Original Research

DENTAL MEDICINE

The impact of physiological and parafunctional posterior occlusal forces on experimental Ti-15Zrsupracrestal dental implant – a finite element analysis

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Abstract

Aim of the study. This study aims to evaluate and compare the stress distribution patterns of two experimental tissue-level, convergent collar implants (one made of Ti-6Al-4V (control) and the other of Roxolid-based (Ti-15Zr) material) using 3D finite element analysis (FEA) under various simulated masticatory conditions.

Methods. A 3D finite element model replicating a tissue-level implant with convergent neck design was developed in ANSYS software, incorporating both cortical and trabecular bone geometry. Implants made of Ti-6Al-4V-Grade 5 and Roxolide-type-Ti-15Zr alloy were simulated under axial (0°) and oblique (45° angle) loading forces (50 N, 200 N, 300 N, and 400 N). The von Mises equivalent stress distribution was calculated to assess the biomechanical performance.

Results. Under masticatory forces simulation, titanium-alloy implants exhibited maximum stress values (400 N) of 260.38 MPa under axial load and 536.2 MPa under oblique load. Ti-15Zr implants exhibited a slightly lower peak stress of 506.95 MPa under a load of 400 N at a 45° inclination and 240.81 N under axial load. Based on 3D finite analysis, the stress distribution maps showed higher concentration in the implant–abutment connection and the cervical region, particularly under oblique loading.

Conclusions. Although titanium implants exhibited higher stress limits, Ti-15Zr implants showed biomechanical stability under oblique simulated forces. Ti-15Zr implants exhibited a more uniform stress distribution with a reduced peak concentration.

Keywords: finite element analysis, Ti-15Zr implants, titanium implants, Roxolid, supracrestal implant, parafunctional forces, tissue-level implant, convergent collar

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Introduction

Edentulism is a medical condition affecting patients in multiple ways, including aesthetics, mental health, and overall wellness. As a result, dental professionals utilize various treatment options, including fixed partial dentures, removable prostheses, and dental implants [1-7]. However, to overcome the limitations of both fixed and removable partial dentures and to protect the mucosal tissues and alveolar ridge, dental implants are increasingly recommended [1-7].

For the past sixty years, dental implants have been established as the gold standard in prosthetic dentistry, offering patients with partial or complete tooth loss predictable, long-term results [3]. The success of implants relies on two main pillars: osseointegration and mechanical stability. Titanium and its alloys, particularly Ti-6Al-4V, have led the field due to their excellent fatigue and corrosion resistance, and also proven biocompatibility, which has been demonstrated over many years of clinical use [2,3,5]. However, attention has increased because of some limitations of titanium-based implants, including aesthetic issues for patients with thin gum tissue, their potential to corrode in saliva and fluoride environments, and growing concerns about titanium particle-induced inflammation and peri-implantitis [8-10].

Under the clinical conditions mentioned above, there is a high demand for metal-free and aesthetically superior options, leading researchers and clinicians to develop and use Roxolid (Ti-15Zr), zirconium-based and ceramic-based implants in clinical settings [11-16]. Roxolid-type implants (Ti-15Zr) are currently the most extensively studied ceramic-based implant materials. Roxolid (Ti-15Zr) provides high flexural strength, resistance to crack growth, chemical inertness, and a tooth-like white color, making it suitable for use in highly aesthetic areas [11,12,14,15]. Additionally, in vitro and in vivo studies have demonstrated that Roxolid (Ti-15Zr) implants exhibit less bacterial colonization and biofilm formation compared to titanium, potentially reducing the risk of peri-implant inflammation and mucositis [9-12]. Moreover, histological evaluations in animal models have demonstrated similar bone-to-implant contact (BIC) for both titanium and Roxolid type (Ti-15Zr) surfaces when proper surface treatments - such as sandblasting and acid-etching. However, concerns about the material's brittle nature, susceptibility to low-temperature degradation (tetragonal-to-monoclinic phase change), and limited long-term survival data remain significant in clinical practice [17-21].

The oral cavity subjects implant-based dental materials to withstand its hostile conditions. One of these conditions is the occlusal status; for instance, this may involve initial parafunctional chewing forces (e.g., clenching teeth, bruxism, etc) when the teeth are present, and these continue even after the teeth are extracted. Moreover, it is known that these high occlusal forces have increased values in the posterior zone compared with the rest of the areas [22-27]. Thus, it is essential to evaluate and consider this when dental titanium or titanium-zirconium-based implants are indicated for missing teeth in the lateral zone.

Different in vitro experiments and test simulations were imagined, but the new digital testing simulation techniques, such as three-dimensional finite element analysis (3D-FEA) assessments, have gained popularity to be used to identify more easily the stress distribution and occlusal stress for various dental biomaterials [24,25,27,28].

Reports of FEA tests have consistently shown that Roxolid-based (Ti-15Zr) implants accumulate higher peak von Mises stresses, particularly at the implant neck and crestal bone, when subjected to oblique forces above 300 N [13,14]. This stress localization significantly increases the risk of mechanical failure in posterior regions.

Different systematic reviews or meta-analyses of clinical reports have corroborated these findings, highlighting higher fracture rates for two-piece implants under occlusal stress, as well as technical complications during insertion due to the material's low ductility [14-17,28,29]. However, based on our search, the suitability of supracrestal Ti-Grade 5 and Roxolid-based (Ti-15Zr) implants subjected to parafunctional masticatory forces has not been widely tested.

This study aims to assess the stress distribution patterns of two experimental tissue-level, convergent collar implants—one made of titanium Grade 5 (Ti-6Al-4V alloy) and the other of Roxolid-based (Ti-15Zr) material—simulated during a clinical setup scenario with standardized axial and oblique parafunctional masticatory forces using 3D finite element analysis (FEA). We formulated the following hypotheses: H1) The Ti-15Zr-based dental implant will exhibit higher von Mises stress limits than the Ti-6Al-4V implant; H2) The Roxolid-type Ti-15Zr-based dental implant will demonstrate uneven mechanical behavior under oblique simulated parafunctional chewing forces.

Methods

Implant design and 3D modelling

For this experimental study, we combined the geometry of a newly developed commercial implant system (tissue-level supracrestal implant, Prama Power Regular Neck implant, Sweden&Martina, Padua, Italy) and two types of dental implant alloys (Ti-4Al-6V alloy (control) and Roxolid-type Ti-15Zr alloy (Roxolid, Institut Straumann AG)

The features of the implants used in this study were based on the anatomy of a first mandibular molar and on the geometry of the previously mentioned commercially available supracrestal implant systems, which incorporate a transmucosal collar modeled as a smooth neck of 2.8 mm high, mimicking the emergence profile commonly used in soft tissue–friendly implant designs, to promote soft tissue stability and biological sealing [30].

The implant was designed as a cylindrical, tissue-level body with a convergent neck measuring 3.8 mm in diameter and 11.5 mm in length, featuring thread geometry at both the apical and crestal regions.

Tissue-level implant designs are extensively recognized in clinical practice for their capacity to reduce bacterial microleakage and to diminish crestal bone remodeling by positioning the implant–abutment interface away from the alveolar crest. Additionally, their design helps preserve peri-implant soft tissue integrity throughout both prosthetic and surgical phases, thereby minimizing inflammation and promoting long-term peri-implant health [30].

All the aforementioned characteristics were applied in both Ti-6Al-4V and Roxolid-type (Ti-15Zr) models for biomechanical consistency.

Figure 1 illustrates the implant placement within a bone block that simulates the mandibular ridge, characterized by a cortical outer layer and a trabecular core. The implant replicates a tissue-level implant design featuring a transmucosal collar.

A CAD model was utilized for the implant design. The implant features a standard cylindrical thread geometry, an internal hexagonal connection, and an apically tapered end. The design reflects real-life tissue-level implant systems used in clinical settings (Figure 2).

Meshing strategy

The implant-bone assembly was discretized using a finite element mesh composed of tetrahedral elements. A global mesh size of 0.5 mm was adopted to balance computational efficiency with solution accuracy, particularly in the vicinity of the implant threads and cortical interface, where stress concentration was expected (Figure 3).

Mesh sensitivity tests compared finer (0.25 mm) meshes with the 0.5 mm mesh to verify that the von Mises stress (vM) values are within a 5% error margin, confirming their consistency.

Material properties assignment

All materials were assumed to be homogeneous, isotropic, and linearly elastic. Additionally, for the Stability factor, the bone and the dental implants were considered to undergo complete osseointegration.

Mechanical properties

Regarding material selection for dental implantology, titanium alloy is one of the most often used and tested materials [2-4]. For this experimental study, the following dental implant materials were considered: a Ti-6Al-4V alloy (control) and Roxolid-type alloy (Ti-15Zr). For both types of materials, a tissue-level convergent neck implant design was designed. The mechanical properties were assigned based on values reported in the literature (Table I) [31-36].

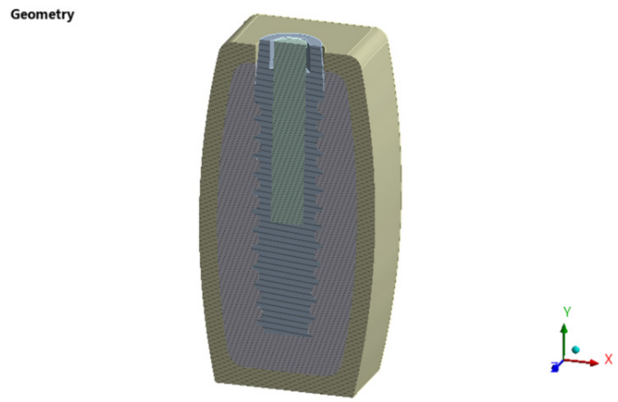

Figure 1. Cross-sectional 3D geometry of the finite element model used in the study.

Figure 2. The CAD model used for the supracrestal with convergent neck Ti-Grade 4/Ti-15Zr implants was analyzed using 3D finite element analysis.

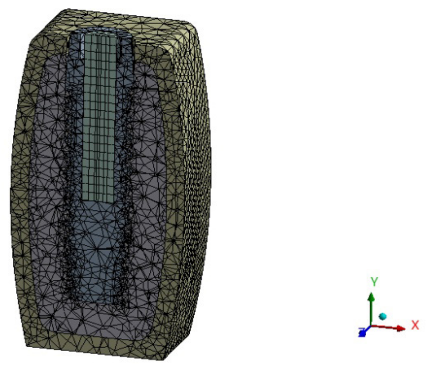

Figure 3. Meshing system used in the study.

Table I. Mechanical properties [31-36].

Component	Material	Young's Modulus (GPa)	Poisson's Ratio
Implant 1	Ti-6Al-4V	110	0.34
Implant 2	Ti-15Zr	103.7	0.33
Cortical Bone	Human Cortical Bone	14.7	0.30
Trabecular (spongy, cancellous) Bone	Human Trabecular Bone	1.47	0.30

Boundary conditions and load application

All the surfaces of the bone block were fully constrained to simulate physiological fixation. No implant displacement was allowed at the apical or lateral walls of the bone.

Loading was applied axially (0°) and obliquely (45°) to the occlusal surface of the implant, simulating parafunctional masticatory forces. The magnitude of force was incrementally increased: 50 N, 100 N, 200 N, 300 N, and 400 N.

Figure 4 illustrates the two loading scenarios employed as a simulation setup for the physiological and parafunctional occlusal forces:

- Scenario A (physiological): Axial loading (0°) to simulate biting force on the posterior teeth.
- Scenario B (parafunctional): Oblique loading (45° angle) to simulate paraxial lateral chewing in the posterior zone.

Each scenario was independently applied to both Ti-6Al-4V and Roxolid-type (Ti-15Zr) tissue-level implants utilizing identical mesh and boundary conditions.

Stress evaluation and output analysis

The output of interest was the maximum von Mises stress values (vM), evaluated across the entire implant structure and at the implant-bone interface. ANSYS 2024R2 software (Ansys Workbench, Canonsburg, PA, USA) was utilized for three-dimensional static analysis.

Solver parameters were configured for static structural analysis. Results were visualized using stress contour plots, and values were extracted at key-point regions: the implant shoulder, the first thread, and the cortical interface.

Representative stress distribution maps were captured directly from ANSYS and are shown in figure 5, figure 6, figure 7 and figure 8.

Results

The numerical analysis showed differences in von Mises (vM) stress distribution between Ti-based alloy and Roxolid-type (Ti-15Zr) tissue-level implants under variable loading conditions. As the applied force increased from 50 N to 400 N, and the angle of application changed from axial (0°) to oblique (45°), stress magnitudes rose consistently in both materials (Figure 9).

Under a 50 N axial load, the Ti-Grade 5 implant displayed a uniform and low-stress field, with peak values of approximately 32.5 MPa, primarily found in the first thread region and the cortical bone interface. Under the same loading conditions, the Ti-15Zr implant showed a slightly lower peak stress of 30.1 MPa, with a more localized concentration near the implant shoulder. As forces increased to 400 N axially, Ti-Grade 5 reached a maximum stress of approximately 260.38 MPa.

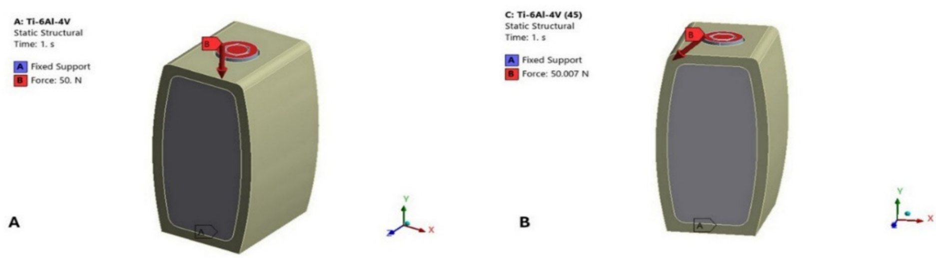

Figure 4. The loading simulated scenarios. A) axial loading (0°) and B) oblique loading (45°).

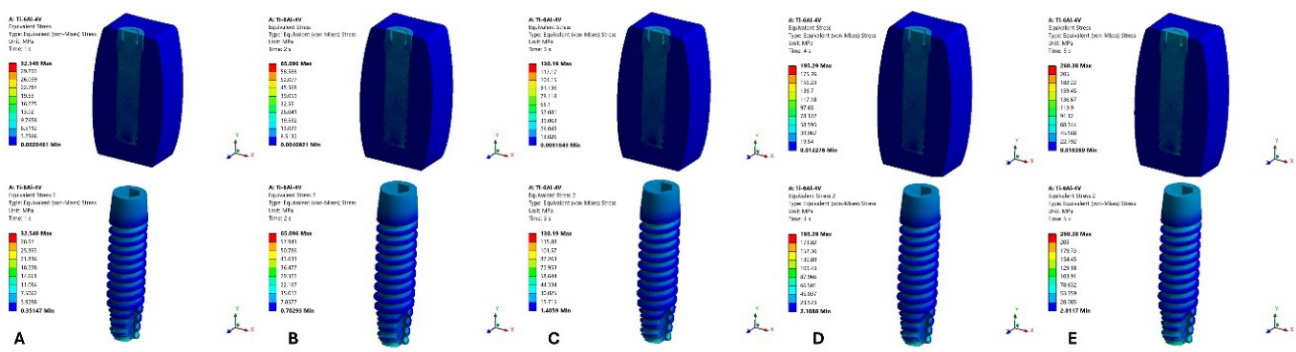

Figure 5. Stress distribution of axial load at 0 degrees in Ti-6Al-4V implant: A) 50 N; B) 100N; C) 200N; D) 300N; E) 400N.

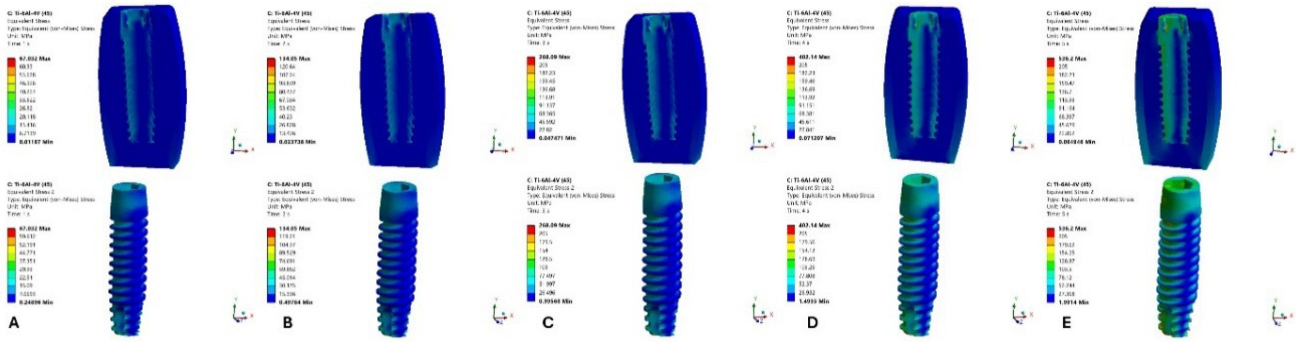

Figure 6. Stress distribution of oblique load at 45 degrees in Ti-6Al-4V implant: A) 50 N; B) 100N; C) 200N; D) 300N; E) 400N.

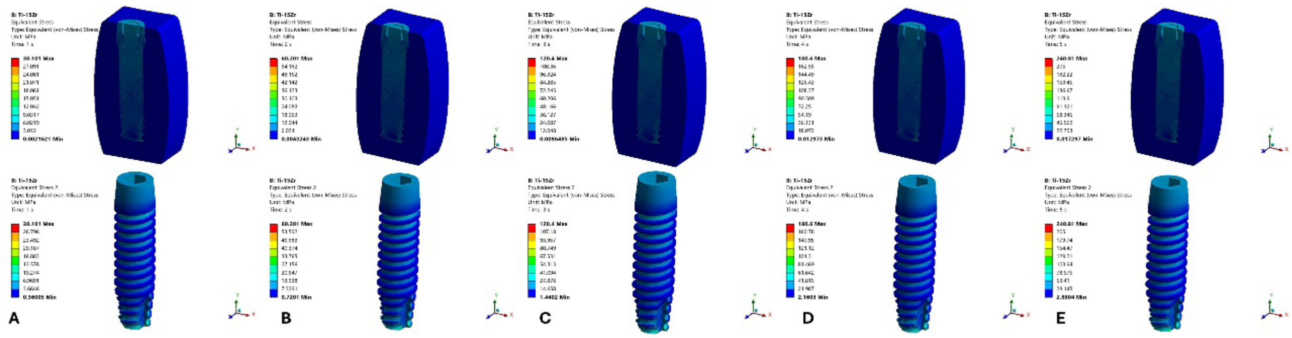

Figure 7. Stress distribution of axial load at 0 degrees in Ti-15Zr implant: A) 50 N; B) 100N; C) 200N; D) 300N; E) 400N.

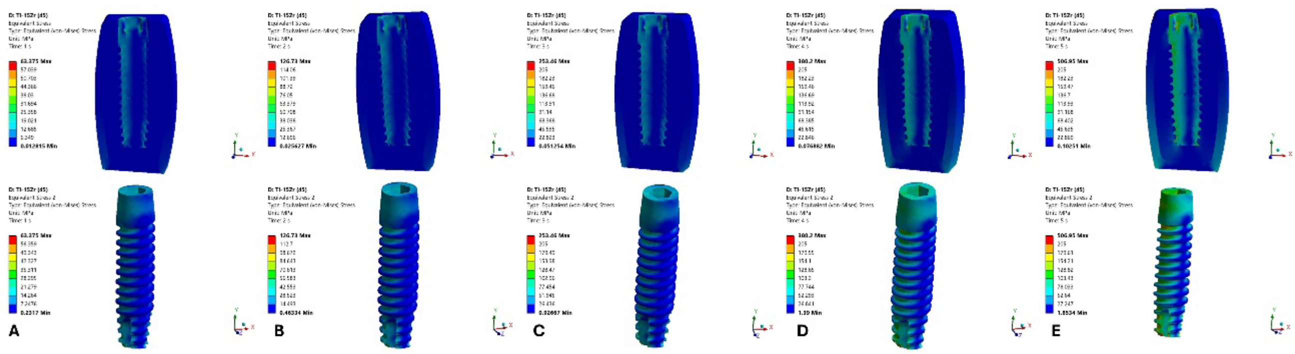

Figure 8. Stress distribution of parafunctional load at 45 degrees in Ti-15Zr implant: A) 50 N; B) 100N; C) 200N; D) 300N; E) 400N.

At the same time, Roxolid-type (Ti-15Zr) reached a peak of around 240.81 MPa, exhibiting a marked stress concentration at the cervical region and the implant-bone junction (Figures 5, 7 and 9).

When oblique loading at 45° was applied, stress patterns changed notably. Titanium alloy Grade 5 subjected to a 50 N up to 400 N oblique parafunctional force registered a bit higher than twice the stress values (67.03 MPa and 536.2 MPa, respectively); with stress localized at the buccal crest and cervical bone (Figure 6). Roxolid-type implant (Ti-15Zr) exhibited similar behavior under the same parafunctional masticatory conditions, with stress values rising from 63.38 MPa (50 N) to nearly 507 MPa (400 N), the latter remaining clinically safe at yield strength thresholds and indicating a potential protection ability for material fracture. These observations were visually confirmed in stress contour plots, where titanium showed a gradual stress gradient with wider diffusion. At the same time, Roxolid (Ti-15Zr) displayed sharply defined peak stress zones at the implant shoulder (Figures 6, 8 and 9).

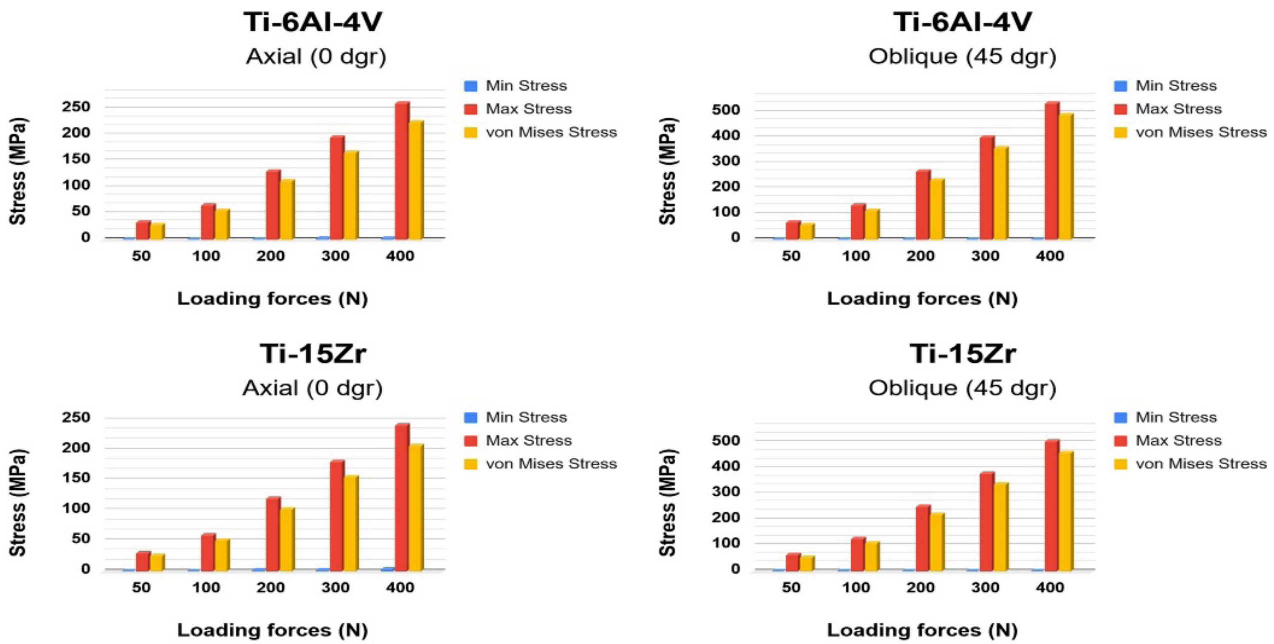

Figure 9. The principal stresses and von Mises values of both one-piece implant types (Ti-6Al-4V and Ti-15Zr) under axial and oblique loading, physiological and parafunctional forces.

The evolution of stress across varying load magnitudes is visually depicted in figure 10. This chart illustrates a linear increase in stress within titanium alloy, which remains within the mechanical safety limits even under severe oblique loading conditions.

On the other hand, Roxolid-based (Ti-15Zr) implants showed an exponential stress response, particularly within the 300–400 N range at 45° angulation, but remaining in the safety zone of the material's vulnerability to fracture (Figure 10). Of particular significance, the steep slope observed in the Ti-15Zr-based implant (45°) curve corroborates biomechanical stability, aligning with earlier mechanical and in vivo investigations that reported fractures in posterior applications [36-41].

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Overall, titanium implants exhibited a resilient stress distribution pattern, with a mechanical response consistent with prior studies by Geng et al. [27] and Himmlova et al. [13], which supports their reliability in load-bearing regions. In contrast, Ti-15Zr's response revealed a similar stress accumulation under parafunctional oblique loads, correlating with fracture-prone regions observed clinically in posterior molar zones [40]. These results underscore the importance of load direction and magnitude in the clinical selection of implant material, and they highlight the Ti-15Zr-based alloy's possibility to withstand complex masticatory forces.

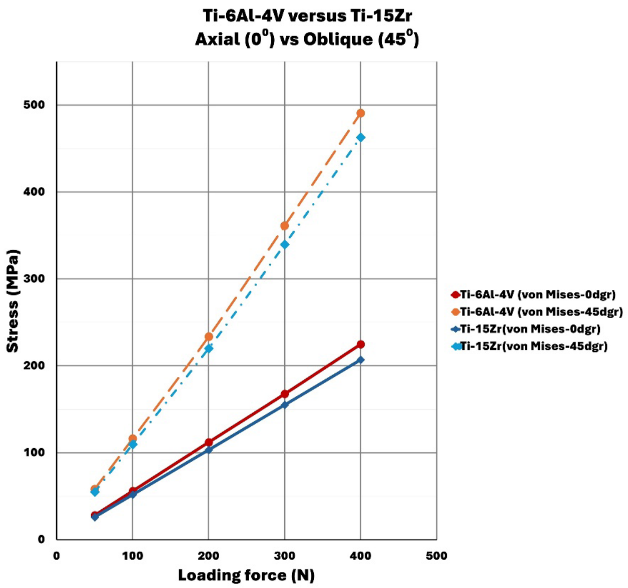

Figure 10. Changes in von Mises stress values for both implant types (Ti-6Al-4V and Ti-15Zr) under axial and oblique loading forces.

Discussion

Occlusion plays an essential role in the stability and osseointegration of dental implants and dental restorations in general [22-26]. Starting from the site of implantation (anterior or posterior), the type of bone (cortical or trabecular), the type of implant (Ti-based, Ti-15Zr-based, Ti-15Zr-Mo-based, alloys etc), its length (long, short), tissue level implantation, or not, convergent neck or not, the general health of the patient, may interfere with the long-term ability of the dental implants to perform and restore the dental tissues functionality [2,4-6,8,11,12,14-19,29-34,36,38,40-46].

The findings of this study show similar mechanical behaviour values between titanium-based alloy and Roxolid-(Ti-15Zr)-based tissue-level convergent collar dental implants under simulated masticatory forces, confirming and expanding on observations reported in recent literature [40-46]. Finite Element Method (FEM) demonstrated that titanium implants distribute occlusal forces evenly and support higher peak von Mises stress values, even under oblique loads. Conversely, Roxolid (Ti-15Zr)-based implants exhibited similar stress concentrations, especially around the implant neck and prosthetic shoulder, under 45° loading (Figure 10). These results align with other literature reports [1,2,5,6,40-46]. Based on these findings, we reject both the H1 and H2 hypotheses.

Moreover, our results are consistent with earlier FEA studies, such as those by Geng et al. [27] and Himmlova et al. [13], which emphasized that material properties, particularly elastic modulus and Poisson's ratio, significantly affect the transfer of stresses from the implant to the surrounding bone. Titanium alloy (Ti-6Al-4V) has a high stiffness value (110 GPa), which leads to higher stress. In contrast, the Roxolid-type alloy's (Ti-15Zr) stiffness (103.7GPa) results in lower stress peaks under similar conditions, which is consistent with the current simulation.

In their study, Correa et al [41] found the value of YTS (yield tensile strength) for Ti-15Zr-based alloy to be around 555±95MPa. In our study results, the maximum von Mises value was 240.81 MPa (axial load) and 506.95 MPa (oblique load). This indicates that this type of implant alloy material and its design (supracrestal implant with a convergent neck) exhibits favourable mechanical behaviour, remaining predominantly in the elastic zone, especially when paraxial forces are applied. Our findings also correlate strongly with other in vitro fatigue testing and clinical reports [5,6,21,22,31,34,35,45-50]. Moreover, we chose to use the tissue-level and convergent neck design for our experimental implants based on other studies that demonstrated their clinical reliability in terms of implant design [30,42,49,51].

On one side, Canullo et al [30] showed that tissue-level convergent neck implants performed well in the anterior region, and Ioannidis et al [43] showed that Ti-15Zr-based alloy implant performed well in the frontal low-load zones and also in the premolar area when using a 3.3 mm diameter implant; on the other side, in our study, we found a good mechanical performance for an implant tested in the mandibular molar region, with a 3.8 mm diameter, which is also consistent with other studies [33,36,40].

It is well known that occlusal forces and cyclic loading may cause the implant materials to behave differently along with oral soft and hard tissues [23-26,44-46]. In the given conditions, to better understand what may happen with the implant materials in the lateral zone, we subjected them to a simulation of physiological and parafunctional masticatory forces; thus, we used axial (0 degrees) and oblique (45 degrees) forces with a range of increasing forces (50N, 100N, 200N, 300N, 400N). The higher values of the masticatory forces (300N and 400N) were observed during grinding or clenching teeth [23-26,52]; thus, we used them to observe the mechanical behaviour of our tested implants.

Brizuela et al [53] demonstrated that a low modulus of elasticity can promote better osseointegration of alloy-based materials used in dental implantology. In our case, the Roxolid-type Ti-15Zr implant with the attributed tissue-level with a convergent collar, remained within the elastic domain even under parafunctional masticatory forces, when compared to the Ti-6Al-4V implant with the same attributed design. Therefore, we believe that the design type and low von Mises stress values contribute to Roxolid-type implants facilitating osseointegration.

The mechanical findings are further interpreted in the light of recent histological, microbiological, and clinical data, offering a comprehensive perspective on the indications and limitations of each material in modern implantology. Thus, histological and immunohistochemical studies have demonstrated improved epithelial adhesion, greater collagen fibre orientation, and reduced expression of inflammatory markers around Roxolid-type (Ti-15Zr) surfaces, which may support long-term peri-implant health [11,12]. Additionally, Roxolid (Ti-15Zr) implants are a valuable solution for patients with a confirmed titanium allergy or those with systemic inflammatory conditions that are aggravated by metal ions [19].

From a biological perspective, Roxolid-type (Ti-15Zr) implants continue to demonstrate notable advantages. Numerous studies, including those by Scarano et al. [10], Kniha et al. [11], and Depprich et al [12], have confirmed that bacterial adhesion to Roxolid-type (Ti-15Zr) is lower than to titanium, which may translate to reduced rates of mucositis and peri-implantitis in clinical practice. Furthermore, soft tissue studies indicate that Roxolid (Ti-15Zr) promotes more favourable fibroblast adhesion and collagen fibre orientation, which can help maintain long-term mucosal sealing and aesthetic outcomes [11,12,20].

These soft tissue advantages, however, must be weighed against the biomechanical risks highlighted in this study and others [38-46]. While titanium has been associated with increased plaque accumulation and corrosion in some instances, it remains the most thoroughly validated material in implant dentistry, with over four decades of clinical data supporting its use in both anterior and posterior regions [3].

Despite growing clinical acceptance, Roxolid-type (Ti-15Zr) implant systems have not yet achieved the same level of scientific and regulatory validation as titanium-based systems. Most Roxolid (Ti-15Zr)-based implant studies are limited by short follow-up periods (<5 years), small sample sizes, and heterogeneity in implant geometry and surface topography [20,21].

Thus, clinically, the decision to use Roxolid-type (Ti-15Zr) or titanium-based alloy should be guided not only by aesthetic requirements or material preference, but also by a comprehensive understanding of the biomechanical environment. For patients with high bite forces, posterior molar restorations, or parafunctional habits, titanium remains the material of choice. On the other hand, Roxolid-based alloy (Ti-15Zr) may be favoured in thin biotypes, aesthetic zones, or in patients with metal allergies or a history of soft tissue sensitivity [41-47].

Nevertheless, in the past decade, new studies have emerged that aim to combine different metallic or non-metallic elements with titanium for improved mechanical or biological outcomes in modern implantology [53-56].

Despite its findings, this study has some limitations that need to be underlined:

- First, the analysis was based on static loading conditions, which do not replicate the complex, dynamic, and cyclic nature of actual mastication. In clinical scenarios, implants experience repeated micro-movements and fatigue over thousands of cycles, which could affect long-term mechanical behavior differently than static simulations predict.

- Secondly, the model assumed that all components, including bone, have homogeneous, isotropic, and linearly elastic material properties. In reality, bone shows anisotropic and viscoelastic behavior that might influence load transfer, especially at the bone–implant interface.

- Thirdly, only one implant geometry (tissue-level with convergent neck design) was examined. While this standardization facilitates direct material comparison, it does not consider variations in implant macro-designs (e.g., tapered vs. parallel walls, thread pitch) that could notably affect stress distribution.

- Fourth, no prosthetic components (such as crowns or abutments) were modeled, and the load was applied directly on the implant platform. While this simplifies the analysis and highlights implant body mechanics, it overlooks the potential effects of prosthetic misfit, occlusal surface design, or cement layer properties.

- Finally, the lack of biological factors, such as bone remodeling, immune response, and healing dynamics, limits the interpretation of results to only mechanical behaviur.

- Real-world outcomes rely on a complex interaction between biomechanics and biology, which cannot be fully captured by FEA alone.

Future research should incorporate dynamic load simulations, fatigue testing, anisotropic bone modelling, and expanded implant geometries to generate more clinically relevant conclusions. Despite these limitations, the current model provides a solid and controlled comparison between Roxolid-type (Ti-15Zr) and titanium-based implants, emphasizing key differences that are important for clinical decision-making.

Conclusions

Within the limits of this experimental study, we may conclude the following:

1. Roxolid-type (Ti-15Zr) implants exhibit similar biomechanical performance to titanium-based materials when subjected to increasing masticatory forces under both axial and oblique loads.
2. Finite element analysis revealed that Ti-15Zr-based implants consistently maintained lower von Mises stress values and more favourable stress distribution across the implant and surrounding bone, even at the maximum applied load of 400 N at a 45° inclination.
3. Ti-6Al-4V implants showed significantly higher peak stress concentrations, especially at the implant shoulder and crestal bone interface.
4. Roxolid-type (Ti-15Zr) alloy remains a valuable implant material in specific clinical situations. However, its use should be limited to carefully selected cases with controlled occlusion and minimal lateral forces.

5. Under the FEA simulation, the tissue-level convergent collar design demonstrated good mechanical behavior for both tested alloy materials.

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