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EVALUATION OF THE BIOMECHANICAL BEHAVIOR OF IMPLANTS WITH DIFFERENT MACROGEOMETRIES IN THE NECK REGION

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Abstract: The present study evaluated the biomechanical behavior, stress distribution, and bone microstrain in two neck implants in different through tridimensional finite element analysis. Thus, a three-dimensional (3D) structure was modeled to represent a section of the maxilla, containing cortical (1.0 mm thick) and cancellous bone tissue. Based on the therapeutic possibilities for the same clinical indication, two different systems were formed. The models were distributed in the respective study groups: C1 (control): Titanium Implant C1 (4.3 x 11.5 mm implant, Bone Level, MIS Implants Technologies Ltd., Bar-Lev Industrial Park, Israel) V3 (experimental): Titanium Implant V3 (4.3 x 11.5 mm implant, Bone Level, MIS Implants Technologies Ltd., Bar-Lev Industrial Park, Israel) titanium prosthetic abutments EZ-base (4.8 x 6.0 x 1.0 mm, EZ-Base System, CPK Transgingival Abutments, MIS Implants Technologies Ltd., Bar-Lev Industrial Park, Israel) with a 6° conical design and internal friction fit were screwed to the implants. Each material was considered isotropic, elastic, and homogeneous. Therefore, all contacts were considered bonded, the cortical bone was fixed and an oblique load was applied (100 N; 30º). Microstrain and von-Mises stress (MPa) were selected as failure criteria. Comparable stress and strain values were shown in peri-implant bone for both implants. The maximum stress produced in the peri-implant region was mostly at the bone level. Under oblique loading, maximum von-Mises stress and equivalent strains were more noticeable in the implant neck. Under an axial load, tension and strain were transferred to the peri-implant bone around the apex of the implant. The maximum tensile stresses that developed for either material was well below its fracture strength. Therefore, the highest stresses were mainly located in the distobuccal region of the neck for both implant materials in either loading condition. Additionally, long-term follow-up studies are necessary to evaluate the long-term success and stability of this implant design in a clinical setting. It is important to consider factors such as bone remodeling, implant survival rate, and patient satisfaction in future research studies to provide more comprehensive evidence of the effectiveness of this implant design. Overall, the results of this study suggest that the triangular implant design is a viable option for the rehabilitation of partially edentulous patients, but further research is needed to confirm these findings and establish the long-term benefits of this implant design.

Keywords: Dental Abutments; Dental Implants; Dental Materials; Finite element analysis.

INTRODUCTION

Osseointegration was initially conceptualized as the anatomical and functional union between remodeled living bone and the implant surface. [1,2] In this sense, conventional rehabilitation protocols suggest an initial healing period of 30 days, where the bone is in the process of initial bone maturation, which can last up to 180 days, where there is properly matured bone. [3,4]

Rehabilitation with dental implants becomes an excellent alternatives for restoring masticatory and aesthetic function in edentulous patients. Since simpler and less invasive treatments are performed, with successful implant-supported restorations. [5,6,7,8] However, although there are immediate and late rehabilitation protocols, validated in the literature, proving their safety and provide high stability in long-term rehabilitation treatment, especially in situations with compromised vestibular bone support. Limitations exist regarding the primary and secondary stability of dental implants.

Knowing that the implant stability process is determined by the characteristics of the micro and macro design since the slightest modification in the micro design can stimulate the migration, growth, and adhesion of cells, proteins, and growth factors to the implant surface. [8, 9,10,11,12] On the other hand, a change in the macrodesign of an implant, whether in the body, neck, geometry and change in threads or even in the variation of the pitch distance [13] influences the tension and deformation over the entire surrounding structure, whether the rehabilitation set as a whole or just hard and soft tissue structures. [14.15]

In this sense, new implant models are produced to improve the biomechanical behavior of restorative systems [16,17,18]. Among the new implant models, a special one has a triangular neck. This modification in the macrogeometry of the implant allows for high primary stability, adequate osseointegration, and high invariability of the peri-implant tissues. [27-30] Furthermore, studies indicate lower proximal bone losses, [28] minimal early changes in implant stability, [29] high primary stability under immediate loads, the accelerated healing process, [30] high preservation of hard tissues and moles in the aesthetic area, anterior region of the maxilla; [31] 0.2 mm space between the implant surface and the buccal cortical bone created in the flat portion of the triangle was filled with bone after 6 months of submerged healing [32] in implants with a triangular neck, when compared to implants with the cylindrical neck.

It is worth mentioning that current technology allows available implants to be standardized, as well as better precision and control in obtaining them; therefore, possible complications inherent to manufacturing are minimized, but can still be observed. Although implants with a triangular neck and cylindrical neck have the same clinical indication, little information is available in the literature regarding the biomechanical behavior of these different rehabilitation systems and their surrounding structures. Therefore, the present study aims to identify, through finite element analysis, possible damage to the peri-implant tissue due to cervical microdeformation and regions of high tension of possible mechanical failure in prosthetic structures with a valid mathematical model of these different combinations.

METHODOLOGY

This study was conducted by numerical finite element analysis, which is a mathematical method used to investigate the biomechanical behavior of different dental implant systems. [21] Using CAD software (Rhinoceros 7.0, McNeel Europe™, Barcelona, Spain), all structures were modeled according to the specifications and geometry of each material and the set gave rise to the final model for each group. Thus, a three-dimensional (3D) structure was modeled to represent a section of the maxilla, containing cortical (1.0 mm thick) and cancellous bone tissue. [22] Based on the therapeutic possibilities for the same clinical indication, two different systems were formed. [22,24] The models were distributed in the respective study groups: C1 (control): Titanium Implant C1 (4.3 x 11.5 mm implant, Bone Level, MIS Implants Technologies Ltd., Bar-Lev Industrial Park, Israel) V3 (experimental): Titanium Implant V3 (4.3 x 11.5 mm implant, Bone Level, MIS Implants Technologies Ltd., Bar-Lev Industrial Park, Israel) titanium prosthetic abutments EZ-base (4.8 x 6.0 x 1.0 mm, EZ-Base System, CPK Transgingival Abutments, MIS Implants Technologies Ltd., Bar-Lev Industrial Park, Israel) with a 6° conical design and internal friction fit were screwed to the implants.

After that, the maxilla section model was subjected to an implant according to the system of each group. A zirconia single-unit prosthesis (upper central incisor) was cemented over each implant. To simulate a condition closer to the clinical condition already reported in the literature,[22] a thin layer of resin cement 0.3 mm thick was added,[23] as shown in Figure 1.

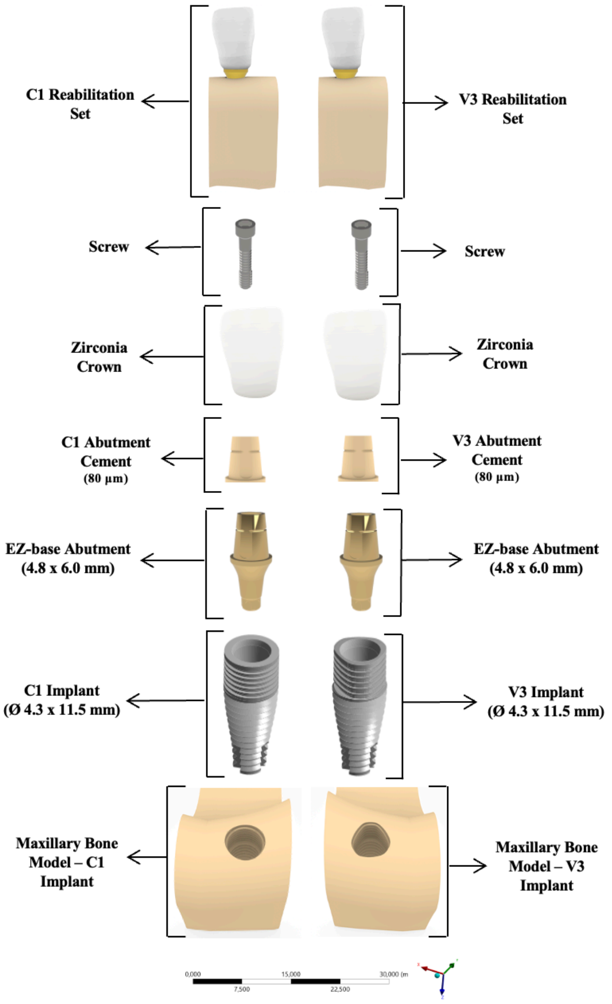

Figure 1. Illustrative of the 3D models following the clinical sequence of an implant-supported prosthesis using the C1 and V3 implant systems.

Then, the solids were exported in STEP format (Standard for the Exchange of Product model data) for software analysis (ANSYS 17.2, ANSYS Inc., Houston, TX, USA). The external surface of the maxillary section was fixed in all directions, applying a static structural load of 100 N with an incidence angle of 30 ° on the palatal surface of the central incisor. A mesh was created after the 10% convergence test [22,24] corresponding to 434.796 nodes and 725.381 tetrahedral elements for the evaluated models (Figure 2). All materials were considered isotropic, linear, elastic, and homogeneous. Between the implant and the bone, the contact was used to simulate complete osseointegration,[24] and the other contacts were considered bonded.

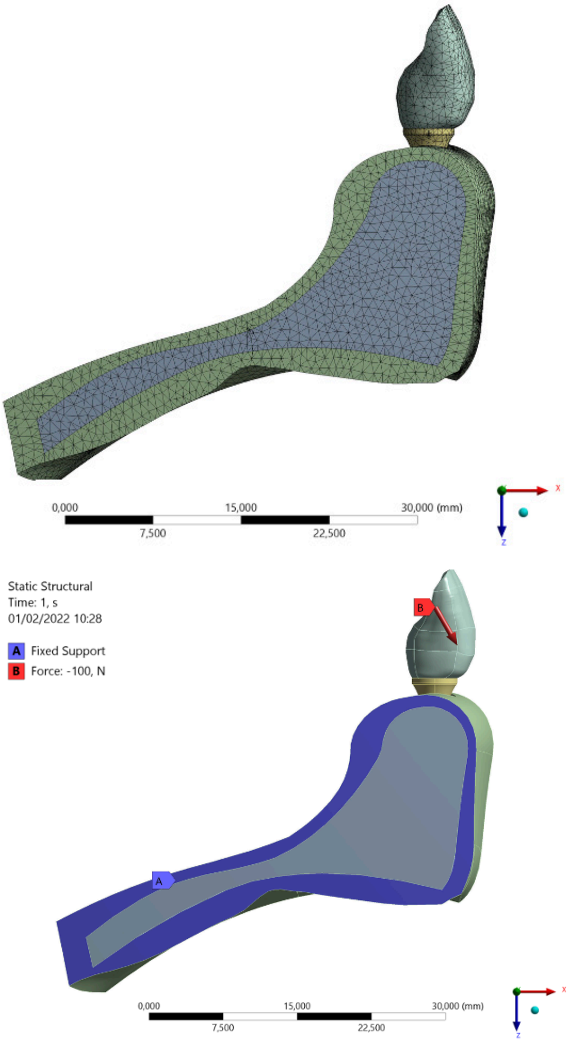

Figure 2. FEA details - Mesh, boundary conditions, loads, and connections.

The mechanical properties of the 3D model structures were defined based on the literature (Table 1). The results of the stress distribution according to the Von-Mises criteria were exhibited using visual plots with a scale in megapascals (MPa) for implants and ceramic structures. The microstrain criteria were used to investigate the bone behavior and its maximum values are shown in Table 2. [25,26]

Material	Young's Modulus (GPa)	Poisson ratio
Y-TZP [27]	220	0.30
Titanium [280	110	0.30
Cortical Bone [29]	13.7	0.30
Cancellous Bone [29]	1.37	0.30
Oral Mucosa [30]	10	0.40
Resin Cement [31]	7.5	0.25

Table. 1- Mechanical properties of the materials.

Stress and strain results those present values with a difference of less than 10% may be located in the convergence range of the analysis software, making it impossible to assume a significant difference. Consequently, the results that present a difference in peak values greater than 10% will be defined as significant. The results of each structure of both groups were compared qualitatively and quantitatively. Microstrain, von-Mises stress, and Maximum Principal Stress were adopted as failure criteria.

RESULTS

In an extensive qualitative analysis, the displacement of the implant prosthesis assembly can be verified in Figure 3A. Mechanical responses were calculated according to the failure criteria of each structure. The results were analyzed in strain based on previous studies. [32-34] Observing the strain distribution represented in Figure 3B e C, it is possible to see that there is a different response pattern between the models for the strain generated in the dental implant; however, the model with circles implant shows a greater magnitude of a cervical strain than the model with a triangular profile.

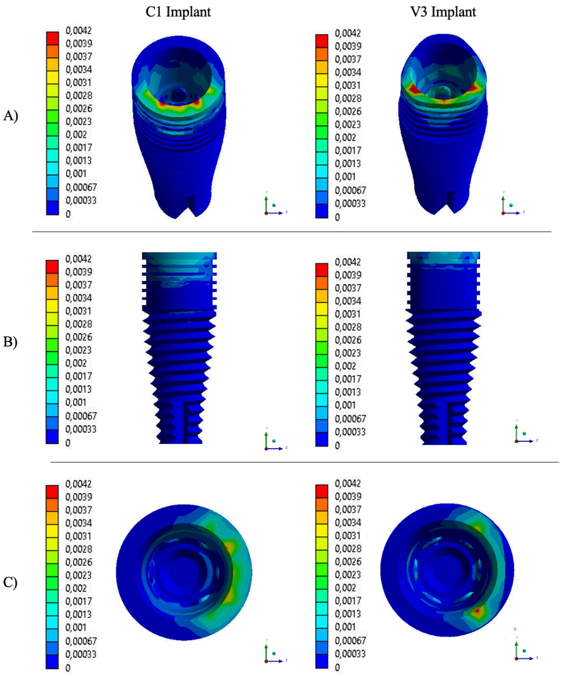

Figure 3. Illustrative of the 3D modeling qualitative analysis of Displacement and Strain Criteria on the structures of each group. A) Displacement Criteria. B) Strain Criteria. Left to Right: C1 Implant; V3 Implant.

This behavior can be described by the tensile stress and the von-Mises map in Figure 4. In ductile solids, such as titanium implants, the stress results followed the von-Mises criteria that help to show the fracture initiation regions in circular metals. However, for a comparative analysis between the models, the results generated were obtained by von-Mises stress and also for the model with a triangular implant.

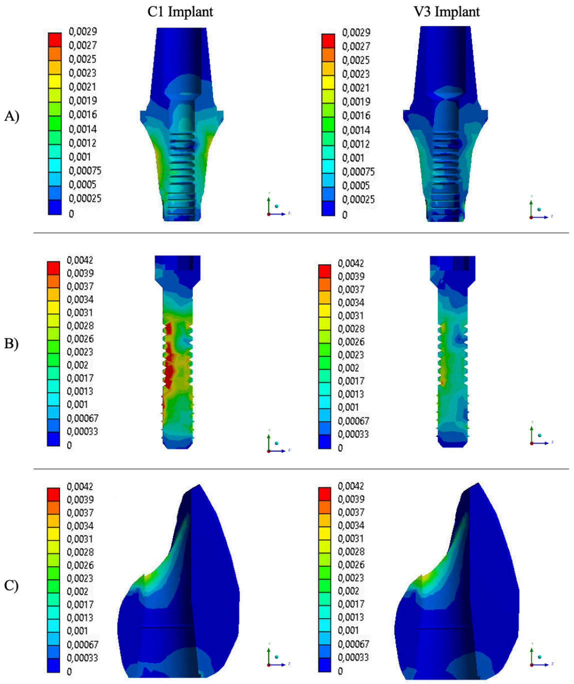

Figure 4. Illustrative of the 3D modeling of the qualitative analysis of Maximum Principal Stress and von Mises (Mpa) Criteria on the structures of each group. A) Maximum Principal Stress Criteria. B) Von Mises Stress Criteria. Left to Right: C1 Implant (Control); V3 Implant. C) Maximum Principal Stress Criteria.

The corresponding applies to the maximum principal stress, which highlights regions of tensile stress, the failure criterion for conventional implant conditions. Thus, both criteria present similar stress maps, but with different magnitude values, as plotted in Table 2. Thus, the triangular implant, abutment, screw, and zirconia crown concentrate less stress in its structure, reducing the energy required for its displacement (Figures 3, 4, and 5).

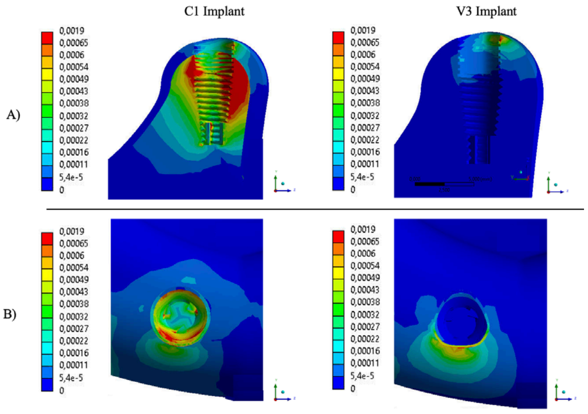

Figure 5. Illustrative of the 3D modeling of the qualitative analysis of Maximum Principal Stress and von Mises (Mpa) Criteria on the structures of each group. A) Maximum Principal Stress Criteria. B) Von Mises Stress Criteria. Left to Right: C1 Implant (Control); V3 Implant.

4. Discussion

It is important to note that the results of this study are consistent with previous studies that highlight the importance of implant neck characteristics in the stability and health of peri-implant tissues. The choice of implant type and implant neck can significantly influence the biological response and long-term success rate of the implant. [35] Furthermore, the average follow-up of 15.6 months is a relatively short period to fully evaluate peri-implant bone loss and other clinical outcomes. Long-term studies are needed to confirm the stability of implants and the health of peri-implant tissues over time. In summary, the results of this study suggest that bone-level implants with polished necks may offer similar clinical and radiographic results to implants with triangular necks concerning peri-implant bone loss and peri-implant tissue health. [36-40] However, more research is needed to confirm these results and evaluate the long-term impact of implant neck characteristics on the stability and health of dental implants.

The primary outcome of the present study was peri-implant crestal bone loss; which was measured immediately after delivery of the final implant-supported prosthesis (baseline) and at the final follow-up visit with standardized periapical radiographs. Secondary outcomes were clinical parameters measured on the mesial and distal aspects of each implant between baseline and condition monitoring through computational analysis. [41-44]

An implant's macrodesign generally refers to the shape of the implant's threads, body, and neck design. Furthermore, this term includes the micromorphology produced by the surface treatment concerning the depth, size, and diameter of the roughness. In a retrospective study in humans, histologically and histomorphometrically evaluated the bone response of around 10 implants with parallel wall configuration, condensed thread macrodesign, and self-tapping apex. High percentages of bone-implant contact were found and the authors concluded that both the macrostructure and microstructure participated in the high survival and success of the implant in the long term. [45-47] Another study, evaluated the influence of implant macrodesign when using different types of neck and thread designs on stress/strain distributions at a maxillary bony site. [48]

They showed that the neck design was the main factor affecting stresses/strains at the cortical bone level. Recently, investigating whether a different implant neck design (wide-neck rough implants vs. reduced-neck rough implants) could affect survival rate and peri-implant tissue health in a cohort of 97 disease-free, partially edentulous patients. After two years of follow-up, survival rates were similar (96.61% vs. 95.82%). V3 implants have a rough and micromorphological surface in their design due to sandblasting and acid conditioning treatment. Additionally, it features micro-rings at the implant neck that have been shown to facilitate increased bone-implant contacts, thus reducing peri-implant marginal bone loss [30,31,32]. Furthermore, it has been shown that flat sides that leave a small gap accelerate the bone formation process when compared to the part of the implant in full contact with the cortical bone [46].

Overall, the macro-design of an implant plays a crucial role in its long-term success and survival. Factors such as thread design, body shape, neck design, and surface treatment can all impact the bone-implant contact and the stress distribution in the surrounding bone. Studies have shown that implants with specific macro-design features, such as condensing thread design, self-tapping apex, and rough wide-neck implants, can lead to better outcomes in terms of survival rates and peri-implant tissue health. Therefore, clinicians need to consider the macro-design of implants when selecting the most suitable option for their patients. [49-54]

Furthermore, the unique triangular shape of the implant neck may also contribute to better esthetic outcomes due to its ability to create a more natural emergence profile of the restored tooth. The wider base of the triangular shape provides better support for the soft tissues surrounding the implant, leading to improved esthetic results in the anterior region of the mouth. [55,56]

Overall, the findings of this study suggest that the V3 implants with a triangular neck shape can provide similar osseointegration and stability compared to conventional round neck implants. Additionally, the unique design of the V3 implants may offer advantages in terms of peri-implant tissue thickness and esthetic outcomes, especially in cases with narrow alveolar ridges and high aesthetic demands. Further research and long-term clinical studies are needed to confirm these findings and evaluate the long-term success of V3 implants in various clinical scenarios. [57-59]

Future studies with larger samples, including upper and lower jaws, and longer follow-up periods are needed to better evaluate the effectiveness of the V3 implant in preserving peri-implant tissues. Furthermore, comparisons between different implant designs and platforms should be carried out to better understand the impact of switching platform studies on the preservation of peri-implant tissue. [60-64]

Overall, the results of the present study suggest that the V3 implant with a platform-switching design concept can contribute to the preservation and maintenance of peri-implant tissues in partially edentulous patients with healed alveolar ridges. This implant design may also be beneficial in cases of immediate implant placement, where the formation of a space between the implant surface and the buccal bone crest may facilitate bone regeneration and improve the emergence profile of the final restoration. [65-70]

It is essential to continue research in this area to improve the quality of life of patients who require oral rehabilitation with dental implants. More research in this area is needed to improve understanding of the factors that influence the reliability of dental implants and to develop strategies to improve their durability and long-term performance. Based on the results of the present study, the connection between the crown and the two-piece implant with a triangular neck appears to be suitable for clinical application when purchased with the conventional cylinder model. However, this new implant system needs to be further proven in clinical studies.

CONCLUSION

Additionally, long-term follow-up studies are necessary to evaluate the long-term success and stability of this implant design in a clinical setting. It is important to consider factors such as bone remodeling, implant survival rate, and patient satisfaction in future research studies to provide more comprehensive evidence of the effectiveness of this implant design. Overall, the results of this study suggest that the triangular implant design is a viable option for the rehabilitation of partially edentulous patients, but further research is needed to confirm these findings and establish the long-term benefits of this implant design.

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DATA AVAILABILITY

All data analyzed during this study are available from the corresponding author upon reasonable request.

DISCLAIMER AND DISCLOSURE STATEMENT

All data analyzed during this study are available from the corresponding author upon reasonable request. The authors report no conflicts of interest about any of the products or companies discussed in this article.

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