and 4, an oblique force (Holmgren et al. 1998) of 133N (Binon 1996) was applied in the occlusal surface (O'Mahony et al. 2000) at the opposite side of the misfit with an angulation of 30 degrees in relation to the long axis of the implant and 2mm off-axis. This force was applied to assess the stress in the prosthesis/implant/retaining screw system considering the unilateral angular misfit between the prosthesis and the implant.

Numerical data produced color graphics for better comparison of the models. The maximum and minimum principal stresses to cortical bone/implant interface, the von Mises stress to prosthesis/implant/retention screw system and trabecular bone, and the displacement of the prosthesis/implant/retaining screw system were calculated and plotted.

3. RESULTS

Assessing the displacement maps of prosthesis/implant/retention screw system and surrounding bone (Fig. 3), it was observed a gradual increase in the displacement of this system due to the decrease of the unilateral contact between prosthesis and implant. In group 1 (prosthesis accurately fitting in the implant), it was verified a system inclination due to loading and not to misfit, with maximum lateral displacement of 0.3101mm. In groups 2, 3, and 4 (gaps with 50µm, 100µm, and 200µm, respectively), the displacement increased to 0.3106mm, 0.3132mm and 0.3179mm (Fig. 3).

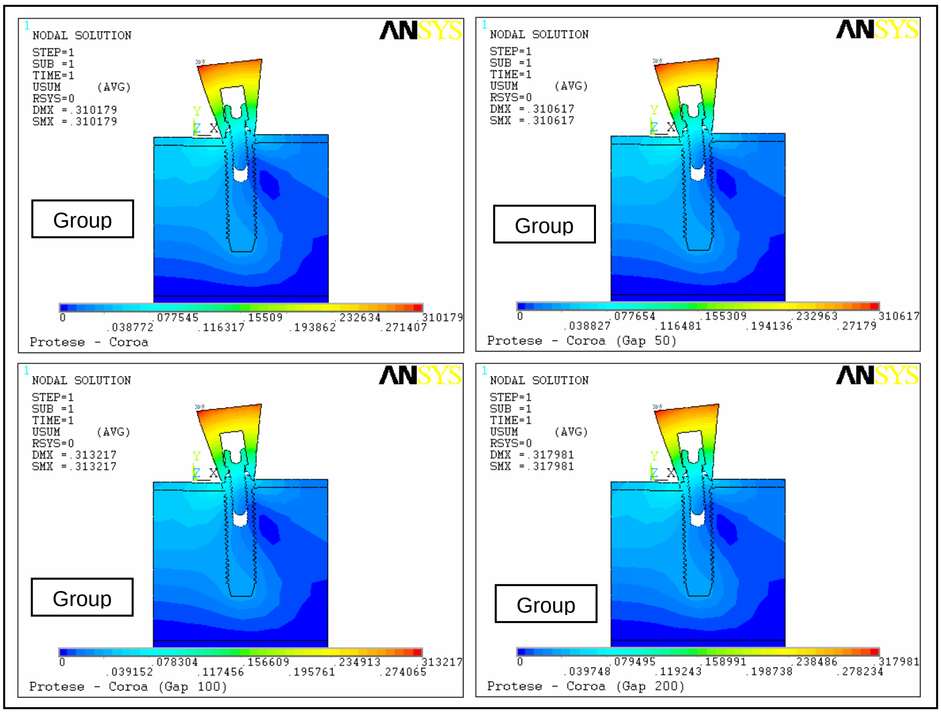

Figure 3: General maps of displacement conditions of the prosthesis/implant/retention screw system for groups 1, 2, 3, and 4.

Stress maps of all groups are presented in a standard scale to allow a better evaluation of components stress distribution. Some points from the components have presented maximum stress values upper to yielding strength. However, this stress was limited to specific areas such as stress concentration points and contact points among the parts and the implant and screw threads. But this situation is not similar to the real structure. These stress peaks are probably related to the mesh since it presents reduced elements in some areas with a reduced geometry too.

Furthermore, the limitations in 2D models are other relevant aspects. The two-dimensional model makes difficult to represent the circumferential contact area between the prosthesis and the implant. This difficulty could be undergone by a three-dimensional model or even by the inclusion of contact elements in the Finite Element model.

So, to evaluate stress distribution through a real way, the stress values scales were adjusted and standardized at the medium value of the control model maximum stress (group 1). According to this, it was possible to discuss the effect of different levels of unilateral angular misfit in the prosthesis/implant/retention screw system.

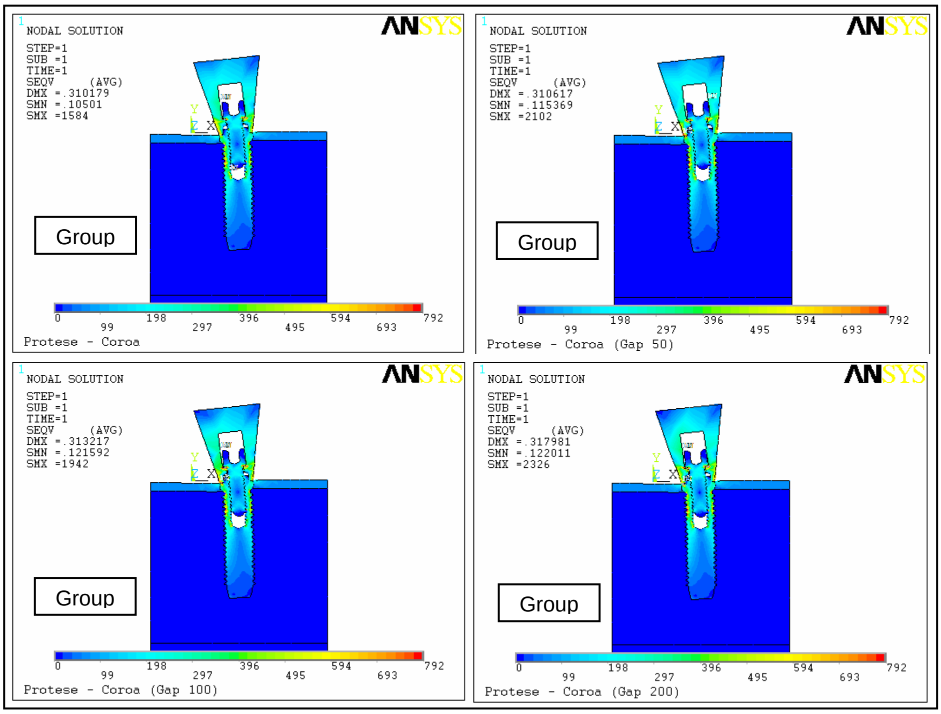

Figure 4: General stresses maps of the prosthesis/implant/retention screw system for groups 1, 2, 3, and 4.

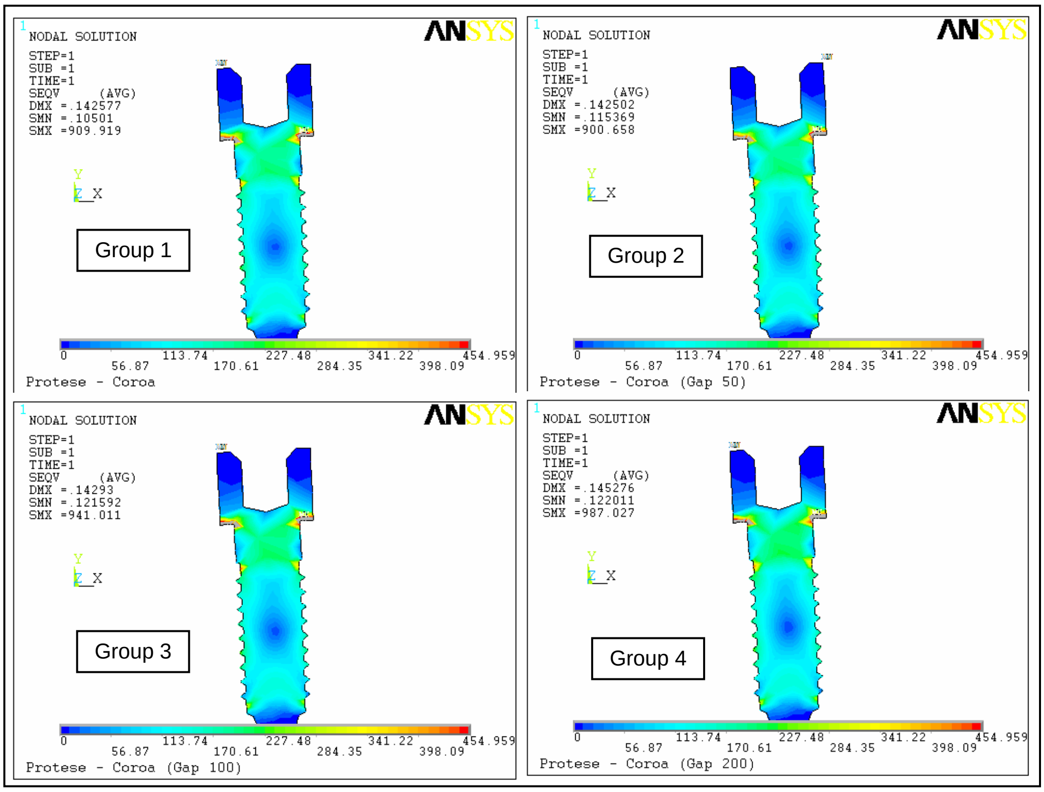

Figure 5: Plotted maps of the von Mises stresses distribution in the retention screw in groups 1, 2, 3 and 4.

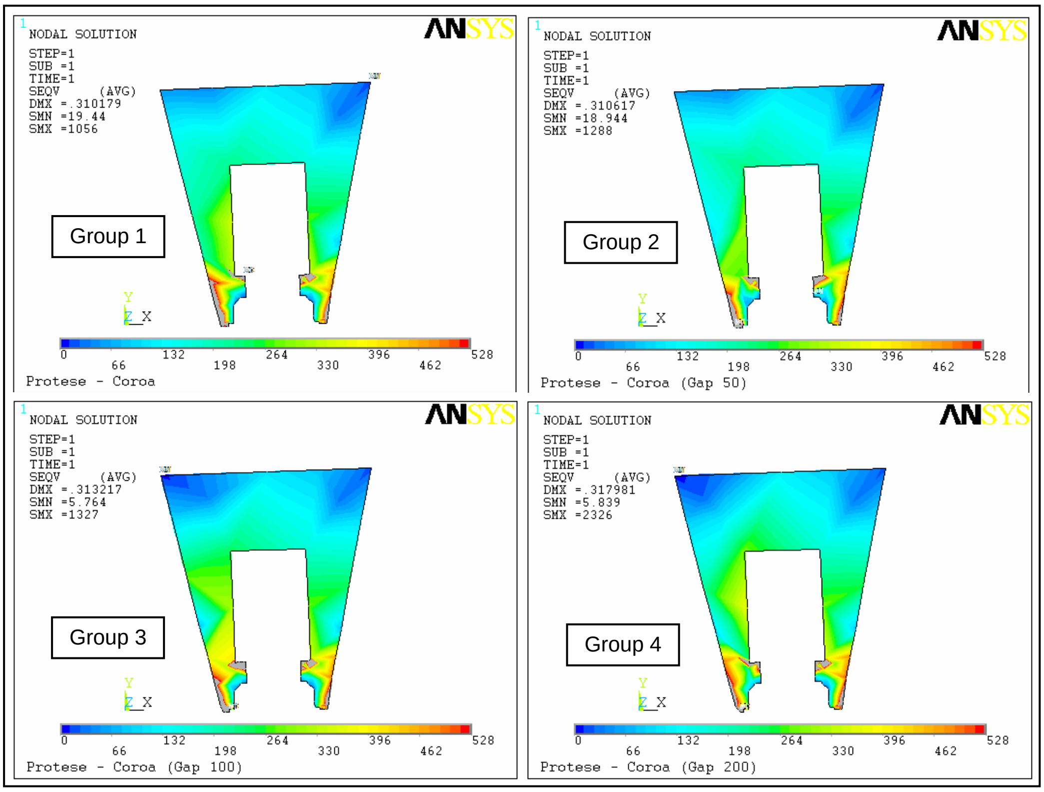

Figure 6: Plotted maps of the von Mises stresses distribution in the prosthesis in groups 1, 2, 3 and 4.

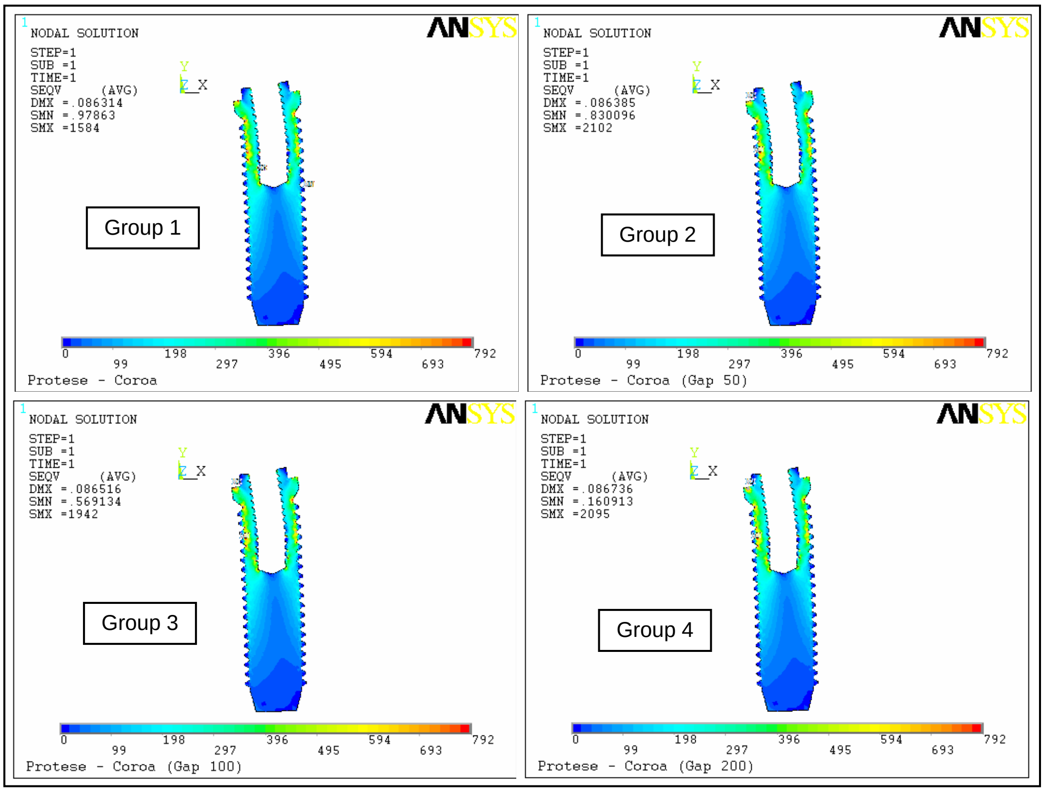

Figure 7: Plotted maps of the von Mises stresses distribution in the implant in groups 1, 2, 3 and 4.

The table 2 shows the maximum and minimum von Mises stresses for all groups. According to a qualitative evaluation, the maximum stress increased with the increase of misfit and was higher with the misfits of 100µm (group 3) and 200µm (group 4). These values are only a reference since they exceed the structure yielding strength in some areas. Although, they make possible the tendency evaluation through stress distribution maps. The Tab. 3 shows the maximum tensile and compressive strain values of the cortical bone region for all groups.

Table 2. Maximum and minimum values of the von Mises stress in the prosthesis/implant/retention screw system and trabecular bone.

Area	Group 1 (Control)		Group 2 (Gap 50)		Group 3 (Gap 100)		Group 4 (Gap 200)	
	SMN	SMX	SMN	SMX	SMN	SMX	SMN	SMX
Prosthesis/implant/ retaining screw	0.105	1584	0.115	2102	0.121	1942	0.122	2326
Retaining screw	0.105	909.91	0.115	900.65	0.121	941.01	0.122	987.02
Prosthesis	19.44	1056	18.94	1288	5.76	1327	5.83	2326
Implant	0.978	1584	0.830	2102	0.569	1942	0.160	2095
Trabecular bone	0.700	20.71	0.699	20.73	0.700	20.77	0.699	20.86

SMN = Minimum stresses values (N/mm^2)
SMX = Maximum stresses values (N/mm^2)

Table 3. Maximum tensile and compressive stresses in the superior cortical bone (N/mm^2) for each group.

Stress	Group 1 (Control)	Group 2 (Gap 50)	Group 3 (Gap 100)	Group 4 (Gap 200)
Tensile	96.55	96.55	97.54	99.41
Compressive	-121.29	-103.17	-81.57	-53.39

4. DISCUSSION

According to several *in vitro* and *in vivo* studies, the retention screw loosening and fracture are frequent complications in implant-supported prostheses (Kallus and Bessing, 1994; Carlson and Carlsson, 1994; Binon, 1996; Huang et al., 2005; Kitagawa et al., 2005; Kano et al., 2006) as consequence of elevated strains in the screw (Geng et al., 2001) and misfit in the prostheses (Rangert et al., 1989; Patterson and Johns, 1992). In this study, finite element analysis (FEA) models have shown that the presence of unilateral gap between superstructure and implant influence the displacement and stresses distribution in retention screw, prosthesis, implant and surrounding bone.

In group 2 (unilateral angular gap of 50µm), the system behavior did not change a lot in relation to its displacement (Fig. 3), the plotted stresses levels in the prosthesis/implant/retention screw system (Fig. 4) and the plotted stresses levels in each structure compared with group 1. According to mechanical principles, this little change was consequence of a little percentage (16%) in the decrease of contact between prosthesis and implant. Regarding groups 3 and 4 (gaps of 100µm and 200µm, respectively), the great decrease of contact between prosthesis and implant, with perceptual values of 33% and 66%, caused more biomechanical changes in the system. Numerically, the displacement values of groups 3 and 4 were slightly altered in comparison with control group and group 2. Considering micrometrics conditions, it was verified an increase in the displacement of 0.5µm, 3.1µm and 7.8µm for groups 2, 3, and 4, respectively, in comparison to group 1 (control). Therefore, this increased displacement in groups 3 and 4 can lead to changes in the stress distribution of the entire system. Furthermore, the tendency of increase displacement of the prosthesis can influence in the fatigue of the elements, and the useful life-time of the components carrying the highest tensile load, similar to previous studies done by Binon (1996) and Patterson and Johns (1992).

The presence of misfit up to 100µm caused an increased stress in the prosthesis retention screw. It was realized that the contact area between prosthesis and retention screw in the opposite side of the misfit showed increased stress due to the prosthesis displacement, which was consequence of the reduction in the contact between prosthesis and implant (Fig. 5). This probably occurred because the mechanical integrity of the system depends on two factors, such as the contact area between the components and the screw effectiveness. So, the adequate contact between superstructure and implant is important in the decrease of loading on abutment and prosthesis retention screws, and thus help to ensure the maximum effectiveness of those components, according to Byrne et al. (1998). However, if this does not occur, the higher loading concentration will be applied on the screw and its fatigue life time will be reduced in the order of weeks instead of years (Patterson and Johns 1992).

Stress maps (Fig. 5) have demonstrated some uniformity in such distribution at the screw body in the different groups and some alteration at the screw area of more concentrated stress, extending from the contact area between the prosthesis and the retention screw to the area of the screw neck and its first thread. Such results are in accordance with the study of Huang et al. (2005), who accomplished a bending strength test with static load of 798.8 ± 4.1N over the abutment screw. These authors verified a screw failure with a bending deformation higher than 2mm at the interface between the stem and first thread of the abutment screw. Through a theoretical analysis of the retention screws fatigue life, Patterson and Johns (1992) also demonstrated that the probable sites for the initiation of fatigue failure at the prosthesis/implant/retention screw system are the regions of stem and first thread of the screw. This is related to fatigue caused by the high stress concentration in the screw as consequence of the different changes in the thread pitch produced by the tensile strain in the bolt or screw and compressive strain in the clamped parts.

The stress maps analysis regarding the completely fitting prosthesis (group 1) demonstrated that the highest stress area was concentrated at the contact region between the prosthesis and the retention screw (Fig. 6). This change occurred at the stress distribution pattern of the system, mainly at the prosthesis, in function of the decreased contact between the prosthesis and the implant. This affirmation is in accordance with the study of Kunavisarut et al. (2002), that evaluated, through FEA-3D, stress distributions at implant components, prosthesis and adjacent bone in 2 elements-fixed-prostheses with and without cantilever and presenting vertical misfit between crown and abutment. The authors concluded that the misfit influenced the pattern and the magnitude of stress distribution at the prostheses, while a good stress distribution was observed in the case of passivity among all components, producing small stress peaks in each structure. Furthermore, Millington et al. (1995) applied a photoelastic analysis to evaluate the nature and magnitude of stress developed on an implant superstructure when different levels of misfit is present. For this, misfit of 6µm and 104µm were created to verify a positive relation between the size of the gap and stress on the superstructure. However, the rate of increase in stress with increasing gap size was nonlinear, as seen at the present study, since the static stress level caused by misfit is dependent on size, shape (vertical, horizontal and angular), and localization of the gap.

Contact alteration between prosthesis base and implant, regarding the different simulated misfit levels, also defined stress at the implant. In group 1, the highest stresses were located at the contact point between the retention screw and the implant. However, with the contact decrease between the prosthesis and the implant, the highest stress changed to the implant base, at the misfit area, evidencing that this area was more prone to stress concentration (Fig. 7) and the highest stress values did not show an increase in a gradual way. Even if the implant stress levels had varied, because of the contact reduction between prosthesis and implant, the levels were inside the limits of proper osseous tissue maintenance, in accordance with the studies developed by Rieger et al. (1990). Besides, it was noticed that the implant area where the use was more concentrated kept defined at the same contact point between the retention screws and the implant for all models, independent of the prosthesis base situation. This tendency at the stress uniformity verified in the implant body can be related to the more rigid material of the prosthesis in relation to the implant material. The same was reported in the study of Sertgoz (1997), which stated that the most rigid materials should be used for the superstructure manufacturing, in order to prevent prosthetic failure. This can reduce the overload risk at other structures such as implant and surrounding bone tissue, once the most resilient materials lead to an increase of stress within the prosthetic retention screws.

The stress maps that individualized the trabecular bone showed that this region did not directly absorbed the effects of change in misfit level between the prosthesis and the implant, due to its uniformity in stress distributions in all groups, besides of very similar maximum stress values (Tab. 2). Such fact proofs the tendency of stress uniformity verified also in the implant, showing that these areas are less used in situations of misfit between the prosthesis and the implant. It was also observed that the areas of higher stresses at the trabecular bone were located in the implant apex region and next to its prosthetic base. The same results were reported by Rieger et al. (1990) comparing, through FEA, stress patterns in trabecular and cortical bone surrounding six post-type endosseous implants. They verified that stress was concentrated at implant neck and apex when a load was applied on implant axis.

With the analysis of the upper cortical bone stress maps, it was verified a uniformity in the compressive and tensile values for group 1 (Tab. 3). However, groups 2, 3 and 4 showed different compressive and tensile values with reduction in the compressive values. So, the decrease of support between the prosthesis and the implant lead to a relief in the cortical bone at the compressive area and, consequently, resulted in the overloading of other system's structures. According to Rangert (1989), when the fit between the implant and prosthesis is not accurate, some of the anchorage units will take the main portion of the load while others will be virtually unloaded. Besides that, bone flexure around implants as a response to the misfit support the clinical concern of potential complications in terms of marginal bone resorption and possible loss of osseointegration (Jemt and Lekholm 1998).

The vast majority of FEA performed in dental research has employed 2D rather than 3D methods. 3D analysis having been found to be much more time-consuming and complicated (Yang et al., 2001). In certain situations combinations of 2D and 3D FEA may offer the best understanding of the biomechanical behavior of complex dental structures. So, investigations involving sophisticated FE models, both in terms of geometry and material properties, are required to better understand the mechanical behavior of restored tooth units (Rommed et al., 2006). Based on the obtained results, future studies should develop the two-dimensional models with the insertion of contact elements between implant platform and prosthesis base interface or create three-dimensional models to simulate more real conditions.

5. CONCLUSIONS

Within the limitations of this study, it is possible to conclude that:

- The decrease of the unilateral contact between prostheses and implant lead to the displacement of all system and change in stress distribution and magnitude, mainly in the prostheses and abutment screw areas. As a general rule, the angular unilateral misfit of 100µm and 200µm showed higher stress values in relation to the control.
- The difficulties on the validations and accuracy of 2D Finite Element model are shown in analyses and it is interesting to develop three-dimensional models in future studies.

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