Primary stability and longevity of zirconia and titanium implants submitted to thermomechanical cycling

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Abstract Purpose: The aim of this study was to compare the primary stability and longevity of zirconia and titanium implants when submitted to thermomechanical cycling, analyzing the maximum pullout strength and removal torque.

Material and Methods: A total of 42 implants were fabricated of each type of the material studied (10mm length of active part x 8mm length of coronal portion and 4mm in diameter with thread pitch of 0.5 mm). The implants were inserted perpendicularly in the center of artificial bone cylinders and then divided into 8 groups (n=10) according to the material (zirconia or titanium), treatment (thermomechanical cycling) and tests (Removal Torque or Pullout Test) they would be submitted. The interface between the implant/artificial bone set was also analyzed (n=2) using high resolution photographs. The maximum pullout strength and removal torque values obtained were submitted to statistical analysis using 2-way ANOVA and Bonferroni tests at a 95% level of significance.

Results: The highest torque removal and maximum pullout strength values were found for the the titanium implants, statistically different ($p<0.05$) from the zirconia implants, irrespective of submission to thermomechanical cycling. When analyzing the effect of thermomechanical cycling on the same material, titanium implants showed a reduction in pullout strength ($p<0.05$), and no difference was found between the zirconia groups ($p>0.05$) submitted to this treatment.

Conclusions: The primary stability of titanium implants is higher than that of zirconia implants, proved by the higher pullout strength and maximum removal torque values presented. In addition, it was concluded that thermomechanical cycling is a significant factor only for the longevity of titanium implant stability.

Keywords: dental implants, material resistance, torque.

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INTRODUCTION

Titanium is the material most successfully used in the fabrication of dental implants, and has become the gold standard for rehabilitation in implant dentistry, due to excellent biocompatibility and mechanical properties.[1, 9, 28] However, treatment with titanium must be seen in a critical manner, since there are population groups that present innumerable diseases related to the use of metals, such as sensitivity and allergies.[2, 22]

Considering the increased expectations for esthetic treatments and the need for metal free implants for titanium allergic patients, new materials have been proposed in Implant Dentistry, such as Zirconia implants (yttrium-stabilized tetragonal zirconia polycrystals (Y-TZP) which have shown excellent results when submitted to simulated masticatory forces.[14,15]

In comparison with traditional titanium implants, the zirconia implants showed encouraging biologic results, with a low level of plaque accumulation,[23, 30] good bone/implant contact values[10, 24] and direct bone apposition with good osteoblastic cell proliferation on the zirconia surface.[12, 15] In spite of these advantages, when submitted to stresses and humidity, conditions present in the oral cavity, destabilization of the tetragonal phase of zirconia could occur, slowly transforming it into a monoclinic phase,[2,16, 30] a process known as low temperature degradation. This process may lead to the formation of micro and macrocracks, followed by superficial roughness and reduction in strength, hardness and density; so that, it is important to evaluate the longevity of these implants in the oral cavity.[17, 30]

Although zirconia seems to be a suitable material for the fabrication of oral implants at present, there are an insufficient number of studies about its physical properties. Considering that the evaluation of primary stability, a property related to the absence of micromovements of the implant during the surgical act and longevity, defined as the implant capacity to remain in function over the years, are essential parameters for predicting the success of rehabilitative treatment,18, 20, 29 the aim of this study was to compare the primary stability and longevity of zirconia (Y-TZP) and titanium (Grade 4) implants when submitted to thermomechanical cycling (TC), analyzing the maximum pullout strength and removal torque. The null hypothesis tested was that there would be no difference in the primary stability of these implants, irrespective of submission to TC.

MATERIAL AND METHODS

A total of 42 implants were fabricated of each type of material studied: zirconia and Grade 4 titanium (10mm length of active part x 8mm length of coronal portion and 4mm in diameter) with thread pitch of 0.5 mm. The thermomechanical test was performed in accordance with ISO 14081.

To obtain the titanium implants, Grade 4 bars with 4.76 mm in diameter, (Realum Ind. Com., Metais Puros e Ligas Ltda., São Paulo, SP, Brazil) were cut and machined on a CNC lathe (Veker – Model FEL-1860 ENC – Bener, Vinhedo, SP, Brazil), at a speed of 600 rpm and depth of cut of 0.1mm (**Figure 1**). Zirconia implants were obtained by machining pre-sinterized zirconia blocks (VIPI BLOCK ZIRCONN, VIPI, SP, Brazil) on a conventional mechanical lathe (Romi ID-20, Indústrias Romi S.A., Santa Bárbara d'Oeste, SP, Brazil).

Figure 1. Machined titanium implant

Figure 2. Final macrostructure of zirconia implant

Two zirconia prototypes were obtained: the first one (Z-01) reproduced the exact macrostructure of titanium implants. However, this design was not capable to resist the tensile stress resulting from the pullout test. This may have occurred because zirconia is a friable material [25] and the stress concentrated in the acute angle of the coronal portion of the implant generated fracture of all the samples tested. Therefore, a second zirconia prototype, with a new design for the coronal part, was prepared, sintered in a furnace (Fornos Jung, Model 0916, Blumenau, SC, Brazil) at a final temperature of 1530ºC and tested, and the final macrostructure determined may be observed in **Figure 2**. Although its coronal portion is different from that of titanium implants, the primary stability - main purpose of the study - varies according to the quantity and quality of the local bone, implant geometry (length, diameter, thread distribution), surgical technique used and diameter of the last bur used.[19] These parameters were maintained during the study for both materials.

The implants were inserted perpendicularly in the center of artificial bone (Nacional Ossos, Bauru, SP, Brazil) cylinders (25 mm in diameter x 22mm high), with a thickness of 2 mm simulating cortical bone (40 pcf = 0.64 g/cm^3) and 20 mm thick simulating spongy bone (20 pcf= 0.32 g/cm^3). The bone bed was progressively prepared, using cutters of different diameters and height markings (NEODENT, Curitiba, PR, Brazil). Each implant was screw-retained to its bone bed by means of a hex key, specifically for each material, and digital torque meter TQ 680 (Instrutherm, São Paulo, SP, Brazil). One hour after insertion,[5] the bone/implant sets were randomly divided into 8 Groups (n=10), according to the implant material, thermomechanical cycling (TC) and tests to which they would be submitted (Removal Torque or Pullout Test), as shown in **Table 1.**

Table 1. Studied Groups

Material	Group	Thermomechanical cycling (TC) /Tests
Titanium	G1	Removal Torque
	G2	Pullout
	G3	TC + Removal Torque
	G4	TC + Pullout
Zirconia	G5	Removal Torque
	G6	Pullout
	G7	TC + Removal Torque
	G8	TC + Pullout

The pullout test was performed using an axial traction force (N) toward the long axis of the implant (1.0 mm/min) through a device, which allowed the implants to remain parallel to the long axis of the mechanical test machine with a load cell of 100 Kgf (EMIC DL 2000, São José dos Pinhais, PR, Brazil). The removal torque (Ncm) was analyzed by means of a digital torque meter TQ 680 (Instrutherm, São Paulo, SP, Brazil), with the implant/artificial bone set adapted to a parallelometer. The thermomechanical cycling (TC) was performed (Sistema de Desgaste Termomecânico ER 37000 – ERIOS Ltda., São Paulo, SP, Brazil) with an axial load of 133 N and temperatures ranging between 5ºC, 37ºC and 55ºC (± 2ºC) for 1,200,000 cycles, at a frequency of 2 Hz, simulating chewing for 5 years.[14] One hour after concluding the TC test, samples were submitted to the pullout or removal torque test. The interface between the implant/artificial bone set was analyzed (n=2) using high resolution photographs (Canon MP-E 65mm, Canon Inc., Japan), immediately after implant placement and after TC. For this purpose, the bones of each implant/artificial bone set were sectioned longitudinally with a cutting machine (SYJ - 150 Digital Diamond Low Speed Saw 4, MTI Crystal, Richmond, CA, USA), and then, images were obtained.

The maximum pullout strength and removal torque values obtained were submitted to statistical analysis using 2-way ANOVA and Bonferroni tests at a 95% level of significance.

RESULTS

Comparison of means of torque removal and maximum pullout values can be observed in Tables 2 and 3, respectively.

The highest torque removal value was found for the titanium implants, statistically different ($p<0.05$) from the zirconia implants, irrespective of submission to TC. This factor was not significant ($p>0.05$) for any type of implant tested **(Table 2).** Table 3 shows that the mean maximum pullout strength values were higher for the titanium implants, different ($p<0.05$) from the zirconia implants, irrespective of the treatments used. When titanium implants were submitted to TC, there was a reduction in pullout strength ($p<0.05$), significant in comparison with the group without TC. There was no difference ($p>0.05$) for the zirconia implants.

Table 2. Comparison of means (standard deviation) of torque removal (Ncm) for titanium and zirconia implants (2-way ANOVA, Bonferroni, p<0.05).

Material	No treatment	Thermomechanical Cycling (TC)
Titanium	24.2 (±6.21) aA	22.4 (±9.43) aA
Zirconia	10.07 (±6.96) bA	6.76 (±5.76) bA

Different letters, lower case in the column and upper case in the line, indicate statistically significant difference.

Table 3: Comparison of means (standard deviation) of maximum pullout strength (N) for titanium and zirconia implants (2-way ANOVA, Bonferroni, p<0.05).

Material	No treatment	Thermomechanical Cycling (TC)
Titanium	575.7 (±55.34) aA	454.8 (±83.60) aB
Zirconia	252 (±92.52) bA	215.2 (±140) bA

Different letters, lower case in the column and upper case in the line, indicate statistically significant difference.

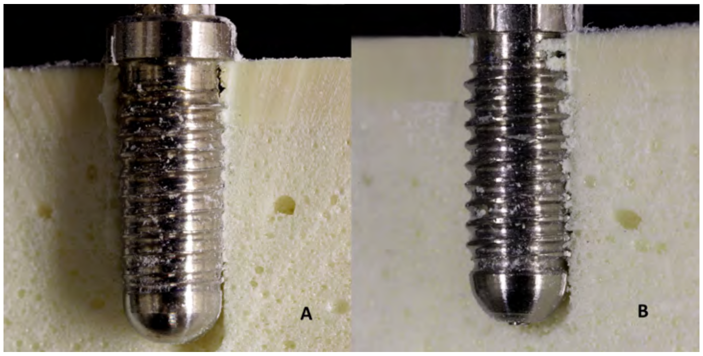

Figure 3. Qualitative analysis of titanium implant/artificial bone interface. A) Immediately after implant insertion into bone. B) After thermomechanical cycling.

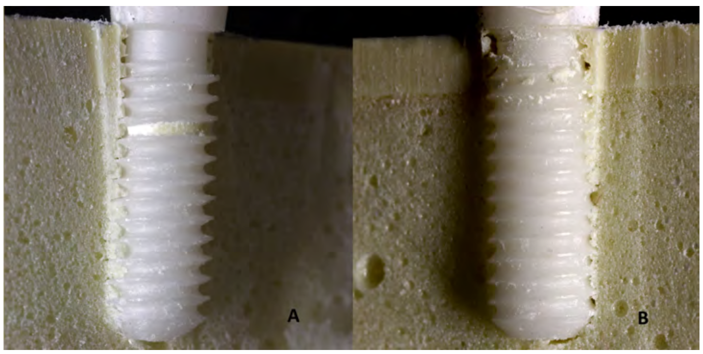

Figure 4. Qualitative analysis of zirconia implant/artificial bone interface. A) Immediately after implant insertion into bone. B) After thermomechanical cycling.

Qualitative analysis of the implant/artificial bone interface, immediately after implant insertion into bone, may be observed in Figures 3A and B. The images show an integrated implant/artificial bone interface for both types of material. After TC, **(Figures 3B and 4B)**, it was verified that the interface remained faultless, demonstrating that TC did not produce loss of implant insertion in artificial bone.

The analysis of the effect of the pullout test of implants on the artificial bone and their interface sectioned longitudinally (Figure 5) showed the presence of artificial bone stuck between the threads of both types of implants, in larger quantity for the titanium implant **(Figure 5- A1)**. When the remaining bone was analyzed, it was verified that the the shape of the spirals was lost in bone that received the zirconia implant **(Figure 5 - B2)**, whereas a larger number of spiral remained in the bone that received the titanium implant **(Figure 5 - A2)**.

DISCUSSION

In this study, the primary stability and longevity of experimental implants of zirconia stabilized with yttrium (ZrO_2_$3\%Y_2O_3$) and Grade 4 titanium of the same model were compared, by means of evaluating the maximum pullout strength and removal torque. The results indicated that there were differences between the titanium and zirconia implants, for both removal torque and maximum pullout strength. Thermomechanical cycling was significant only with regard to maximum pullout force in titanium implants, and therefore, it was not possible to accept the hypothesis of the study.

The implant resistance to pullout suggests the correlation between shape, physical and chemical properties of the screw surface[13] and implant stability in the axial direction.[21] The removal torque test measures the bone/implant strength when the implant is removed from bone[4, 26] thereby quantitatively obtaining the tensile strength necessary to remove it from the bone bed.[18]

Since the parameters of bone quantity and quality, implant geometry (length, diameter, and thread distribution) and diameter of the last bur used were maintained for the two materials tested, the primary stability was compared considering only the material used for fabricating

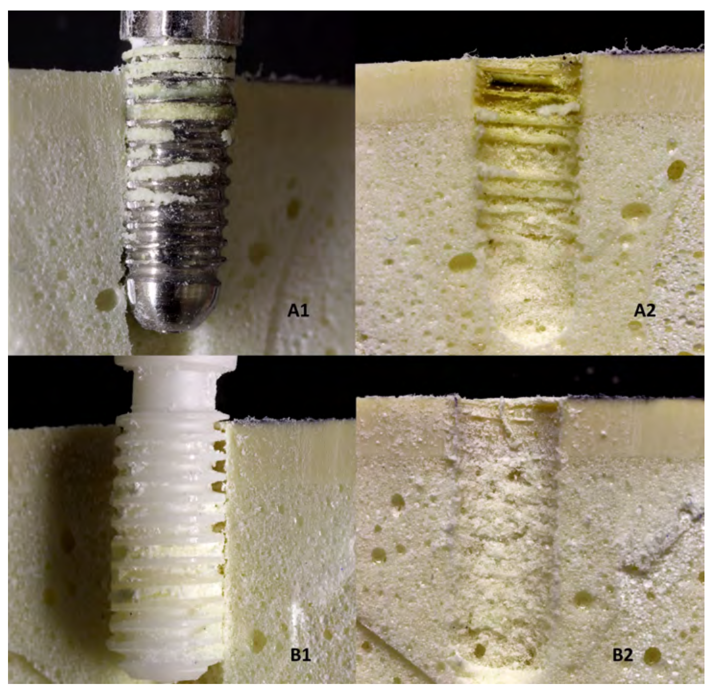

Figure 5. Analysis of the effect of the pullout test of implants on the artificial bone. A1-A2) Tinium. B1-B2) Zirconia.

the implants and its mechanical properties. Thus, any differences in the results would be related to the intrinsic properties of the materials.

Titanium and zirconia present physical, chemical and mechanical differences that characterize them. It is known that zirconia partially stabilized with 3% mol of Y_2O_3 presents high compressive strength (2000 MPa), density of approximately 6.00 g/cm^3, porosity lower than 0.1%, mean grain size of 0.2-0.4 μm, flexural strength of 900-1200 MPa, Vickers hardness 1200 MPa, Weibull modulus 10-12, fracture strength from 7 to 10 MPa, and modulus of elasticity of 210 GPa, double that of titanium.[3, 6, 8, 27, 30] Whereas, Grade 4 titanium presents a mean density of 4.51 g/cm^3 , modulus of elasticity of 103-107 GPa, Young modulus of approximately 120 GPa, flow limit of 500MPa, tensile strength limit of 550Mpa and elongation of 15%.[8]

The pullout maximum force and the removal torque of zirconia implants were not influenced by TC ($p>0.05$). However, TC had an influence on the results of maximum pullout force for the titanium implants ($p<0.05$), demonstrating that the alveolar bone adjacent to the implant responded differently to the load applied. Furthermore, due to the thermal conductivity shown by this material, the temperatures used during thermal cycling could have damaged the properties of the surrounding artificial bone,[7] which would also explain the statistically significant effect of the TC on the results of the pullout test of titanium implants.

The lower results obtained for zirconia, differing ($p<0.05$) from those of titanium implants, can be explained by the process of machining zirconia, which could have introduced superficial cracks in the material, causing a reduction in its strength.[11] Although TC had no influence on zirconia implants, the mean maximum pullout and maximum removal torque values, when compared with the gold standard titanium implants, were still far below the values expected in order for them to be a feasible alternative for dental implants.

The images obtained of the implant/artificial bone set showed greater artificial bone destruction after pullout of the zirconia implant. These results may be explained because zirconia presents double the modulus of elasticity of titanium, which guarantees the greater rigidity of this material.[8] Therefore, the stress on the material will be greater in the surrounding bone.[8]

Titanium, however, is more ductile and has a lower modulus of elasticity. Therefore, when tensile load is applied to pullout the implant, titanium undergoes plastic deformation (elongation) with a reduction in its diameter, which allows some of the spirals of the adjacent bone still to remain without destruction.

The results obtained in this study showed that the mean pullout strength of zirconia implants represents less than half the strength of that of titanium implants. In spite of this, zirconia with a lower pullout strength caused greater destruction of the artificial bone, due to its inherent mechanical properties.

CONCLUSION

It was concluded that the primary stability of titanium implants was higher than that of zirconia implants, proved by the higher pullout strength and maximum removal torque values presented. In addition, it was concluded that thermomechanical cycling is a significant factor only for the longevity of titanium implant stability.

Espíndola, E. et al, Estabilidad primaria y longevidad de implantes de titanio y zirconio sometidos a fatiga termomecánica.
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Resumen Objetivo: El objetivo de este estudio fue comparar la estabilidad primaria y la longevidad de implantes de zirconio y de titanio sometidos a fatiga termomecánica, analizando la máxima resistencia a la tracción y torque de remoción.

Material y métodos: Un total de 42 implantes (10mm de parte activa x 8 mm de porción coronal y 4 mm de diámetro con paso de rosca de 0,5 mm) fueron fabricados con cada material estudiado. Los implantes fueron insertados perpendicularmente en el centro de cilindros óseos artificiales y luego fueron divididos en 8 grupos (n = 10) de acuerdo con el material utilizado (zirconio o titanio), el tratamiento (fatiga termomecánica) y ensayos (resistencia a la tracción o torque de remoción) a los que serían sometidos. También se analizó la interfase entre el implante/hueso artificial (n = 2), utilizando fotografías de alta resolución. Los datos fueron analizados estadísticamente mediante el Análisis de Varianza (ANOVA) de dos vías y la prueba de Bonferroni considerando una p<0,05 como estadísticamente significativa.

Resultados: Los valores más elevados de resistencia a la tracción y torque de remoción se encontraron para los implantes de titanio, estadísticamente diferentes (p <0,05) de los implantes de zirconio, independiente de la fatiga termomecánica. Al analizar el efecto de la fatiga termomecánica en el mismo material, los implantes de titanio mostraron una reducción de la resistencia a la tracción (p <0,05), y no se encontraron diferencias entre los grupos de zirconio (p> 0,05) sometidos a este tratamiento.

Conclusiones: La estabilidad primaria de los implantes de titanio fue mayor que la de los implantes de zirconio, demostrado por la mayor resistencia a la tracción y torque de remoción presentados por este material. Además, se concluyó que la fatiga termomecánica es un factor significativo sólo para la longevidad y estabilidad primaria en implantes de titanio.

Palabras clave: implantes dentales, resistencia de materiales, torque.

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