Journal of the International Academy of Periodontology 2021 **23/1:** 65–71

Reduced Periodontal Support for Lower Central Incisor – A 3D Finite Element Analysis of Compressive Stress in the Periodontium

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Abstract

Background: The aim of this study was to assess the stress concentration in simulated periodontal alveolar bone containing healthy teeth with and without attachment loss.

Methods: Six 3-D models of a lower central incisor were created simulating the teeth structure, cancellous and cortical bone and periodontal ligament. Each model presented a 1mm increasing distance between cement-enamel junction (CEJ) and alveolar bone crest (ABC) (1 to 6mm). A 100N, 45-degree load was applied to the buccal face of the lower central incisor. The effects of Minimum Principal Stress (MPS) on lamina dura (LD) and ABC were analyzed.

Results: The results showed an increase of MPS in the surrounding bone (ABC and LD) due to periodontal attachment loss. The 6mm attachment loss model showed the highest ($p<0.001$) magnitude in MPS. Each millimeter increase in CEJ-ABC distance generated a 12% pattern of attachment loss and an increase at least of 65.7% for ABC and 33.6% for LD.

Conclusion: Under simulated conditions, attachment loss increases stress concentration in the surrounding bone suggesting a partly explanation regarding bone resorption risk for teeth with periodontal attachment loss.

Keywords: Periodontium, finite element analysis, bone, incisor

Introduction

The primary function of the human dentition is food preparation and processing through a biomechanical masticatory process. This process is involves transferring masticatory forces to the periodontium and this is mediated through the teeth (Versluis and Versluis-Tantbirojn, 2011). The periodontal apparatus (cementum, periodontal ligament and alveolar bone) plays an important role in stabilizing teeth. The forces produced during mastication are distributed and absorbed by the alveolar process through the alveolar bone. In health, the tooth-periodontium complex, maintains tissue homeostasis when subjected to physiological forces (Cattaneo *et al*., 2009).

Chronic periodontal disease is a major public health condition that affects more than one third of the population, 10-15% in its most severe form (Eke *et al*., 2012). Chronic periodontitis is the primary cause of tooth loss in people over age 35 (Deng *et al*., 2010). Diminished periodontal support results from the surrounding chronic inflammation arising in respons to the presence of a periodontal pathogenic biofilm (Cattaneo *et al*., 2009). Even after effective chronic periodontal disease treatment, a subsequent optimal maintenance phase, and the advances in bone regeneration therapies, vertical bone regeneration around tooth is an unsolved challenge for clinicians (Van Dyke *et al*., 2015).

Evidence in the literature indicates that previous attachment loss is classified as a risk indicator for recurrent disease (Takeuchi *et al*., 2010; Martin *et al*., 2010; Hirata *et al*., 2019). This risk may be explained by the diminished periodontal support removing the capability of teeth to withstand physiological chewing forces (Takeuchi *et al*., 2010; Martin *et al*., 2010).

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Among the methods for stress analysis of complex structures, finite element method (FEM) is a widely applied tool for bioengineering studies in dentistry (Dal Piva *et al*., 2019; Tribst *et al*., 2020). Different mechanical stimuli can impact the balance of bone homeostasis (Mercuri *et al*., 2016). The relationship between bone and mechanical stimuli has been evaluated by FEM analysis and PET/CT scanning (*in vivo*) with good correlation between these two methods (Suenaga *et al*., 2015).

Three-dimensional finite element analysis has been used in periodontology to estimate the potential effects of mechanical stimuli and stress on the periodontal apparatus (Poiate *et al*., 2008; Ona *and* Wakabayashi, 2006; Kondo and Wakabayashi, 2009; Tajima *et al*., 2009; Papadopoulou *et al*., 2013; Wakabayashi *et al*., 2008).

Therefore, the aim of this study was to use finite element analysis to measure and map the stress distribution of simulated normal and reduced periodontal support.

Materials and Methods

A computational-laboratorial study was conducted using a three-dimensional human lower central incisor model, constructed into the BioCAD protocol that consists of creating virtual geometric models of biological structures based on anatomical references (Papadopoulou *et al*., 2013). A three-dimensional scanned image of a lower central incisor with 19 mm length (9 mm crown; 10 mm root) was used as the reference for modeling the structures (Poiate *et al*., 2009). The complete model was constituted of cancellous bone, 1.0 mm cortical bone, 0.2 mm periodontal ligament (Wakabayashi *et al*., 2010) space and tooth (enamel, dentin and pulp) (Figure 1).

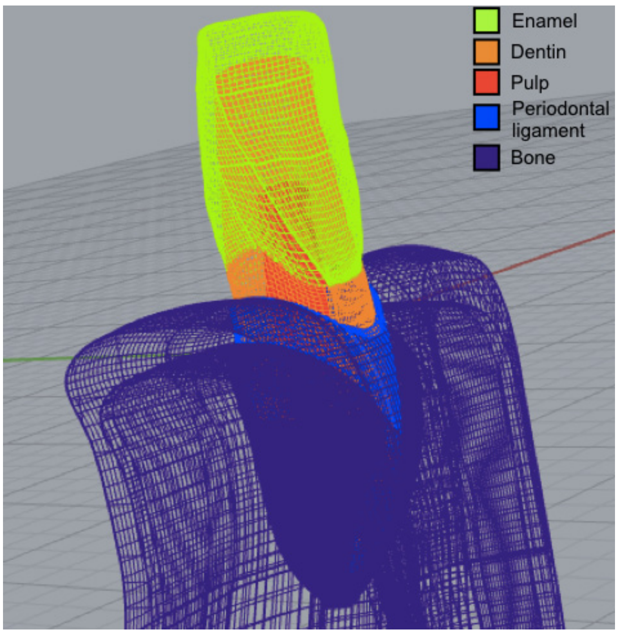

Figure 1. Geometric modeling of structures

Computer-aided design (CAD) software Rhinoceros 4.0 (McNeel North America) was used to achieve the 3-D model. Six different geometries of periodontal attachment were performed, in order to simulate different levels of periodontal attachment loss. In each situation different distances (1 mm; 2 mm; 3 mm; 4 mm; 5 mm and 6 mm) between the enamel-cement junction (CEJ) and alveolar bone crest (ABC) were simulated.

The geometric data were imported into Ansys software (version 16.0; Ansys, Canonsburg, PA) for static structural analysis. The mechanical properties of the tissues mechanical considered were: elastic, homogeneous, linear and isotropic. Biomechanical proprieties of the tissues was based on previously published data (Table 1) for bone (Moroi *et al*., 1993), enamel, dentin and periodontal ligament (Monteiro *et al*., 2018) and pulp (Toparli *et al*., 1999).

Table 1. Mechanical properties of materials/tissues simulated

Material/tissue	Young's Moduli (GPa)	Poisson Ratio
Enamel	84,1	0,30
Dentin	14,7	0,31
Pulp	0,000003	0,45
Periodontal ligament	0,0118	0,45
Cortical bone (Moroi, 1993)	14,7	0,30
Cancellous bone (Moroi, 1993)	0,49	0,30

Mesh generation used tetrahedral elements. The overall mean number of units was 197,908 elements and 347,271 nodes. The elements had 0.2 mm mean size and mesh surface convergence applied was 5%. It was ensured that all contacts were considered fully bonded, which means that the model was considered solid, with no gaps between structures.

A simulated 100N and 45-degree angled load applied at the buccal incisal edge of the lower central incisor. Nodal restriction was applied at the cortical bone base in all directions. The Consistency of the results was verified by total displacement analysis and von Mises criteria.

The stress concentration was analyzed using the Minimum Principal Stress (MPS) criteria, where positive values were related to tensile stresses and negative values to compressive stresses. Data processing performed was arranged in stress color maps and numeric values.

Mechanical stress was analyzed in the cortical bone and focused in two critical structures: alveolar bone crest and lamina dura. Stress variations are presented as a scale color map, where different colors mean different stress concentrations. Qualitatively the proximity colors with red in the scale, indicates higher stress concentration. For quantitative analyses the numerical values of minimum principal stress distributed in each structure (alveolar bone crest and lamina dura) were assessed. The colorimetric scales were adjustable for a visual comparison between the groups.

Results

The qualitative analysis (Figure 2) shows a color map illustrating the MPS distribution among the models. In the analyses of alveolar bone crest, an increase of compressive zones could be verified when the cement-enamel junction (CEJ) to the alveolar crest (ABC) distances were increased. In the 1 mm model compressive stress concentration peaks were observed on the lingual bone crest. With an increase in the CEJ-ABC distance, an increase in the minimum principal stress was located mainly on lingual face and in the 5 to 6 mm models some peaks were noted on the buccal face. For the lamina dura color map, an increasing CEJ-ABC distance lead to wider compressive stress concentration areas. In the 1 to 3 mm models, compressive areas were primarily located to proximal regions (near to fulcrum area). For 4 mm, the location peaks of compressive stress started to spread to buccal and lingual areas. It is noteworthy that in all models, the 6 mm situation presented the broadest areas of compressive stress.

Quantitative analyses were also performed and revealed the same pattern of qualitative data, augmented values of MPS showed an increased distance for CEJ-ABC. For each millimeter increase in CEJ-ABC distance, about 11% of the linear attachment was lost up to a 12% total attachment area loss (Table 2).

Minimum principal stress distributions, as assessed by scatter plots for 2D distribution, showed statistical significant differences (SSD) among groups for changes in alveolar bone crest and lamina dura. The compressive stress values were also compared in pairs (1 vs. 2, 2 vs. 3, 3 vs. 4, 4 vs. 5 e 5 vs. 6). Statistical significant differences were found for both the alveolar bone crest and lamina dura (Figure 3). Moreover, it was noted that with a decrease in periodontal support the intra model variance of MPS display amplification (Figure 3).

Pearson's correlation coefficient analyses between attachment loss and peak of MPS were performed for ABC and LD. Statistical significant difference and high

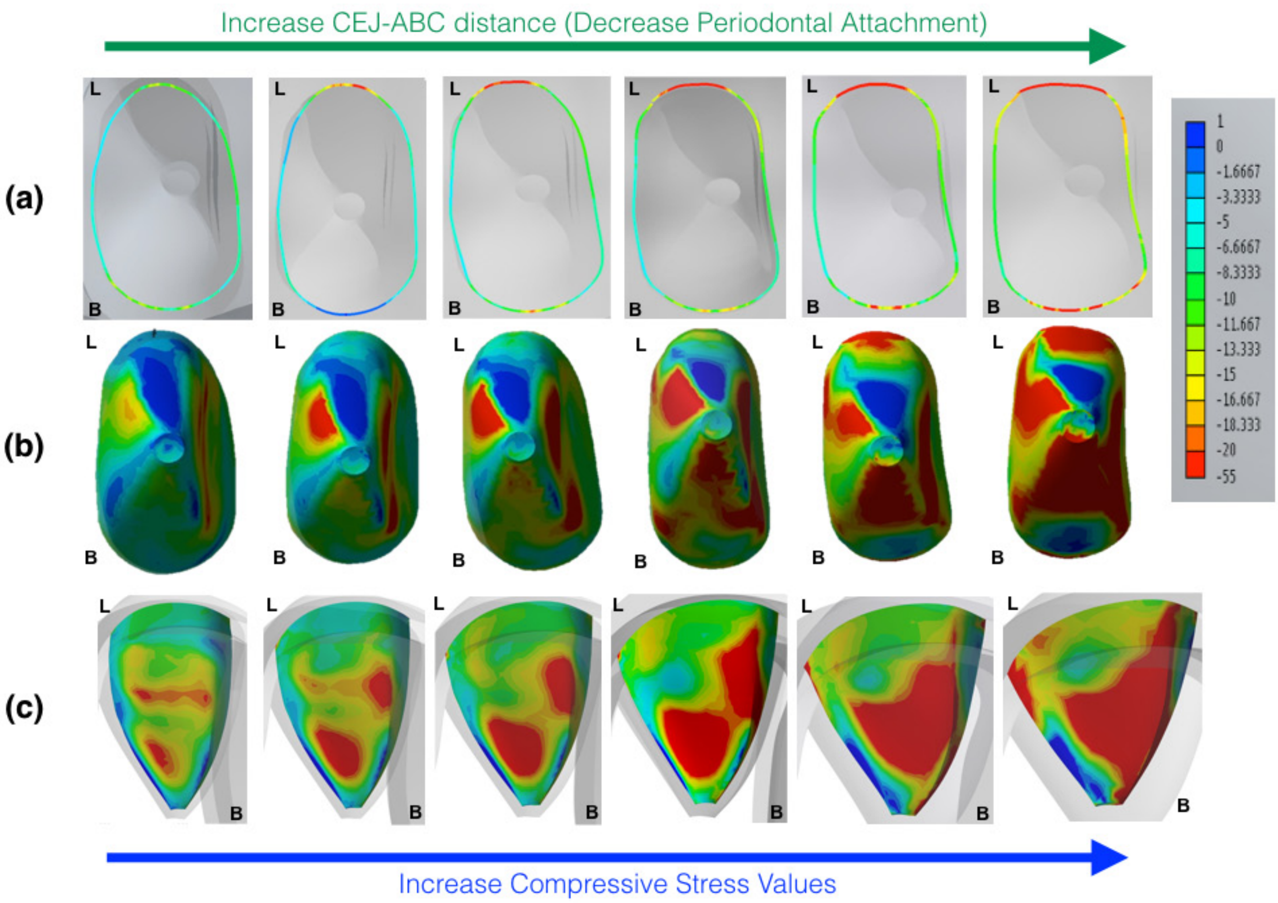

Figure 2 - Color mapping of compression stress in the alveolar bone (a) ABC view, (b) LD occlusal view, (c) LD proximal view

Table 2. Descriptive statistics of compressive stress in ABC and LD in each simulated CEJ-ABC distance

Distance of CEJ-ACB	Alveolar Crestal Bone: Number of nodes	Alveolar Crestal Bone: % of linear attachment lost	Alveolar Crestal Bone: Minimum Principal Stress (MPa) Peak	Lamina Dura: Number of nodes	Lamina Dura: % of attachment area lost	Lamina Dura: Minimum Principal Stress (MPa) Peak
1 mm	178	0,0%	-14,76	6176	0,0%	-21,64
2 mm	183	11,1%	-24,46	5463	12,4%	-28,91
3 mm	181	22,2%	-25,37	4290	24,7%	-33,07
4 mm	175	33,3%	-33,86	3601	36,9%	-45,99
5 mm	170	44,4%	-48,96	3080	48,4%	-60,51
6 mm	160	55,6%	-52,04	2333	59,3%	-122,18

CEJ - Cementum Enamel Junction
ABC - Alveolar Bone Crest
MPS - Minimum Principal Stress

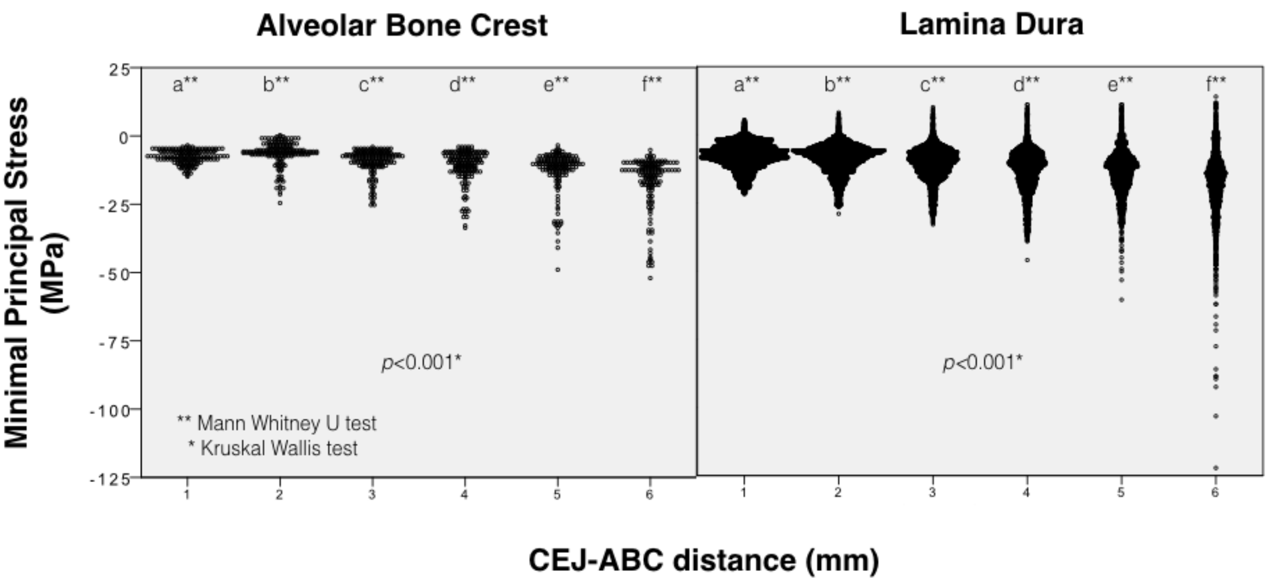

Figure 3. Chart of distribution of Minimal Principal Stress values among groups

positive correlation (p=0.020; r=0.882) were found for LD. SSD had a very high positive correlation (p=0.001; r=0.975) for ABC.

The MPS peak increase in the no attachment loss model, showed that the peak of compression stress increased by 65.7% (ABC) and 33.6% (LD) with 11% of attachment loss (2 mm model), and up to 252.6% (ABC), 464.6% (LD) and 55.6% of attachment loss (6 mm model) (Figure 4).

Discussion

Horizontal attachment loss is a consequence of periodontitis that remains even with the reestablishment of periodontal health. Reduced periodontal support does not seem to limit bite force (Kleinfelder and Ludwigt 2002). Subjects with attachment loss can exert up to three times higher forces on the teeth. These functions may related to affected sensory function of the periodontal ligament (Johansson *et al*., 2006). Different mechanical stimuli can modulate bone-remodeling processes (Burger *et al*., 1999), and alter molecular pathways in bone metabolism (Rubin *et al*., 2006). Excessive mechanical stress during hyper-occlusion may lead to alveolar bone destruction during occlusal traumatism (Tsutsumi *et al*., 2013). An important gap in knowledge still remains unanswered whether the masticatory loads in severe attachment loss can exceed bone adaptive load bearing capability leading to periodontal tissue damage.

In the present study an overall increase in the minimum principal stress (mainly compressive stress) was

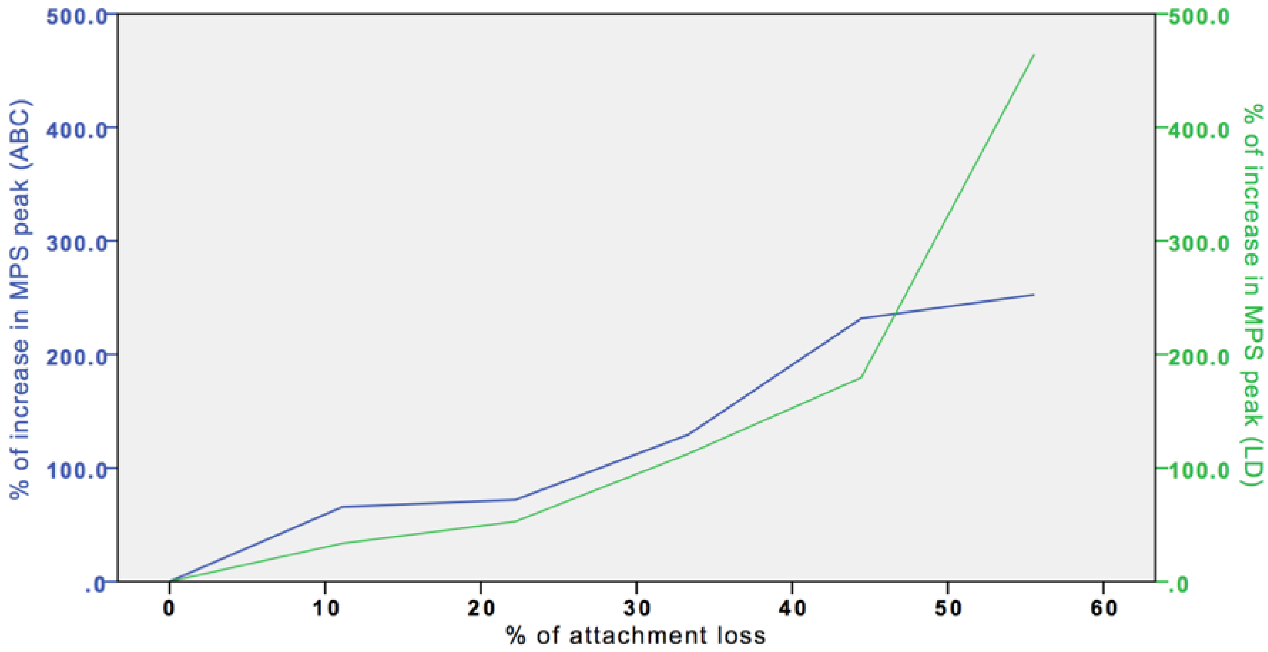

Figure 4. Chart of Minimal Principal Stress peak increase in relation to no attachment loss model

demonstrated in the target bone structures (alveolar bone crest and lamina dura). This result shows that even with the same force (that simulated bite forces), the tooth surrounding bone structures were subjected to higher compressive stress. Cyclic stress may generate cumulative damage to the bone (Hambli *et al.*, 2016). Therefore, if a tooth has reduced periodontal support, the cyclic occlusal forces can intensify bone damage. In periodontal maintenance therapy, reinforcement of oral hygiene and biofilm removal is indicated (Armitage *et al.*, 2016). Also in this phase, occlusal adjustment has been reported to improve periodontal health in terms of bacterial profile and clinical appearance (Meynardi *et al.*, 2016).

The distribution of stress values presented a non-parametric distribution in the investigated bone structures, this is expected due to anatomic characteristics of the designed structures, the vector force incidence, and the axis of tooth rotation. Other studies have shown a similar distribution configuration (Ona and Wakabayashi, 2006; Geramy *et al.*, 2004).

Stress values exceeding the critical threshold of between 50 and 60 MPa have been reported to cause detrimental effects on human cortical bone (Sugiura *et al.*, 2000). In our study, peaks of MPS were reached in the 5 and 6 mm model in lamina dura. These findings are not in agreement with a previous study that found the height bone reduction potentially did not cause mechanical damage (Ona and Wakabayashi, 2006). It is noteworthy that literal interpretation of the stress values is not a straightforward matter and characteristics such as position of the teeth (Gerami *et al.*, 2016), oclusal dynamic and cyclic loading conditions should all be taken into account (Benazzi *et al.*, 2013). Caution also is necessary since the effects of forces are dependent on the accuracy of the elastic properties that are being fed into the program and the accurate biomechanical proprieties of tissues (McGuinness *et al.*, 1991). Alveolar bone was chosen for analysis because it is one of the first tissues affected by the inflammatory response to bacterial stimuli (Nakamura *et al.*, 2010). Biochemical mediators regulate inflammation and bone resorption and some *in vitro* studies have shown that these sites can also be be modulated by mechanical stimuli (Hienz *et al.*, 2015). The lamina dura area was chosen for analysis because it has an intimate anatomical relationship with the root surface and during injury, adaptive remodeling occurs during the repair phase aiming to better cope with excessive loads (Gerami *et al.*, 2016).

An increase in the intensity of the MPS peak was clearly seen in the LD when 40% of the attachment area was lost, this increase also showed a peak increase in the ABC, but without any change in pattern. The correlation coefficient between the MPS peak and percentage of attachment loss reveled the high degree dependence between these parameters. When the force of occlusion was constant, and the attachment area of the tooth became smaller, the compressive/area stress tended to increase.

Even considering the inherent limitations of finite element analysis, and the restrictions in the created computational mathematical model, such as simplification of structures mechanical properties (Cook and Mongeau 2007), the specific dental element designed and its anatomical morphology are reasonable if their impact on the conclusions is carefully taken into account. It has been shown, for example, that the assumption properties for periodontal ligament could interfere with the stress values, but this did not change the biomechanical behavior of tooth-periodontal structure (Wood *et al.*, 2011). Moreover, force application is a difficult task to mimic because of the nature of masticatory function and natural loading scenario. However, the patterns of compressive stress distribution values found in the simulated models, clearly indicated a trend towards increase stress concentration when periodontal attachment was reduced.

The results of this study provide some knowledge to understanding the relationahip between occlusal trauma in teeth with reduced attachment apparatus and normal periodontal ligament space. Clinically, this suggests that *in vivo*, similar clinical situations, submitted to chewing forces can generate stresses that exceed physiological limits and cause periodontal bone damage. Questions about the threshold capability should be explored. These findings may potentially assist in the development of treatment strategies and prevention to avoid alveolar bone injury during periodontal treatment maintenance phase. Thus, teeth with attachment loss and normal periodontal ligament space, should receive special attention in relation to occlusal relations and masticatory loads.

Limitations of this study are that the present models do not represent all the oral variations such as changes in pH, temperature, sliding occlusal loading, presence of bacteria, different antagonistic materials, and parafunctional habit. The simulated condition used for this study were considered isotropic and homogeneous with a simplified behavior.

Conclusion

The results of this study demonstrate that attachment loss around teeth increases stress concentration in the surrounding bone. Despite inherent limitations of the model used the results define a biomechanical changing in stress pattern, which help to partly explain bone resorption risk for teeth with periodontal attachment loss and normal ligament space.

Acknowledgment

CAPES/FAPITEC/SE supported this research.

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