Mechanical behavior of dental implants in different positions in the rehabilitation of the anterior maxilla

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Statement of problem. In dental rehabilitations that involve implants, the number of implants is sometimes smaller than the number of lost teeth. This fact can affect the biomechanical behavior and success of the implants.

Purpose. The purpose of this study was to investigate the mechanical behavior of different implant positions in the rehabilitation of the anterior maxilla.

Material and methods. Three-dimensional models of the maxilla were created based on computed tomography images for 3 different anterior prosthetic rehabilitations. In group IL, the implants were placed in the lateral incisor positions with pontics in the central incisor positions; in group IC, the implants were in the central incisor positions with cantilevers in the lateral incisor positions; and, in group ILIC, one implant was in a lateral incisor position and one was in a central incisor position, with a pontic and a cantilever in the remaining positions. A 150 N load was distributed and applied at the center of the palatal surface of each tooth at a 45-degree angle to the long axis of the tooth. The resulting stress-strain distribution was analyzed for each group.

Results. The lowest displacement of the prosthetic structure was observed in group IC, although the same group exhibited the largest displacement of the bone tissue. In the bone tissue, the von Mises stress was mainly observed in the cortical bone in all groups. The maximum value of the von Mises stress shown in the cortical tissue was 35 MPa in the implant that neighbors the cantilever in group ILIC. The maximum von Mises stress in the trabecular bone was 3.5 MPa.

Conclusion. The prosthetic configuration of group IC limited the displacement of the prosthetic structure but led to greater displacement of the bone structure. The use of a cantilever increased the stress concentration in the implant and in the bone structure adjacent to the cantilever under the conditions studied here. (J Prosthet Dent 2014;111:301-309)

Clinical Implications

Overload is the most common mechanism of failure in dental implants. The appropriate positioning of dental implants and knowledge of the distribution of strain and/or stress can help to avoid mechanical overload, prevent failures, and ensure the success of dental implants.

The high rate of success of rehabilitation with dental implants and implant-supported prostheses has not only increased the number of indications for functional recovery but also increased esthetic demands made by patients and clinicians.[1-4] To obtain satisfactory functional and esthetic results, it is essential to achieve appropriate 3-dimensional positioning of the implants. The buccolingual positioning of the implant is mainly determined by prosthetic planning and by the anatomic occlusal conditions of the patient. The implant should be placed in the center of the crest bone by visualizing an imaginary line that connects the incisal edge of the adjacent teeth[5] and must also preserve a bone thickness of approximately 2 mm on the labial and palatal bony walls.[4]

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Furthermore, adequate buccolingual and mesiodistal positioning of the implant is important. Thus, the implant must be kept at a distance of 2 mm from the adjacent teeth and 3 mm from other implants to ensure the preservation of the crestal bone.[6] However, for many patients, the mesiodistal distance in the arch is not sufficient to allow for the placement of an implant for each lost tooth; in this situation, implant restorations are associated with pontics to optimize spacing and improve esthetics.[7]

Although Naert et al[8] in their systematic review did not find studies without bias or that support an adequate relationship between cause and effect between occlusal overload and bone and/or implant loss, there is a consensus that, when the number of implants is reduced, the biomechanical load in the system will increase and the implant overload may lead to bone loss.[9-14]

This study used the finite element method (FEM) to study the biomechanical behavior of a system missing 4 anterior teeth with 2 implants in the maxilla. FEM is a technique in which a physical prototype is studied by creating virtual mathematical models.[15,16] The geometric model is subdivided into small elements that are interconnected by nodes, to generate a finite element mesh.[17,18] This model can be solved by software implementing a large number of mathematical equations to simulate the specific structure.[19-22]

In the current work, a maxilla was geometrically modeled based on real computed tomography data, which made it possible to determine the stress and strain that result from the application of a force in the finite element model. The null hypothesis was that no significant difference among the groups would be found in the mechanical behavior of dental implants.

MATERIAL AND METHODS

To represent a clinical situation, a 3-dimensional (3D) model of the anterior maxilla was created with an intercanine distance of 27.3 mm, based on a database of computed tomographies available at the Renato Archer Center of Information Technology. This anatomic model was generated by combining several anatomic maxillary structures averaged over the database of the computed tomography.[23] The model then was used to construct a simplified geometric model with software (Rhinoceros 4.0 SR8; McNeel). The geometric models of the abutments, screws, and implants were constructed in the same modeling software used for the maxilla, based on images provided by the manufacturers (Neodent Ltda).

A specific model was created for each group: group IL, implants in the lateral incisor positions and pontics in the central incisor positions; group IC, implants in the central incisor positions and cantilevers in the lateral incisor positions; and group ILIC, 1 implant in a lateral and 1 implant in a central incisor position, with a pontic and a cantilever in the other positions. Each model was imported to the software (FEMAP v10.1.1; Siemens) for preprocessing, and the information required to characterize the biomechanical situation was provided. The mechanical properties of the structures were characterized in terms of the elastic modulus (E) and Poisson ratio (ν), with the values shown in Table 1 given by the manufacturer (Neodent Ltda) or available in the literature. All materials were considered isotropic, homogeneous, linear, and elastic.[24,25]

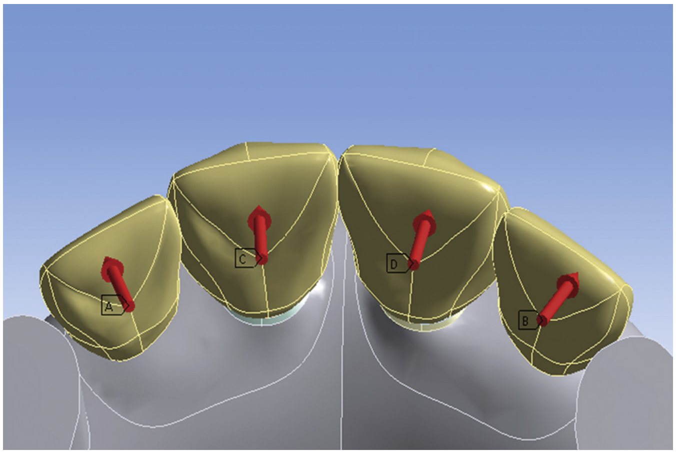
The mesh was constructed with tetrahedral elements with 10 nodes. A total load of 150 N was distributed and applied at the center of the palatal surface of each tooth at a 45-degree angle to the long axis to simulate functional occlusion (Fig. 1).[26-31] The bone-implant interface was considered bonded, and all the screw threads were filled with bone to simulate an osseointegrated implant. The interfaces between cortical-trabecular, trabecular-implant, cortical-implant, prosthetic structure-abutment, and abutment screw-implant were considered bonded; the interfaces between abutment-implant and abutment-abutment screw were considered common contact. The meshes contained an average of 1 245 854 nodes and 806 171 elements.

RESULTS

In group IL, the peak displacement in the prosthetic structure was 0.095 mm in the region of the central incisors, with less displacement observed when approaching the cervical region of the lateral incisors and the ends of the maxilla (Fig. 2A). The stress dissipation in the maxilla was symmetric. The peak of the displacement was approximately

TABLE 1. Material properties used in finite element analysis studies of dental implants

Materials	Young Modulus (E), MPa	Poisson Ratio (ν)	Study
Cortical bone	13.7	0.3	Menicucci et al,[32] 1998; Meijer et al,[33] 1995
Trabecular bone	1.3	0.3	Menicucci et al,[32] 1998; Meijer et al,[33] 1995
Implant (titanium comercialmente puro grade 4)	103	0.361	Manufacturer
Abutment and abutment screw (titanium alloy)	105	0.361	Manufacturer
Prosthetic structure (nickel-chromium alloy)	210	0.28	Anusavice,[34] 2012



1 Representation of load application.

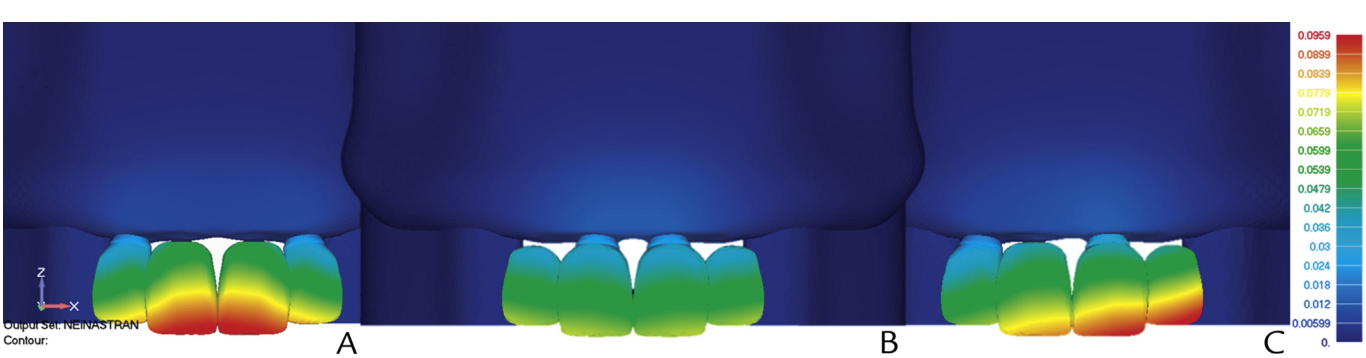
0.01 mm from the labial region of the implant toward the labial and mesial region in the maxillary bone (Fig. 3A). In group IC, the peak displacement in the prosthetic structure was lower than in the other groups, at approximately 0.079 mm, was homogeneously distributed, and ended at the maxilla (Fig. 2B). However, this group featured the highest displacement of the maxillary bone, with a maximum displacement of approximately 0.013 mm (Fig. 3B). In group ILIC, the maximum displacement in the prosthesis region was similar to that of group IL, but the peak stress was shifted to the lateral incisor, which corresponded to the cantilever side (Fig. 2C). The distribution of displacement in the maxillary bone was asymmetric as was the prosthesis, with the highest displacement observed in the region adjacent to the implant in the central incisor, with a peak displacement slightly higher than that in group IL (Fig. 3C).

In group IL, when the maximum principal stress in the cortical bone was analyzed, the tensile stresses were located in the mesiodistal region, the site of implant insertion, with values that ranged from 14 to 18 MPa (Fig. 4A). When the minimum principal stress in the cortical bone was analyzed, the compressive stress was located on the labial wall where the implants were inserted. These compressive stresses ranged in magnitude from −20 to −22 MPa (Fig. 4D). In group IC, the tensile stress was located in the mesiopalatal and distal region of the implant insertion site. The tensile stresses were between 9 and 12 MPa (Fig. 4B). The compressive stress was also located in the labial region of the implants, with values ranging from −12 to −15 MPa (Fig. 4E).

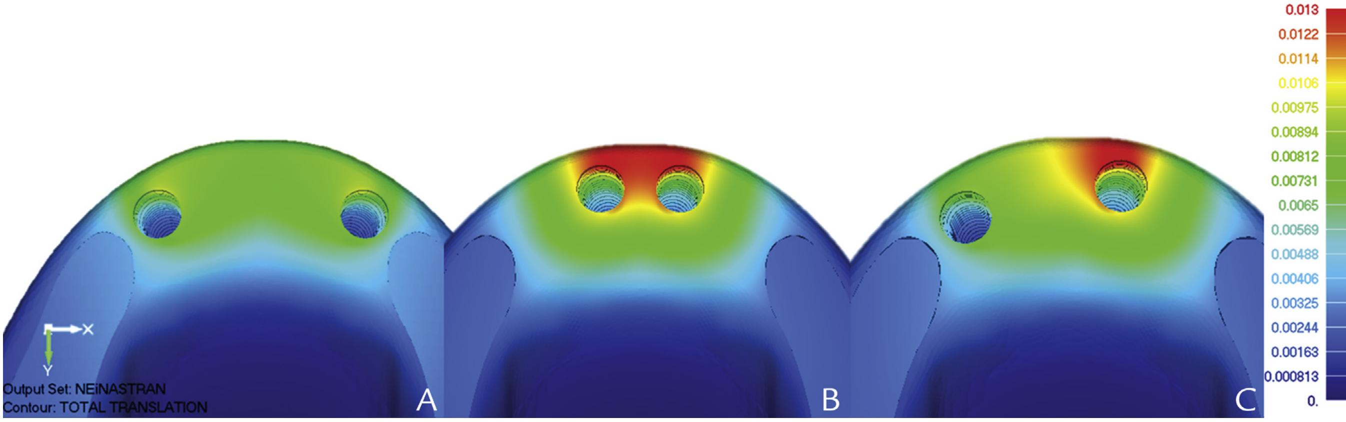
In group ILIC, the tensile stress was located in the mesiopalatal and distal incisor and in the distal portion of the implant in the lateral incisor implant, with values of 15 to 18 MPa. Stresses greater than 20 MPa likely result from premature contact with the mesh, viewed as dappled areas (Fig. 4C). The compressive stress also was located in the labial region of the implant insertion site, with values between −15 and −20 MPa and in the region of the lateral implant and values between −20 and −30 MPa in the region of the central implant (Fig. 4F).

When the maximum principal stress in the trabecular bone was analyzed, the tensile stresses in all groups were located in the labial wall (region near to cortical region) and the region of apex of the implants, with values that ranged from 2 to 3 MPa (Fig. 5A-C). When the minimum principal stress in the trabecular bone was analyzed, the compressive stress in all the groups was located in the labial wall (region near to cortical region) and region of the apex of the implants. These compressive stresses ranged in magnitude from −2 to −3 MPa (Fig. 5D-F).

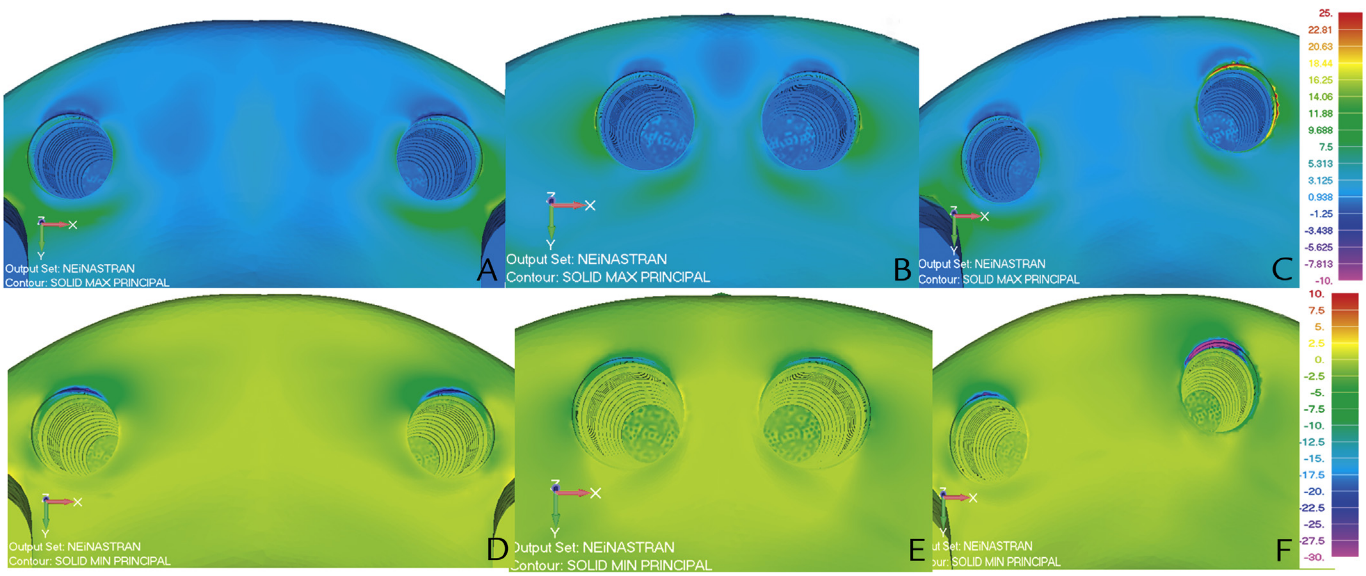
In this study, the von Mises stress was used as a parameter to view the mechanisms of stress dissipation and to compare among the models, not as a parameter for the identification of critical regions of stress in bone or other brittle structures. When the von Mises stress in the sagittal section of the left implants was analyzed, the stress was found to be mostly dissipated by the cortical maxillary bone. The highest von Mises stress was observed in group ILIC (note the scale), followed by group IL and group IC (Fig. 6A-C). The view of the trabecular region of the left implants verified that the maximum stress (value 3.5 MPa, with a similar value observed for the implants on the right side) was lower than the stress observed in the cortical region. The areas of concentration of stress in trabecular bone were



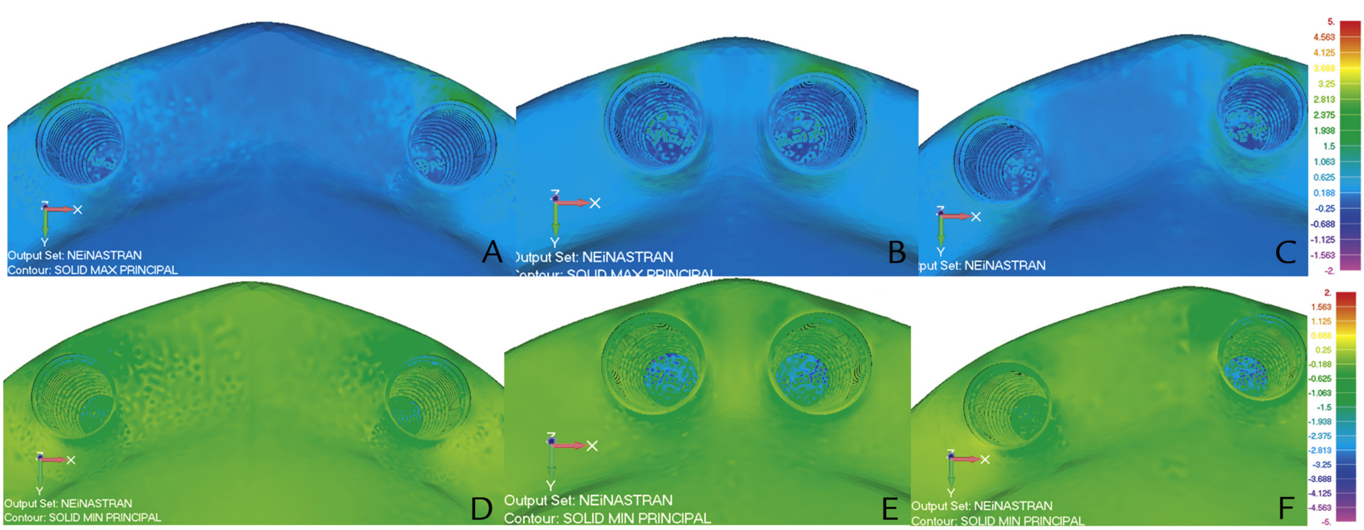
2 Front view of displacement of prosthetic structure. A, Group IL. B, Group IC. C, Group ILIC.



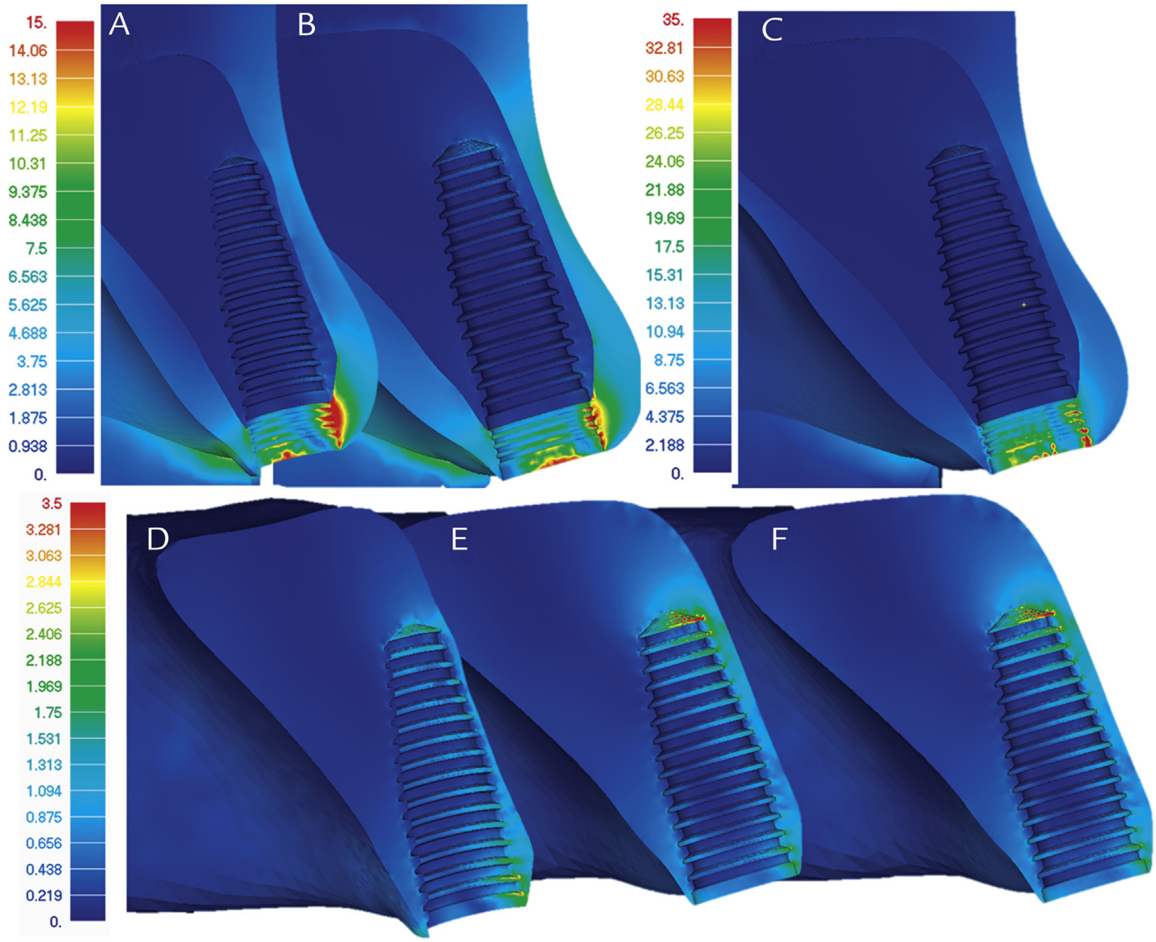
3 Occlusal view of maxillary bone. A, Group IL. B, Group IC. C, Group ILIC.



4 Maximum principal stress in cortical bone, occlusal view (A-C). A, Group IL. B, Group IC. C, Group ILIC. Minimum principal stress in cortical bone, occlusal view (D-F). D, Group IL. E, Group IC. F, Group ILIC.



5 Maximum principal stress in trabecular bone, occlusal view (A-C). A, Group IL. B, Group IC. C, Group ILIC. Minimum principal stress in trabecular bone, occlusal view (D-F). D, Group IL. E, Group IC. F, Group ILIC.



6 Sagittal view of von Mises stress of cortical and trabecular bone of left implants (A-C). A, Group IL. B, Group IC. C, Group ILIC. Sagittal view of von Misses stress of trabecular bone (D-F). D, Group IL. E, Group IC. F, Group ILIC.

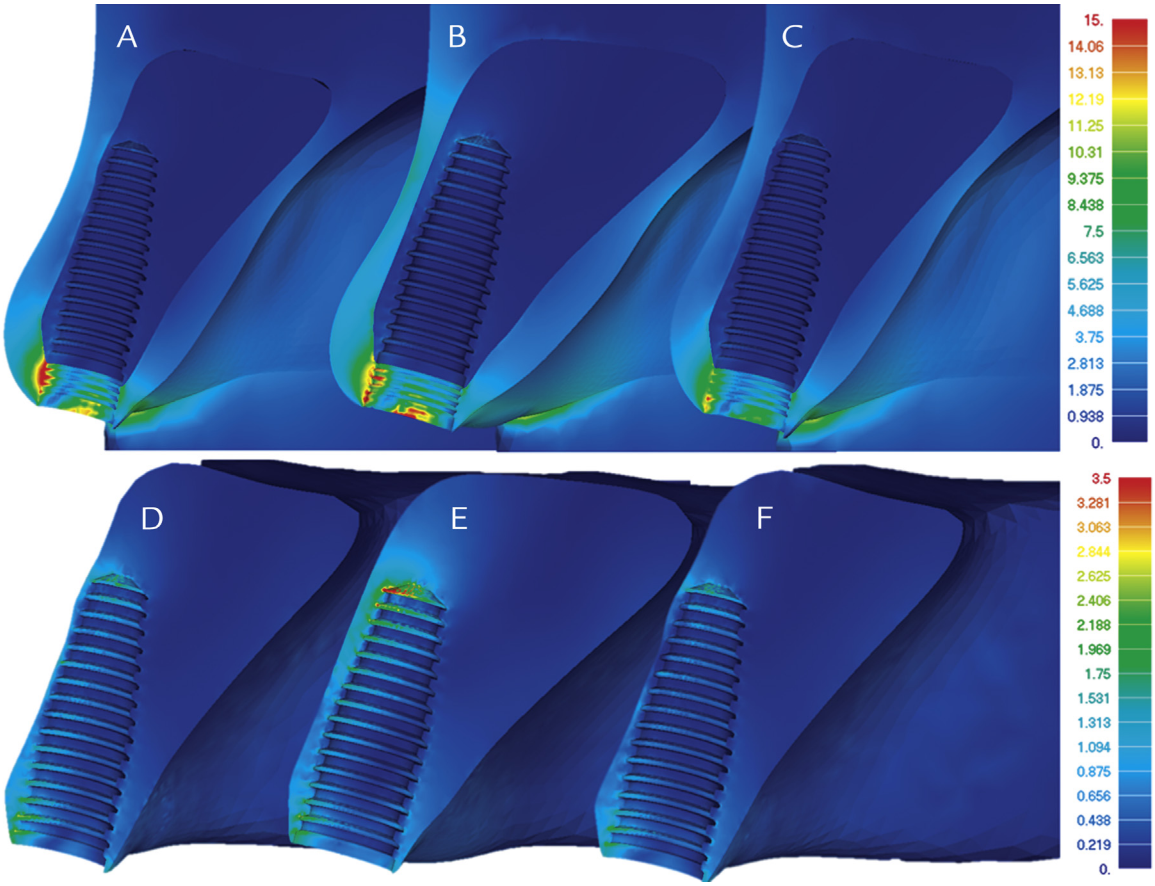
located in the cervical region, adjacent to the area of greatest concentration of stress on the cortical bone. The stress was directed toward the apex from the labial wall (Fig. 6D-F). The right implants had similar stress distributions among the 3 groups. The lowest values were observed in the implants of group ILIC. The stress in all groups was highest in the cervical region. Similar to the left implants, the stress was directed toward the apex from the labial wall (Fig. 7A-F).

When analyzing the von Mises stress in dental implants in all groups, considerable stress existed in the labial region of the internal hexagon and in the labial region of the platform implant (Fig. 8A-C). Groups IC and IL showed similar stress distributions, predominantly on the inner side of the hexagon of the implants, with group IC showing fewer areas of maximum stress (Fig. 8A, B). In group ICIL, the stress was mainly distributed at the implant plateau and on the inner side of the hexagon of the implant (Fig. 8C). The stress was predominantly distributed in the first threads of the implant, which corresponded to the region of insertion of the implant in the cortical bone (Fig. 8A-C).

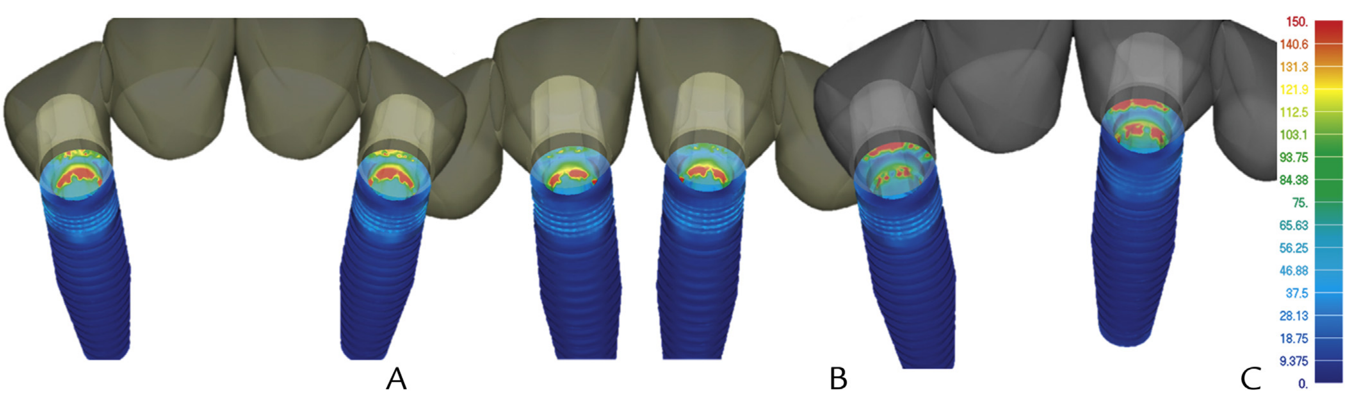
When analyzing the von Mises stress in the abutments, a significant area of stress was observed in the labial region for all abutments, more specifically on the plateau of the abutment and at the edges of the hexagon. In the posterior region, the stress was mainly located at the top of the hexagon. The bending motion of the prosthetic abutment was characterized in Figure 9A-C. When analyzing the von Mises stress in the abutment screws in a frontal view, the stress appeared to be concentrated in the region in which the head screw makes contact with the abutment, propagated along the screw shaft and increased again in the third screw thread. A higher value of stress was observed in the screw of group IL, followed by group ILIC and then group IC (Fig. 10A-C). The distribution of stress on the palatal side was similar to the distribution on the labial side (front view), but the values were higher on the palatal side. Higher values of stress in the abutment screws were again observed in group IL, followed by group ILIC, and then group IC (Fig. 10D-F).

DISCUSSION

The null hypothesis of this study was rejected based on the difference among the mechanical behavior of dental implants in the different positions studied. The success of treatment with dental implants depends mostly on the biomechanical behavior of the implant and its components.[16] Application of



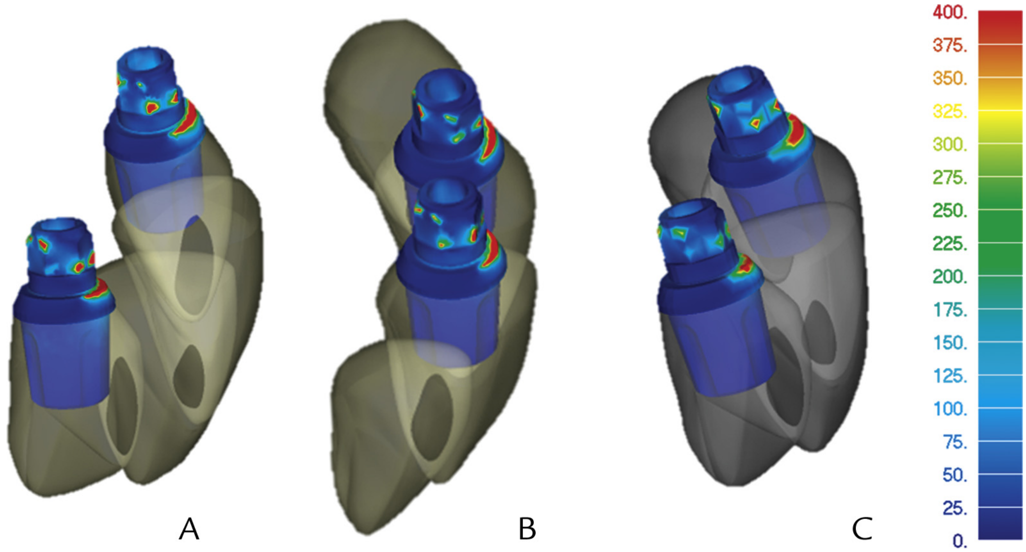
7 Sagittal view of von Mises stress of cortical trabecular bone of right implants (A-C). A, Group IL. B, Group IC. C, Group ILIC. Sagittal view of von Misses stress of trabecular bone (D-F). D, Group IL. E, Group IC. F, Group ILIC.



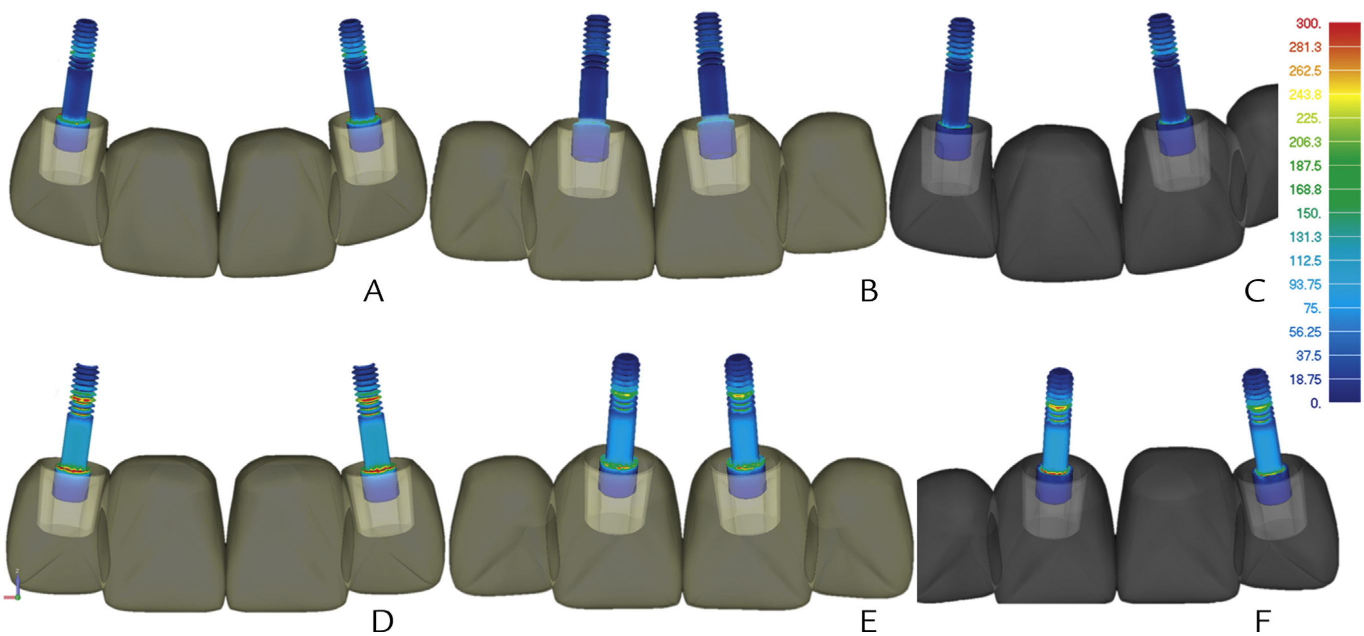
8 von Mises stress of dental implants. A, Group IL. B, Group IC. C, Group ILIC.

an overload to the prosthetic structure causes stresses, strains, and displacement in the implant system, which can affect the bone remodeling process around implants.[9,10,13,14,22] The lowest displacement values of the bone structure were observed in group IL, in which the implants were fixed in the region of the lateral incisors. The displacement results presented in this study are consistent with those presented in the study by Hsu et al[22] that used FEM to evaluate the stress-strain distribution in bone around maxillary implants under 3 different off-axis loading conditions.

Although the groups have different stress distributions, from the biomechanical point of view, there are no contraindications to the use of any of the conditions studied here because the maximum tensile and compressive stresses in bone tissue found in this study were below the overload and



9 von Mises stress of abutments. A, Group IL. B, Group IC. C, Group ILIC.



10 Frontal view of von Mises stress in abutment screws (A-C). A, Group IL. B, Group IC. C, Group ILIC. Posterior view of von Mises stress in abutment screws (D-F). D, Group IL. E, Group IC. F, Group ILIC.

likely-to-fail limits (above 100 MPa for tensile stress and 170 MPa for compressive stress) according to the classification adopted in the study by Bozkaya et al.[18]

In the trabecular portion, stresses of −2 to −3 MPa were observed, mainly at the apex of the implant and in the cervical region of the implant, which was near the highest stress concentration in the cortical region. This result agrees with the finding by Martin et al[12] who reported a stress in trabecular bone, which ranged from 2 MPa to 5 MPa. Although group IC exhibited the lowest displacement of the prosthetic structure, which indicates that this configuration facilitates the stability and preservation of the prosthetic structure, this configuration also led to a higher displacement of the bone tissue adjacent to the implant compared with other groups.

The propagation of stress in the implant body follows the same pattern of propagation in all studied groups, which means that all stress was mainly focused on the first threads of the implants, the region that corresponds to the cortical bone. These results agree with those of studies performed by Natali et al,[15] Bonnet et al,[23] and Chun et al,[24] and with in vivo studies that demonstrate bone loss, particularly during the first year after implantation.[10,11]

In the region of the internal hexagon of the implant and the abutment, the stress distribution patterns were similar among all 3 groups. This distribution pattern occurs in response to a bending movement of the prosthesis in response to the direction of the applied force. The implant configuration in group IC results in lower levels of stress in the internal region of the hexagon and on the implant platform. The pattern of distribution of stress inside the implant and abutment was similar to that described by Pessoa et al.[29] Group IC exhibited the lowest values of stress in the prosthetic screw in both views (labial and palatal). The location of the stress in the screw was similar to that found in a study by Wang et al,[25] with the highest values of von Mises stress observed in the region of the top of the screw shaft, the bottom of the screw shaft, and the top of the screw thread.

The present study assumed an occlusal force of 150 N. The force was applied to the cingulum of each tooth at a 45-degree angle to the long axis of the tooth to simulate mastication.[30-32] For dentate humans, the occlusal force varies among individuals and among different regions of the dental arch. Regalo et al[27] reported masticatory force in the region that corresponds to the incisor of 194 N for indigenous individuals and 117 N for white individuals.

In any FEM study, the extrapolation of the results to clinical situations is limited. The structures in the model were all assumed to be homogenous, isotropic, and linear elastic. However, bony tissue is an orthotropic material and is anisotropic. These assumptions were made because of the absence of reliable data and to allow conditions that enabled the solution of the proposed problem with the computational program.

In addition, the model considered 100% osseointegration.[22] The interfaces between the prosthetic structure and the abutment or abutment screw and the implant or bone and implant were assumed to be bonded, which does not necessarily represent the real conditions in which microdisplacements exist between the structures. However, FEM is an excellent method of obtaining detailed quantitative data and enables accurate visualization of the stress distribution and displacement in models of complex geometries such as the maxilla.[17,21] The use of a fine mesh is important in enabling an accurate FEM model.[22] Thus, the FEM is able to provide information that is not available from clinical and experimental studies.[19] The outcomes of this study, with its limitations kept in mind, can help clinicians to evaluate the performance of different implant distributions and prosthetic configurations. The validation of the 3-dimensional model with an experimental technique is suggested for future study.

CONCLUSIONS

The prosthetic configuration in which the implants were located in the lateral incisors limited the displacement of the prosthetic structure but led to greater displacement of the bone structure than of other configurations. Regardless of the positioning of the implants, the cortical part of the bone receives and dissipates most of the stress. However, the cortical and trabecular bone were not overloaded in any of the groups. The use of a cantilever led to a greater stress concentration in the implant and bone structure adjacent to the cantilever; however, these values were below the limit considered as representing an overload.

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Noteworthy Abstracts of the Current Literature

Clinical evaluation of 1,132 zirconia-based single crowns: a retrospective cohort study from the AIOP clinical research group

Monaco C, Caldari M, Scotti R
Int J Prosthodont. 2013;26:435-42

Purpose: The aim of this retrospective cohort study was to gather the outcomes of zirconia single crowns made by 16 members of the Italian Academy of Prosthetic Dentistry (AIOP) over a time period of up to 5 years.

Materials and Methods: A total of 398 patients treated in private practices with 1,132 zirconia-based single-crown restorations made on natural teeth from January 2005 to July 2010 were included. Three hundred forty-three anterior restorations (30.3%) and 789 posterior crowns (69.7%) were made with 16 types of zirconia, using primarily chamfer or knife-edge tooth preparation, and examined according to the esthetic, functional, and biologic criteria. To evaluate the relationship of parafunction with mechanical failure, patients with clenching or bruxism were not excluded from the study group.

Results: The cumulative survival rate of all restorations was 98.1%, while the cumulative success rate was 94.3%. Functional criteria had the highest number of failures. The odds ratio (OR) for all restorations was calculated to clarify the relationship between patients who were subject/not subject to parafunctions and technical complications; the OR was 2.60. An association between parafunction and mechanical failure was found in patients with severe parafunction.

Conclusions: Porcelain-veneered zirconia single crowns with chamfer and knife-edge preparations showed good clinical results over a period of up to 5 years. Technical complications were few and were limited primarily to patients with parafunction.

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