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MATERIALS AND METHODS FOR EVALUATING ZIRCONIA ALTERNATIVES IN IMPLANT-SUPPORTED PROSTHESES

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Cesar Ricardo Rodrigues[1], Cássio de Barros Pontes[2], Fabiano Perez[3], Eduardo Mukai[4], Ervino Siebel Neto[5], Jenival Correa de Almeida Júnior[6] and Newton Sesma[7]

ABSTRACT

The demand for metal-free dental restorations has driven the development of materials that emulate natural tooth structure. This study aimed to compare the stress distribution in implant-supported fixed prostheses made from zirconia and polyoxymethylene (POM) using the finite element method. Three- dimensional models represented screw-retained prostheses on cylindrical external hexagon-type implants in the mandibular region. The experimental group used a POM base, and the control group used zirconia, both with the same geometry. Results indicated a significant increase in stress under the zirconia abutment, with higher intensity transmitted to other components. A 41.96 MPa stress variation was observed in the prosthetic screw with a POM base compared to zirconia. No significant differences were noted in bone tissue stress between the two materials. In conclusion, POM demonstrated superior stress dissipation, potentially reducing mechanical failure risks.

Keywords: Biomedical and Dental Materials. Dental Implants. Dental Prosthesis. Polyacetylene Polymer.

[1] Msc Master in Digital Dentistry São Leopoldo Mandic Dental Research Center, São Paulo, São Paulo, Brazil
ORCID: https://orcid.org/0009-0004-6468-3477
E-mail: drcrr@icloud.com
[2] PhD Doctor in Dentistry, Oral Rehabilitation, University of São Paulo, São Paulo, Brazil
ORCID: https://orcid.org/0000-0002-6031-1279
E-mail: pontesscb@yahoo.com.br
[3] PhD Doctor in Oral Rehabilitation, São Leopoldo Mandic Dental Research Center, Campinas, São Paulo, Brazil
ORCID: https://orcid.org/0000-0002-3399-1002
E-mail: fabiano.perez.odonto@gmail.com
[4] PhD Doctor of Dental Prosthodontics, University of São Paulo, São Paulo, São Paulo, Brazil
ORCID: https://orcid.org/0000-0002-0408-5799
E-mail: mukaiodonto@gmail.com
[5] Msc Master in Dental Prosthetics, Center for Advanced Dentistry, COA, Ilhéus, Brazil
ORCID: https://orcid.org/0009-0005-5329-430X
E-mail: ervino2003@yahoo.com.br
[6] PhD Doctor in Implantology, Master of Dental Prosthodontics, São Leopoldo Mandic Dental Research Center, Campinas, São Paulo, Brazil
ORCID: https://orcid.org/0000-0001-6788-402
E-mail: drjenival@gmail.com
[7] PhD
Associate Professor, Doctor of Dental Prosthodontics, University of São Paulo, São Paulo, Brazil
ORCID: https://orcid.org/0000-0001-5044-1742
E-mail: sesma@usp.br

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INTRODUCTION

Natural oral health is inherently linked to an individual's overall well-being, playing a crucial role in essential functions such as mastication, phonation, and aesthetics. The loss of a tooth affects not only aesthetics but also self-esteem, consequently reducing the individual's quality of life (Liu et al., 2021).

Tooth loss can occur due to various factors, including trauma, infection, tumor resection, congenital abnormalities, periodontal inflammation, abscesses, dental extraction, and age-related bone atrophy. The consequences of tooth loss extend beyond compromised speech, swallowing, and breathing, leading to severe psychosocial problems for the patient. Therefore, the replacement of missing teeth is crucial to restore the defect and regain the aesthetics and functionality of the stomatognathic system, aiming to achieve both the objective and subjective satisfaction of the treated patient (Gaihre; Uswatta; Jayasuriya, 2017).

As a result, the prevalence of individuals with compromised functional dentition, tooth loss, and edentulism has posed a challenge for implant dentistry and digital dentistry. These fields have been striving to enhance surgical techniques, materials, and software to restore native morphofunctional characteristics. The primary benefit of these advancements is the ability to provide less invasive and more precise rehabilitative treatments (Yelick; Sharpe, 2019).

In recent years, a wide range of implant installation methodologies, types of dental implants, and prosthetic materials that mimic natural teeth have been developed and/or improved. Technological innovation in prosthetic materials has opened up new perspectives in the field of implant-supported fixed prosthetic treatment, with the aim of increasing the success rate. This is because the longevity of such prostheses is directly influenced by various factors, including the type of prosthesis, retention mechanism, supporting structure, prosthesis manufacturing process, or implant length and type (Ionescu et al., 2022).

With advancements in dentistry, the use of metal-acrylic restorations on implants has been replaced by metal-ceramic restorations to overcome their drawbacks. Currently, new materials are being tested to achieve prostheses with characteristics that mimic natural teeth in terms of functionality and aesthetics. Among them are monolithic zirconia, ceramic-coated zirconia, titanium and ceramic, lithium disilicate, hybrid ceramics, poly(methyl methacrylate) (PMMA), poly(ether-ether-ketone) (PEEK), 3D printed resins, or the polymer polyoxymethylene (POM), all esteemed for their biological and mechanical properties (Pituru et al., 2020).

In recent decades, it has been observed that metal-free restorations have played a fundamental role in dental practice, an aspect closely related to the increasing demand in the aesthetic market. Among the materials, zirconia, also known as zirconium oxide, is a promising non-metallic alternative. It exhibits high biocompatibility and excellent mechanical properties as it accurately reproduces the masticatory load in the oral cavity, preventing bone tissue atrophy. Moreover, zirconia offers aesthetic benefits with a wide range of shades, facilitating precise matching with the patient's natural tooth color. Thus, it fulfills key criteria for patient satisfaction, including comfort, functionality, social aspects, and appearance (Grech; Antunes, 2019).

However, the material's hardness has raised some concerns regarding its friction against the tooth root and wear on opposing teeth, as well as the generally higher cost compared to other materials and the complexity of the prosthesis production process. In this context, polyoxymethylene (POM) has proven to be a viable and promising alternative to metals due to its desirable mechanical properties, high chemical and creep resistance, low water absorption, low friction coefficient, high biocompatibility, low production cost, and ease of processing. These attributes make it suitable for a wide range of applications in medicine, and CAD/CAM techniques pave the way for its application in dentistry (Rokaya et al., 2018).

In terms of optical appearance, POM is characterized by uniform surfaces and a high degree of crystallinity, approximately 90%, which provides high intrinsic whiteness and detail precision, favoring processability, the resulting product's appearance, and, consequently, aesthetic tooth color matching (Dechet; Baumeister; Schmidt, 2020).

Despite these advantages, there is a scarcity of information about POM in dental scientific literature. Therefore, in this study, we aim to elucidate key aspects related to the success of aesthetic and functional rehabilitation using POM in the fabrication of dental prostheses as an alternative material to zirconia, through finite element modeling, to predict the characteristics of occlusal stress distribution.

Hence, the alternative hypothesis is that the use of polyoxymethylene (POM) infrastructure in implant- supported prostheses may be an alternative material option to zirconia.

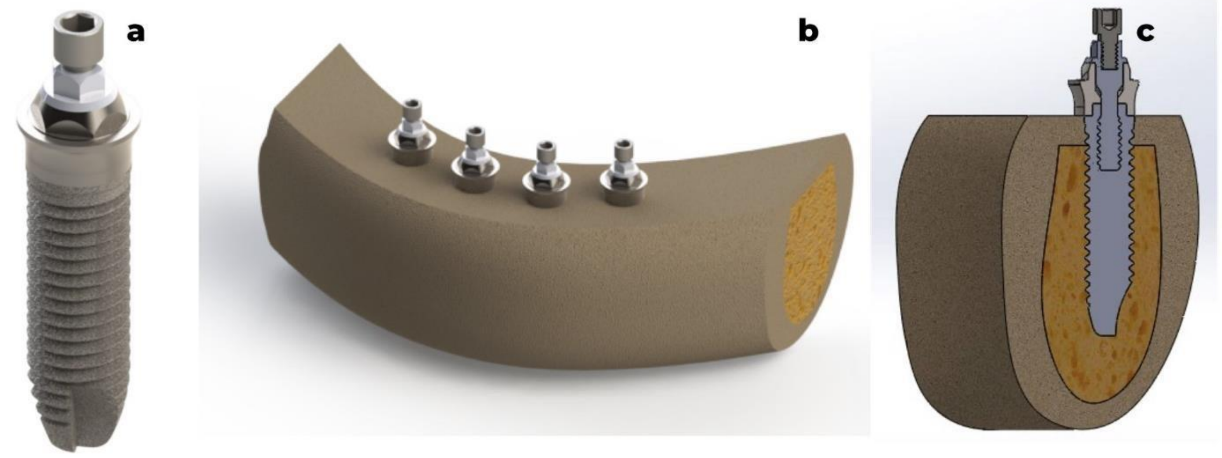
The objective of this study is to comparatively evaluate the influence of zirconia vs. POM materials on the distribution of stresses in a fixed implant-supported rehabilitation using the finite element method (FEM).

METHODS

A three-dimensional virtual model was created using SolidWorks 2013 software (Dassault Systèmes S.A., USA). The model included a simplified representation of cortical bone (1.5 mm thick) and medullary bone based on literature-derived data, as using patient-specific data raised ethical concerns.

To perform finite element analysis (FEA) in the peri-implant region, simplifications were made. The model incorporated four equidistant external hexagonal connection cylindrical implants (3.75 x 10 mm), and commercially available dental implant components were used without specifying a particular manufacturer. Each implant consisted of a mini-abutment made from zirconia with specific dimensions, along with its respective fixation screw and prosthetic screw (Figure 1a to c). The mini- abutment and fixation screw were designed to simulate clinical conditions. On top of this assembly, we simulated a monolithic protocol-type prosthesis made from a single material to create a comprehensive representation of the components used in the study.

Figure 1: Three-dimensional geometric model representing: a- Implant with mini-abutment and respective abutment retention screw and prosthetic screw; b- Mandibular bone section with 4 implants positioned equidistantly; c- Section cut showing the positioning of the implant-abutment assembly on the bone model.



The three-dimensional models were individually constructed and aligned using concentric references. Component fitting was achieved through boolean operations of combination, addition, and subtraction. The assembly of the components was created in the

SolidWorks 2013 software's assembly environment, ensuring there were no clearances or interferences that could compromise the analysis's accuracy.

The generated model was imported into Ansys Workbench 14.0 software for further processing and mathematical analysis. Material properties, specifically the modulus of elasticity and Poisson's ratio, were assigned based on available literature data - Elastic modulus and Poisson's ratio were used for the mechanical characterization of the materials: Titanium and zircônia Elastic Modulus (110.000 vs. 200.000 Mpa), Poisson Coefficient (0.35 vs. 0.31), respectively (Benzing; Gall; Weber, 1995)

At this stage, two groups were created based on variations in material properties related to the prosthetic base: Experimental Group: Comprised a polymeric base (polymer) and Control Group: Zirconia (for comparison purposes). Both models shared the same geometry, with variations limited to the properties of the prosthetic bases.

For the mathematical analysis, the three-dimensional model was divided into smaller elements, creating a mesh consisting of quadratic tetrahedral elements with a size of 0.5mm per element, connected through nodes. The mesh generation resulted in a total of 769.894 nodes and 455,956 elements in the models. The element size was determined following a convergence analysis with a 5% tolerance.

Convergence analysis involved conducting FEA with a hypothetical mesh size, calculating stress values. Subsequently, mesh refinement was performed, reducing element size and increasing their number. New analyses were generated, and stress values were calculated. Mesh refinement ceased when the stress value difference between a mesh and its most refined version equaled or was less than 5%. This criterion was adopted as further refinement would increase processing requirements without significantly affecting stress values.

Bound ary conditions involved providing support by selecting the two lateral faces and the bottom face of the bone model. The analysis was of the linear type, assuming a perfect union between bone-implant and prosthetic components. To simulate the load, a vertical force of 300N was applied to the distal region of the implants on the occlusal representative surface with anterior sliding. The 300N force was chosen to represent masticatory forces in clinical situations. The direction of force application was vertical, simulating an occlusal load, which is a critical condition to be evaluated in dental implants.

Theoretical deformation was calculated based on tensile, compressive, and shear stress for the bone tissue and Von-Mises stress for the prosthetic components, with values expressed in MegaPascals (MPa).

RESULTS

Bone Tissue Behavior: In the context of bone tissue behavior, it was observed that the group utilizing a polymer structure exhibited absolute stress values that differed from the zirconia structure. These differences ranged from 0.02 to 0.39 MPa when evaluating the same criteria. Absolute shear, tensile, and compressive stress values (MPa) calculated for cortical and cancellous bone: Polymer Cortical vs. medullary (8.14 and 1.05), (9.93 and 2.94), (20.06 and 1.69) and Zirconia Cortical vs. medullary (8.18 and 1.07), (10.32 and 2.99), (20.14 and 1.78), respectively.

To illustrate the distinctions between groups based on absolute values, please refer to - Numerical difference (MPa) in the variation of stresses for cortical and medullary bone between the groups when comparing within the same criterion. Negative values indicate a decrease in stress when using the polymer prosthesis compared to zircônia: Cortical and medullary – shear, traction and compression (-0.04 and -0,02), (-0,39 and -0,05) and (-0.08 and -0.09) respectively.

Negative values indicate a lower stress concentration in the polymer group compared to the control group (zirconia). Among the various types of stress, compressive stress exhibited the highest values, particularly in cortical bone tissue, followed by tensile stress. Shear stress, on the other hand, demonstrated the lowest range of stress values. Notably, the peak stress concentration for both shear stress and tensile stress was consistently located in the cervico-lingual region, particularly in contact with the first threads of the implant. This concentration displayed a radial distribution pattern, with higher concentration observed in the distal implants bilaterally. These observations apply across different criteria and are depicted in Figure 2.

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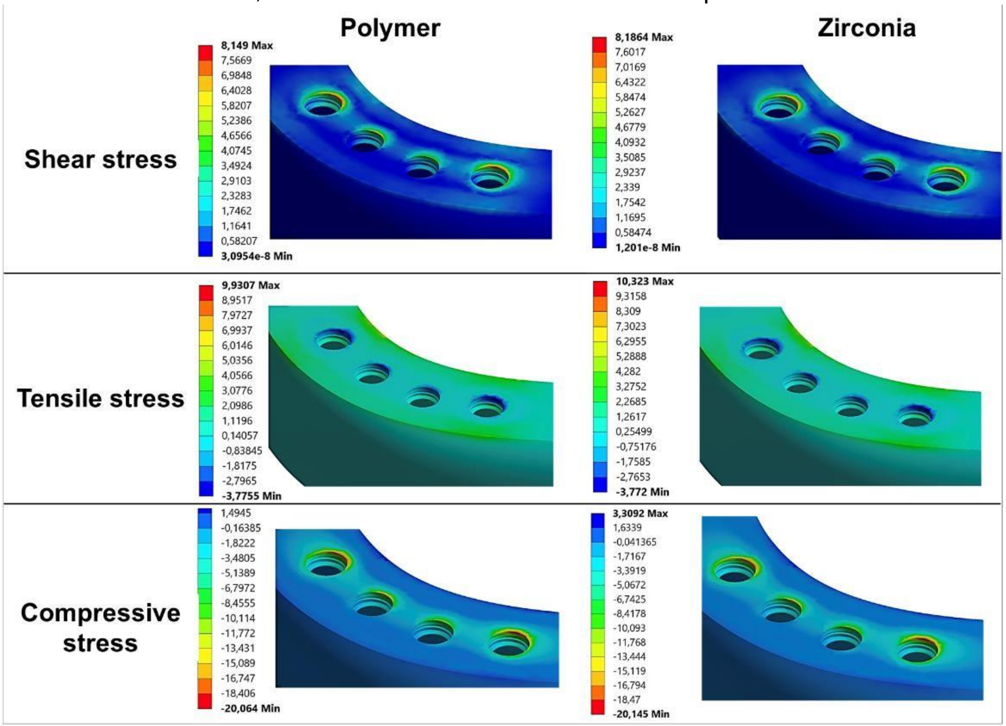
Figure 2: Stress values according to the criterion used for the bone tissue. Values close to warm colors indicate peak stress concentration, while cool colors indicate stress dissipation.



Implants Results: The results for implants are summarized below, which presents the obtained von-Mises stress values for both implants and prosthetic components. Absolute values of von-Mises stress (MPa) for the implant and prosthetic componentes: Implant, Abdument, Abutment screw and Prosthetic screw – Polymer and Zirconia respectively (36.54 and 35.23), (27.45 and 41.25), (19.14 and 65.6) and (11.23 and 53.19).

Specifically concerning the implants, the polymer group displayed a higher stress concentration localized in the platform region (36.54 MPa) compared to the zirconia group (35.23 MPa). This difference amounts to 1.31 MPa and is detailed below (refer to Figure 3): Numerical difference (in MPa) in the variation of stresses in implants or prosthetic components. Negative values indicate a decrease in stress magnitude when using a polymer prosthesis compared to zircônia – Implant, Abutment screw and Prosthetic screw (Von-Mises: 1.31 and -13.8 and -46.46 and -41.96, respectively).

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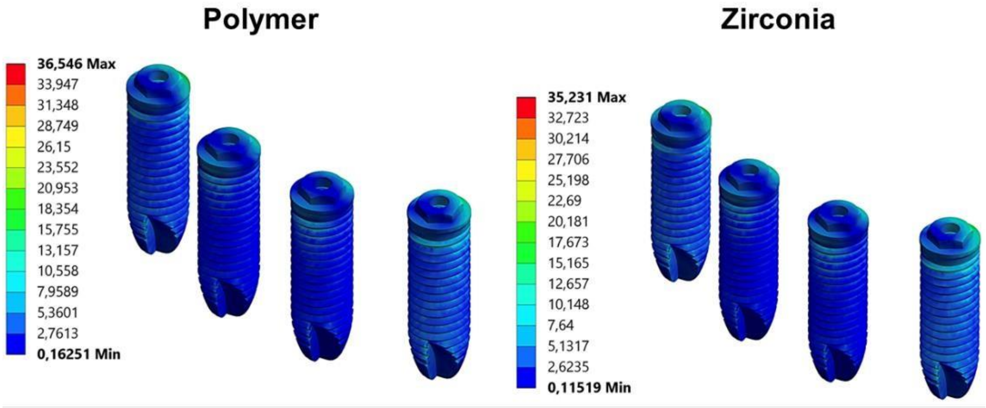
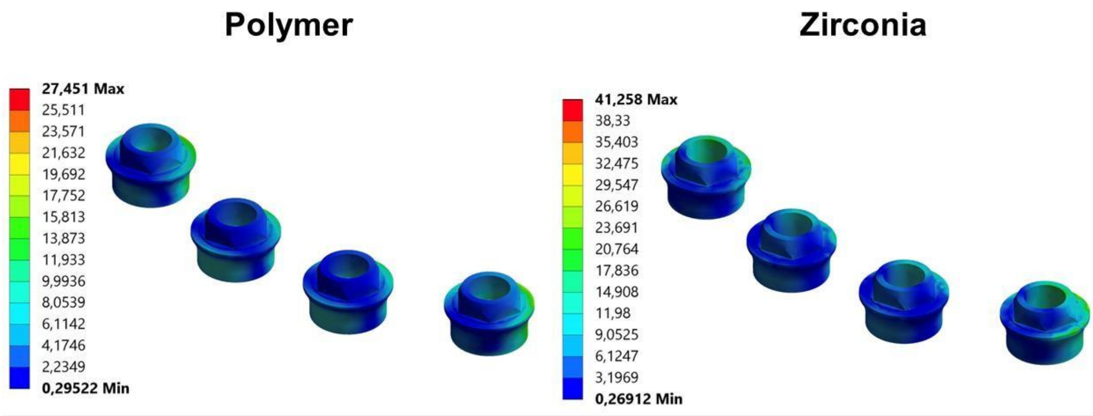
Figure 3: Von-Mises stress values in the implant with a peak concentration in the platform region.



Prosthetic Components Results: Moving on to prosthetic components, including abutments, abutment screws, and prosthetic screws, it is evident that the utilization of a polymer base resulted in lower von-Mises stress concentrations in comparison to zirconia. More specifically, within the polymer group, the abutments exhibited -13.8 MPa of stress when compared to the zirconia group. This stress concentration was most pronounced at the base of the abutment and its sidewalls, as depicted in Figure 4.

Figure 4: Von-Mises stress in the abutments with a peak concentration located at the base and side walls.



The most significant differences between the two groups were observed in the screws. The abutment screws in the polymer group displayed -46.46 MPa when compared to the zirconia group, while the prosthetic screws in the polymer group exhibited -41.96 MPa of von-Mises stress. Interestingly, there was a noticeable trend towards a more homogeneous stress distribution in the abutment screw when a polymer prosthesis was utilized in contrast to the use of zirconia. Zirconia- based prostheses exhibited a peak

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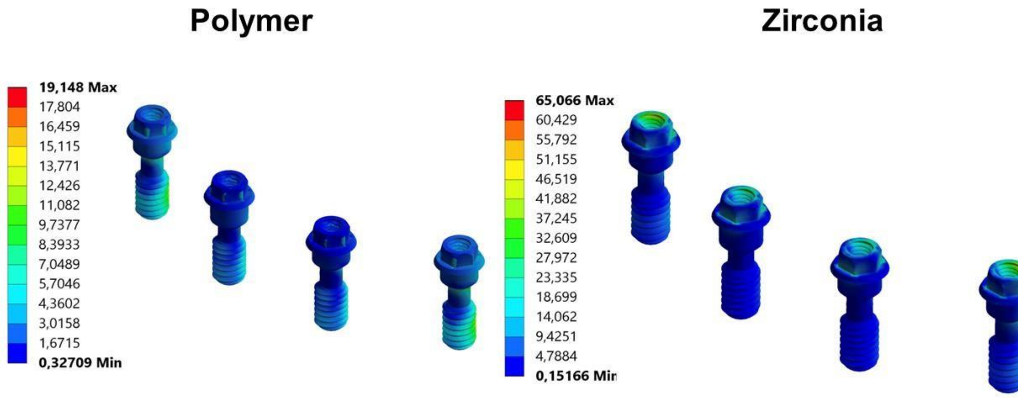
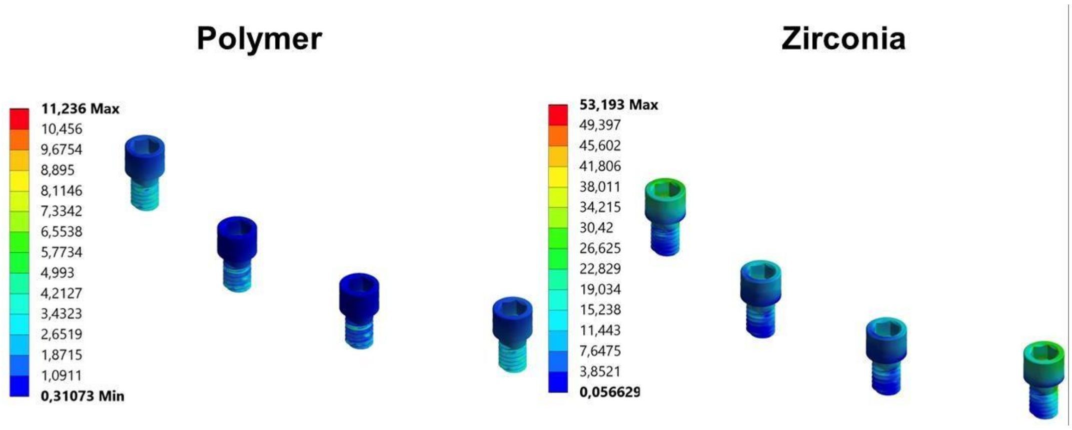
stress concentration in the screw, particularly in the region in contact with the prosthetic screw. These observations are clearly presented in Figure 5.

Figure 5: Von-Mises stress in the abutment retention screws. A difference in the pattern of stress concentration is observed between the screws. In the polymer usage, the distribution was homogeneous across the screw. With the use of zirconia, the peak concentration was located in the thread region in contact with the prosthetic screw.



Stress Distribution Patterns: The analysis of stress distribution in the abutment screw unveiled significant differences between the utilization of polymer and zirconia in the prostheses. When polymer was employed, there was a notable stress concentration in the screw region, particularly in the area in contact with the prosthesis. This concentration can be attributed to the flexibility of the material. In contrast, when zirconia was used, a more uniform stress distribution in the screw was observed due to its higher strength and resilience, as illustrated in Figure 6.

Figure 6: Von-Mises stress in the prosthetic screws demonstrating different behavior patterns.



Stress in the Prosthetic Base: Focusing on the prosthetic base, the tensile stress values were 4.81 MPa for the polymer base and 9.79 MPa for the zirconia base. The

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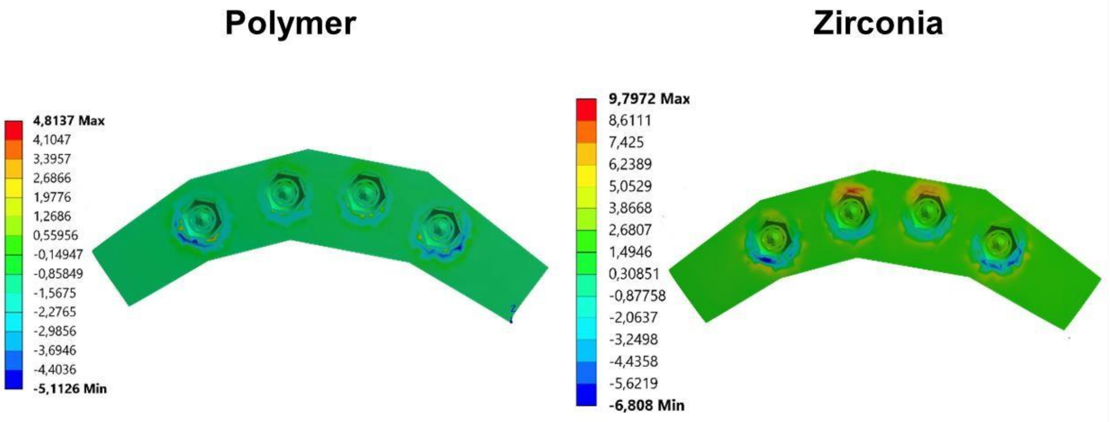
zirconia base exhibited a 4.98 MPa difference when compared to the polymer base, with stress concentration more localized in the anterior region of the abutments closer to the midline. The stress distribution in the polymer base displayed a more homogeneous pattern in comparison to the zirconia base, as visualized in Figure 7.

Figure 7: Tensile stress at the prosthetic base in contact with the abutments.



DISCUSSION AND CONCLUSION

The relevance of scientific studies to clinical practice regarding the selection of prosthetic materials for implant-supported restorations is an additional factor to be considered along with the type of prosthesis material and manufacturing process, the prosthetic retention mechanism, support structure design, and implant type (Ionescu et al., 2022).

Thus, high-performance polymers, chemically inert, such as POM investigated in this study, are biomaterials based on polyoxymethylene, developed as a promising alternative to metallic dental materials for the superstructure of dental implant prostheses, aiming to ensure strength and smile aesthetics (Maloo et al., 2022).

In addition, the feasibility in versatile clinical applications and aesthetics, along with mechanical properties that provide higher elongation and reduced fracture area compared to other materials, have increased the notoriety of these polymers (Schierz et al., 2021).

Thus, the results of the three-dimensional finite element analysis, considering the inherent limitations of the present study, allow us to conclude that the POM material significantly exhibited better stress dissipation in the implant and prosthetic components, suggesting it is less susceptible to mechanical failures such as loosening and/or fracture.

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As mentioned earlier, quantitative analyses of the distribution of shear, compression, and tensile stresses were performed with a load of 300N applied on the occlusal surface in a vertical direction with anterior sliding. Therefore, when considering the same geometry, the applied force is divided by the same area, ensuring that the mechanical difference observed is inherently related to the properties of the zirconia and polymer materials (Chuchulska et al., 2018).

Conceptually, the modulus of elasticity of a material refers to its stiffness, that is, its ability to resist applied forces, thereby avoiding fracture or excessive deformation. However, it generates an opposing reaction, and this external force divided by the area of the solid body to which it is applied equals the value of the average stress produced in the structure (Souza et al., 2021).

Thus, the occlusal load applied is transferred along the axis to the prosthetic components, implant, and cortical/medullary bone, where the magnitude and distribution of the generated stress will directly depend on the modulus of elasticity of the material (Haroun; Ozan, 2021).

Regarding a stiffer base/prosthesis, that is, with a higher modulus of elasticity, as is the case with zirconia material (Bidra; Rungruanganunt; Gauthier, 2017), the imminent result is a higher concentration of stresses as this force is dissipated, not in the same intensity, but to a greater extent compared to the polymer protocol.

When it comes to a stiffer base/prosthesis, that is, with a higher modulus of elasticity, such as zirconia material, the imminent result is a higher concentration of stresses as this force is being dissipated, not at the same intensity, but to a greater extent compared to the polymer protocol (Serpa et al., 2022).

In reference to Figure 8, we observe a significant increase in tensile stresses at the prosthetic base in contact with the abutments, as indicated by the red-colored region on the color scale. These stresses are subsequently transmitted with greater intensity to the other components before reaching the implant.

Regarding the bone tissue, regardless of the criterion (shear, compression, and tension), there was no significant modification when comparing zirconia bar vs. Polymer (POM). The highest stress concentration remained in the region beneath the zirconia bar.

The comparison between POM and zirconia revealed that the polymeric base concentrated a lower level of stress, with a greater concentration in the implant region, and less influence on the bone tissue (Giudice et al., 2022).

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As suggested by previous studies, the difference in stress distribution around the implant region between polyoxymethylene (POM) polymer and zirconia can be attributed to the morphological characteristics of the respective materials. POM, an amorphous polymer with randomly entangled molecular structure, may exhibit a less uniform stress distribution, resulting in a higher concentration of stress in that region. On the other hand, zirconia, with its well-defined crystalline structure, exhibits a more uniform stress distribution, leading to a lower concentration of von Mises stress (Tashiro; Wu; Kobayashi, 1988).

Specifically, in the prosthetic screw, the numerical difference in stress variation was 41.96 MPa lower when a polymer base was used compared to the zirconia base. Regardless, the higher stress concentration in the screw indicates that there will likely be more force directed in that region, which is consistent with studies by Melo et al. (2019).

Moreover, the geometry and the screw are the same, which allows us to associate this difference in stress with the altered factor in this study, the bar material. During functional loading in the oral cavity, cyclic loads cause the material to undergo different movements, reaching a certain level of strain, which may lead to the initiation of fatigue failure, also known as cold-working (Shemtov-Yona; Riytel, 2016) *.*

Additionally, under very low force, while remaining under the same loading conditions, the material will experience deformation and eventual fracture. These micro-movements, combined with localized stress in specific areas, cause the generated stress to propagate to the opposite region. This can result in, for example, wear of thread portions. Consequently, the screw may loosen due to loss of preload or concentrate stress in the innermost part of the thread, which is thinner, leading to fracture (Bertolini et al., 2019).

This prosthetic failure represents a frequent problem in clinical practice, as it requires additional time in clinical appointments for tightening the screw, replacement, or even removal of fragments (Huang; Wang, 2019).

As a valuable contribution to the scientific community, there is the possibility of achieving a more homogeneous distribution of stresses by using materials such as POM polymer, reducing stress concentration in the prosthetic components, particularly in the screw, leading to improved biomechanical behavior of the overall prosthetic system.

In light of this, the mechanical characteristics of polymer material make it highly attractive for dental applications due to its lower incidence of prosthetic failures, thereby alleviating the stress on prosthetic componentes (Dechet; Baumeister; Schmidt, 2020).

Our results are consistent with the findings of Sirandony et al. (2019), who also reported lower stress values in the framework when using polymer, but with higher stresses in the bone. The difference in results when comparing it to our study may be related to the fact that the authors tested only the framework material without the use of any prosthetic material on top of the framework.

Thus, the use of these polymer-based materials in combination with framework materials can act as a stress buffer, resulting in lower stress values in the bone when using POM compared to zirconia frameworks.

The investigations by Haroun and Ozan affirmed that the use of rigid materials with higher modulus of elasticity can transfer greater stresses to prosthetic components and consequently to the implant. Thus, the use of more flexible materials such as polymers, PEEK, and POM can result in lower stresses, ensuring greater reliability and a lower fracture rate (Haroun; Ozan, 2021).

In summary, most polymers have lower modulus of elasticity and provide greater fracture elongation compared to other types of materials. Therefore, it is more advantageous to use the POM polymer as it reduces the accumulated stress in both the bar and the abutment screw.

Together, observations during a follow-up of approximately 10 months were described in clinical studies, involving prosthetic rehabilitation of a patient with removable dentures made from POM. Scientific data and clinical observations indicate that POM is a promising material that fills gaps in dental therapeutic options for patients with special material demands, such as sufficient color stability and low plaque adhesion in clinical use (Schierz et al., 2021).

Due to the irregular nature of biological materials, finite element analysis (FEA) has proven to be a valid approach for investigating the mechanical behavior of materials in the oral cavity. FEA provides the ability to visualize overlapping structures and allows the determination of the location, magnitude, and direction of a force applied at any point. Since FEA does not alter the physical properties of the material, the analysis is also easily repeatable (Lisiak-Myszke et al., 2020).

However, it is important to note that the results obtained were based on computer simulations and finite element analysis. For a more comprehensive validation, further research is needed, including in vitro experiments, longitudinal clinical studies, and more detailed analyses. These complementary approaches will help confirm and expand upon the findings obtained through finite element analysis.

In accordance with the ongoing advancements in dental material technology and the limited information currently available in scientific literature regarding POM, it is evident that long-term in vivo studies are essential. We acknowledge the necessity for further research, which should encompass clinical studies with varying parameters, such as the number of implants, different implant configurations, diverse implant sizes, and various combinations of prosthetic materials. Such comprehensive clinical studies can provide substantial support for this investigation, thereby contributing to a more profound understanding of the prospective behavior of prosthetic components, implants, and surrounding bone.

The complexity of these studies will allow a deeper exploration of POM's interaction with other prosthetic components, the implant's specific geometry, and the occlusal forces encountered during real clinical applications.

Regarding the limitations of this study, it is imperative to acknowledge certain factors that may influence the generalizability of the results. These include the nature of finite element analysis (FEA) as a simulation method and the assumptions made during the study. Moreover, while FEA offers valuable insights into the mechanical behavior of materials, real-world variations in patient conditions and clinical scenarios may differ.

In conclusion, our findings suggest that materials characterized by a low modulus of elasticity, such as POM, may offer advantages in minimizing the transmission of stress to prosthetic components and the surrounding bone compared to zirconia. However, further research is necessary to confirm and extend these findings, and we emphasize the importance of conducting in vitro experiments, longitudinal clinical studies, and more detailed analyses for comprehensive validation. Such investigations will lead to a deeper understanding of the clinical implications and material selection in dental implant prostheses.

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