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Evaluation of Zirconia and High Performance Polymer Abutment Surface Roughness and Stress Concentration for Implant-Supported Fixed Dental Prostheses

Roberto Lo Giudice [1,*], Alessandro Sindoni [2,3], João Paulo Mendes Tribst [4], Amanda Maria de Oliveira Dal Piva [4], Giuseppe Lo Giudice [5], Ugo Bellezza [6], Giorgio Lo Giudice [7] and Fausto Famà [1]

1 Department of Human Pathology in Adulthood and Childhood "G. Barresi", University Hospital "G. Martino" of Messina, 98123 Messina, Italy; ffama@unime.it
2 Department of Public Health and Infectious Diseases, Sapienza University of Rome, 00185 Rome, Italy; alessandrosindoni@alice.it
3 Medical Director Office, University Hospital Umberto I, 00161 Rome, Italy
4 Department of Dental Materials, Academic Centre for Dentistry Amsterdam (ACTA), University of Amsterdam and Vrije Universiteit Amsterdam, 1081 LA Amsterdam, The Netherlands; joao.tribst@gmail.com (J.P.M.T.); amodalpiva@gmail.com (A.M.d.O.D.P.)
5 Department of Biomedical and Dental Sciences and Morphofunctional Imaging, University of Messina, 98123 Messina, Italy; giuseppe.logiudice@unime.it
6 Department of Dentistry, Sapienza University of Rome, 00185 Rome, Italy; bellezzaugo@gmail.com
7 Maxillofacial Surgery Unit, Department of Neurosciences, Reproductive and Odontostomatological Sciences, University of Naples "Federico II", 80131 Naples, Italy; giorgio.logiudice@gmail.com
* Correspondence: rlogiudice@unime.it; Tel.: +39-393-439-9197

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Abstract: Background: The High Performance Polymer is a based polymer biomaterial that was introduced as dental material to manufacture dentures superstructure and dental implants abutments. However, its surface characteristics and stress state still need to be properly described. The aim of this study was to compare the surface characteristics of a High Performance Polymer (Bio-HPP, Bredent, Senden, Germany) for computer-aided design and computer-aided manufacturing (CAD/CAM) milling and a Zirconia (Zirkonzahn, Steger, Ahrntal, Italy). Methods: The abutments surface roughness (Ra) was evaluated for each abutment material (N = 12) using a confocal laser microscope. Data were evaluated using One-Way ANOVA and Tukey tests ($p < 0.05$). In addition, a finite element analysis software was used to present stress measurement data as stress maps with 100 N loading. Results were generated according to Von-mises stress criteria and stress peaks were recorded from each structure. Results: Results showed a mean Ra of 0.221 ± 0.09 µm for Bio-HPP and 1.075 ± 0.24 µm for Zirconia. Both surface profiles presented a smooth characteristic regardless the measurement axis. The stress peaks from implant fixture and screw were not affected by the abutment material, however the high performance polymer showed the highest stress magnitude for the abutment region. Conclusions: Comparing the present results with the literature it is suggested that the CAD/CAM High Performance Polymer abutments present an adequate surface roughness with acceptable values of stress.

Keywords: dental implant-abutment design; polyetheretherketone; surface properties; finite element analysis; dental materials

1. Introduction

The use of prosthetic abutments is an important part of implant treatments. For many years, standard stock titanium abutments were the only option available for the dentists [1]. Various materials could be used for fabrication of individually customized prosthetic abutments, such as metals, ceramics, hybrid materials [2] and composites [3]. However, the titanium is the most used material due to its mechanical characteristics as strength and resistance to distortion. Systematic reviews have shown excellent results promoting titanium abutments as highly reliable [4–6]; however, sometimes it is necessary to replace it by other materials. The usage of titanium as substrate can generate a gray zone effect on the peri-implant marginal mucosa, dampening the treatment aesthetics and the patient satisfaction [7]. The balance between a successful restoration and the patient's aesthetic expectations is always difficult, making necessary the use of alternative materials for some implant-supported restorations. The zirconia as a polycrystalline ceramic material diminishes the grayish effect on the mucosa promoting adequate aesthetics and durability [8]. During the incidence of masticatory forces, zirconia abutment can develop surface defects and promote plastic deformation in the metal [9]. Therefore alternatives biomaterials, for both titanium and zirconia should be investigated such as Bio-HPP.

High Performance Polymer (Bio-HPP) are polyetheretherketone (PEEK) based biomaterials, that have been developed as a promising alternative to metallic dental materials for dentures superstructure on dental implants [10,11]. Bio-HPP is a semi-crystalline linear polycyclic thermoplastic that can be applied to materials as a superstructure, implant abutment, or implant body. Comparing to the titanium alloys, Bio-HPP has some clinical advantages: it promotes lower hypersensitive and allergic reactions, it is radiolucent and reduces the incidence of artifacts on magnetic resonance imaging, it does not have a metallic color, and it is a versatile biomaterial that can be submitted to different surface preparations [4]. The feasibility, versatile clinical applications, higher elasticity and aesthetics increase the Bio-HPP popularity for implant-supported restorations [5]. However, despite the advantages, if bacterial challenges are present and excessive host responses are evoked peri-implant mucositis will occur even when Bio-HPP are used (similar to titanium or zirconia). If peri-implant mucositis cannot be treated, it will lead to peri-implantitis that can even promote the loss of the implant [5].

According to the literature, the suggested threshold surface roughness for bacterial retention is Ra = 0.2 μm, below which no further reduction in bacterial accumulation could be expected [7]. In addition, every dental biomaterial needs its own treatment modality in order to obtain and maintain a surface profile as smooth as possible [7]. An ideal abutment should be a good substrate for a rapid fibroblast and epithelial cell proliferation and attachment, but showing a reduced biofilm and bacterial adherence [8–15]. These characteristics have already been demonstrated for Zirconia abutments. In addition, scientific literature shows that Bio-HPP can be favorable for fibroblast and epithelial cell response and might provide reduced biofilm formation [12]. However, the average surface roughness values (Ra) range widely when considering dental Bio-HPP (from 0.032–2.52 μm). In addition, the surface cleaning protocol can significantly influence roughness, contact angle, and fibroblast proliferation on this polymer-based material [8].

In this sense, composite abutments represent a reliable alternative thanks to their mechanical characteristics [3], fatigue resistance and objective esthetic indexes similar to zirconia in several in vitro and vivo tests. However, the reaction of soft peri-implant tissues in human is unclear due to the lack of histologic, morphologic, and topographic data [12–17].

The implant abutment profile is directly associated with the establishment of an adequate surrounding epithelial attachment that is necessary to the initial healing and emergence profile contour definition [18]. This positive relationship between soft tissue and implant abutment creates a protective barrier between the oral environment and the peri-implant bone [19]. In addition, it is evident that the surface topography affects the soft-tissue cell behavior [20,21]. Among the available abutment materials, Bio-HPP can be considered as a biologically satisfactory material, however, additional studies are still need for a complete understanding of the Bio-HPP abutments' performance in relation to oral tissues [18], while favorable clinical data become available for zirconia and alumina [17,18].

In vitro studies showed that a smooth substrate is linked to a faster fibroblasts adhesion meanwhile rough surfaces, are linked to a more rapid proliferation, instead the epithelial cells favor for both adhesion and proliferation [20–22].

Bio-HPP, approved as a Class II medical device, is a semi-crystalline and pigmented thermoplastic material that contains 20% of homogeneous ceramic filler with the grain size of 0.3 to 0.5 µm [13]. This biomaterial shows a modulus of elasticity around 4 GPa, a water solubility of <0.3 µg/mm^3 and low reactivity to other materials [23,24]. Prosthetically, Bio-HPP shows higher bond strength to composite resin (31.1 ± 3.5 MPa) compared to titanium, a good marginal gap width fit of 19 ± 4 µm and fracture resistance [25].

Biologically, the literature shows how the PEEK represents a reliable alternative to titanium showing an absence of increased risk of marginal bone loss and soft tissue recession during the initial healing period in implant supported prosthetic treatments [26]. Moreover, despite the increased roughness when compared to titanium, this material appears to be less plaque retentive [25,27]. As PEEK has very low or no solubility in conventional solvents (at room temperature), procedures related to surface modifications by physical agents were determined according to the dental PEEK manufacturer [25–28]. In this sense, choosing a PEEK abutment with adequate surface characteristics is mandatory to the clinical success.

This study aimed to evaluate the surface morphology of two different abutments (in zirconia or in Bio-HPP) and the stress distribution in the implant, abutment, and screw. The null hypotheses were that there would be no difference between the abutment materials (1) surface morphology and (2) stress distribution.

2. Materials and Methods

2.1. Surface Roughness

Dental implants abutments (2.7 mm height, 3.2 mm diameter) were obtained from the manufacturer for PEEK (Bredent, Senden, Germany) and sintered Zirconia (Zirkonzahn, Steger, Ahrntal, Italy) (Figure 1). In this study, no finishing/polishing protocol was applied in the samples surfaces since they are indicated to be used as abutments for cement-retained crowns. In addition, the sintering firing has been performed according to the manufacturer's recommendations.

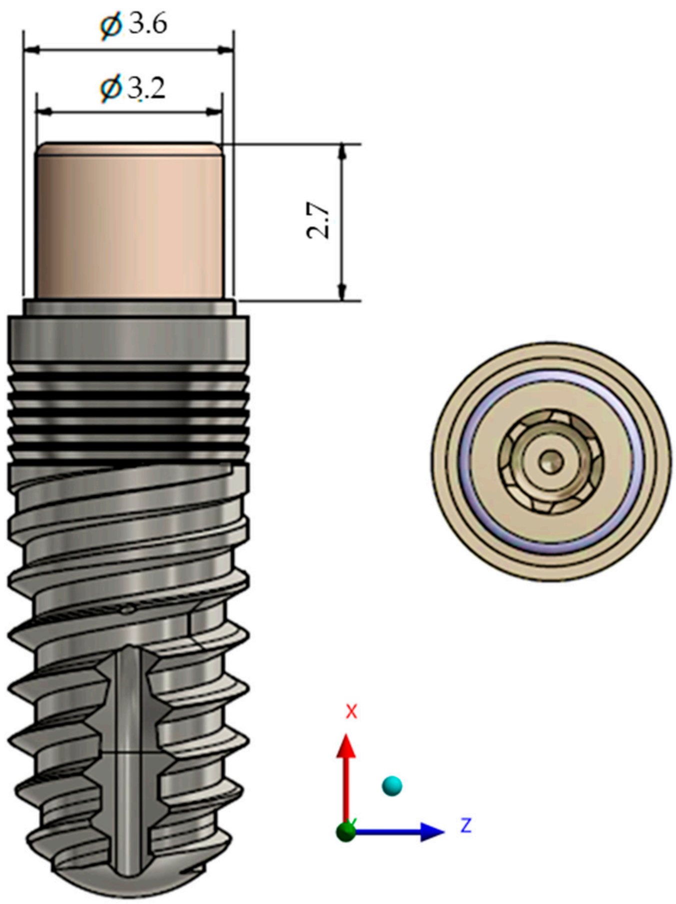

Figure 1. Schematic illustration of the experimental abutment design in lateral and occlusal views.

Using 6 samples with two directions of measurement, the surface roughness was analyzed with the confocal Laser microscope µ-surf (NanoFocus AG, Oberhausen, Germany) with the lens 320 S. This evaluation technique does not require any additional step for the sample preparation (e.g., anti-reflective coatings or sputtering). For each sample, three different areas in a field with the dimensions of 320 µm × 320 µm were evaluated. In this field, a series of profile measurements were performed in both horizontal and vertical directions to determine Ra in µm. Ra parameter is the arithmetical average value of all absolute distances of the roughness profile from the center line within the measuring length. This parameter was measured with Gaussian-Filter, 0.08 mm using 320 µm of profile cut length including the waviness and 240 µm of profile cut length without waviness. The surface data was evaluated in compliance with international standards such as the international ISO standard 25178. The µsoft software (Version 6.0, NanoFocus AG, Oberhausen, Germany) was used to measure the samples surface and to create the dataset. Using the OpenEpi website (accessed on 16 January 2021), a power of 85.4% was calculated using a two-sided 95% confidence interval for 6 samples per group. Data were analyzed using One-Way ANOVA and Tukey tests ($p < 0.05$) in a statistical software (Minitab 16.1.0, Minitab, Coventry, UK).

2.2. Finite Element Analysis (FEA)

The 3D file in Standard for the Exchange of Product Data (STEP) from implant (10 mm × 4.1 mm), hybrid abutment (2.7 mm × 3.2 mm) and screw have been created according to the manufacturer's information and dataset in the modelling software (Rhinoceros version 5.0 SR8, 2013, McNeel North America, Seattle, WA, USA). In addition, the titanium base was modelled (2.5 mm × 3.1 mm) following the manufacture dimensions (Bio-HPP SKY elegance titanium base). The resin cement was considered with 0.1 mm thickness, with a homogeneous solid layer between the mesostructure and the titanium base. The setup has been fixed in a cylinder following the ISO 14801. To allow a similar quantity of faces between the volumetric structures, a Boolean difference was applied between them, allowing perfect fit contacts. The solid model was exported to the computer aided engineering (CAE) software (ANSYS 19.0, 2018, ANSYS Inc., Houston, TX, USA) and a 10% mesh control convergence test was applied determining the total number of nodes and tetrahedral elements based in the total deformation criteria (Figure 2). The mechanical properties are summarized in Table 1 [28,29].

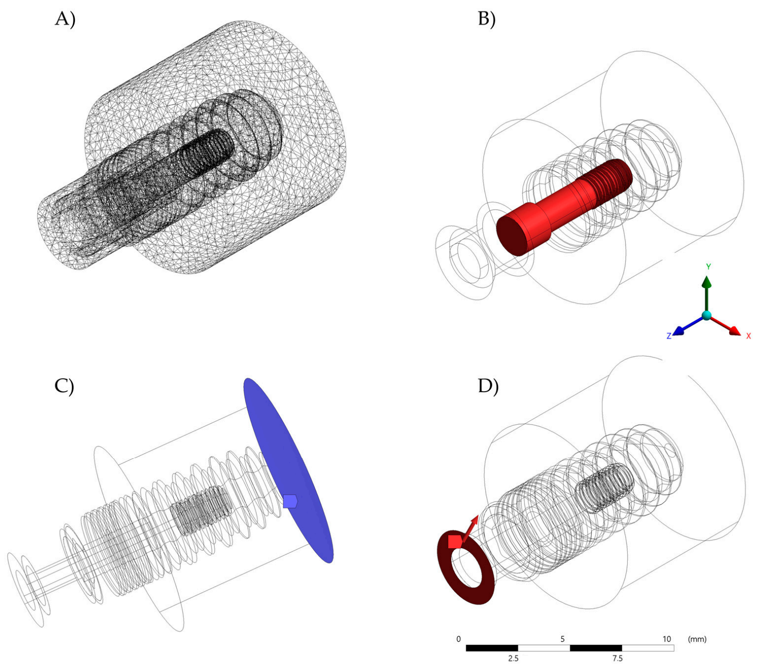

Figure 2. Numerical model and boundary conditions. (**A**) Mesh model containing implant, (**B**) bolt pre-tension, (**C**) Fixed support at the base and (**D**) Force load applied on the top.

Table 1. Mechanical properties of the materials/structures used in the current study.

Material/Structure	Elastic Modulus (GPa)	Poisson Ratio
Fixation base (Polyurethane resin)	3.6	0.3
Resin cement	8	0.3
Titanium	110	0.3
Zirconia	200	0.3
PEEK	3.0	0.3

The boundary conditions were simulated with a compressive load applied at 30 degrees from the implant axis, with magnitude of 100 N [23]. The cylinder base was fixed at the bottom surface. The stress–strain relation was applied, assuming the general behavior of isotropic structures. Von-Mises stress maps were calculated for the qualitative evaluation and the stress peaks values in each structure were obtained for quantitative comparison.

3. Results

3.1. Surface Roughness Analysis

One-Way ANOVA revealed significant difference between the surface roughness according to the abutment material (F = 64.14, $p < 0.01$). Table 2 presents mean and standard deviation for surface roughness according to the abutment material with grouping distribution. And Figure 3 shows the data distribution in a boxplot graph. The surface morphology profile presented a smooth characteristic regardless the measurement axis and material.

Table 2. Surface roughness mean and standard deviation (μm) for different abutment material. Grouping defined according to TUKEY test result.

Abutment Material	Mean	Grouping *	
Zirconia	1.075 ± 0.24	A	
PEEK	0.221 ± 0.09		B

* Different capital letters correspond to statistical difference between the groups.

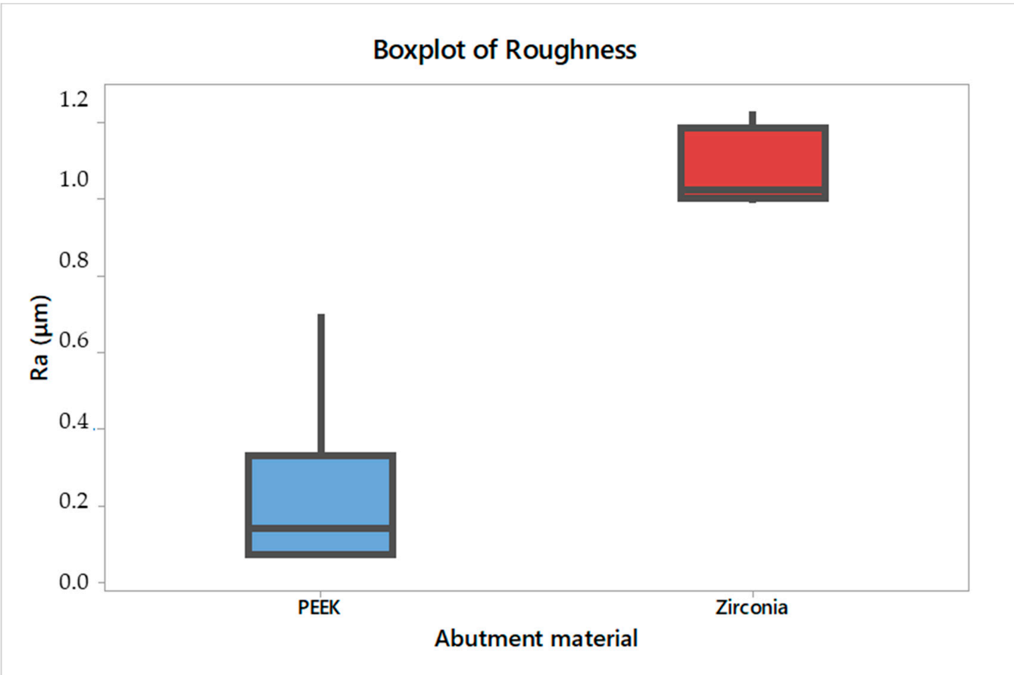

Figure 3. Boxplot of average roughness (Ra) according to the abutment material.

The representative surface topography analysis was summarized in Figure 4 and the representative profile cut (vertical) including waviness are presented in Figure 5.

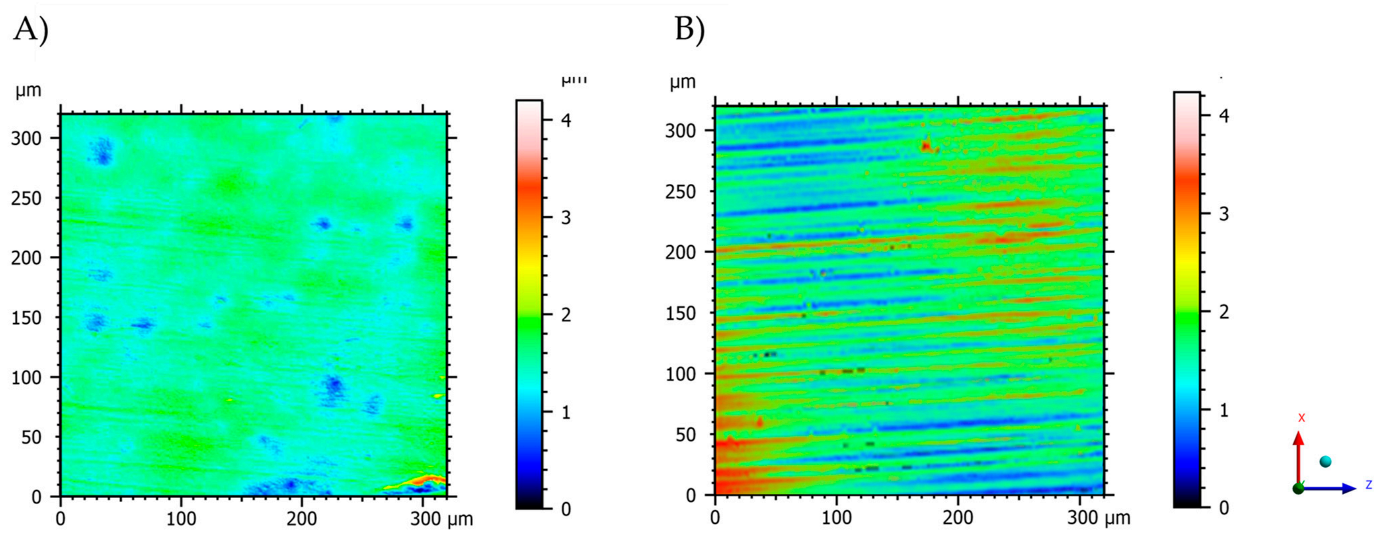

Figure 4. Representative images of the surface topography with shaped removed, showing different topographic patterns. (**A**) Bio-HPP and (**B**) Zirconia abutment.

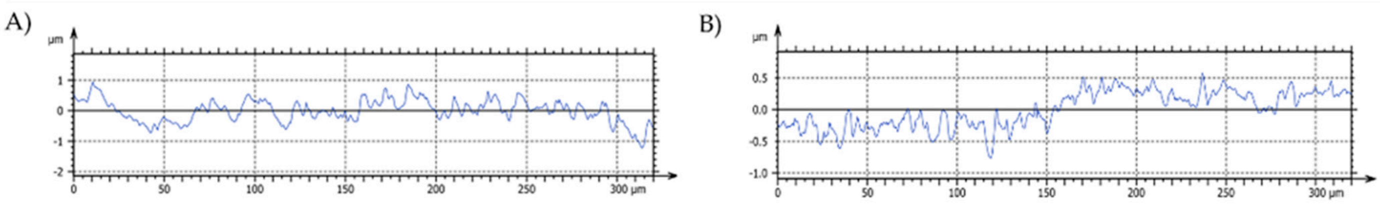

Figure 5. Representative profile cut (vertical) including waviness for Zirconia (**A**,**B**) Bio-HPP samples.

3.2. Finite Element Analysis (FEA)

The FEA allowed the obtention of stress peaks in the implant, abutment, and screw (Table 3). Results show that, regardless the abutment material, the highest peak values were presented in the abutment structure, followed by the implant and the screw.

Table 3. Stress peak (MPa) calculated for each structure according to the abutment material.

Abutment Material	Implant	Abutment	Screw
Zirconia	65.2	66.4	31.5
Bio-HPP	64.9	78.3	32.1

Figure 6 displays the convergence analysis using total deformation as analysis criteria. Figure 7 displays the von-Mises stress in the implant according to the different abutment materials. Observing the stress distribution there was a similar stress pattern between the models for the mechanical response in the exposed threads.

Figure 8 shows the von-Mises stress in the abutment according to the different materials. Observing the stress distribution, there is a higher magnitude for Bio-HPP, caused by the higher deformation generated at the loading moment. However, the inner portion with the implant connection was similar for both models.

Figure 9 shows the von-Mises stress in the screw according to the different materials. There is a similar stress pattern in the threads, where the highest stress magnitude occurred. The Bio-HPP model, however showed other zones of stress concentration in the head of the screw.

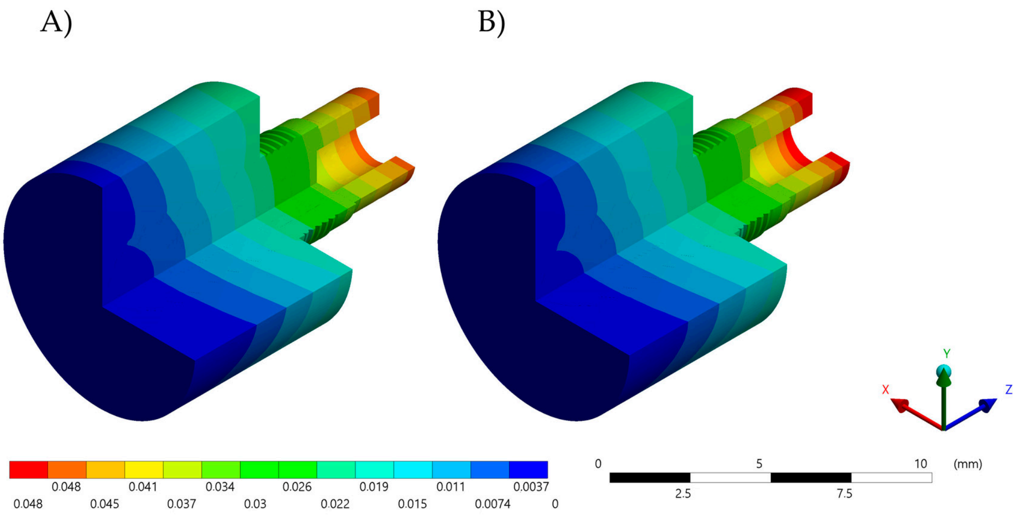

Figure 6. Convergence results verification using Total Deformation (mm). (**A**) Zirconia abutment and (**B**) Bio-HPP abutment.

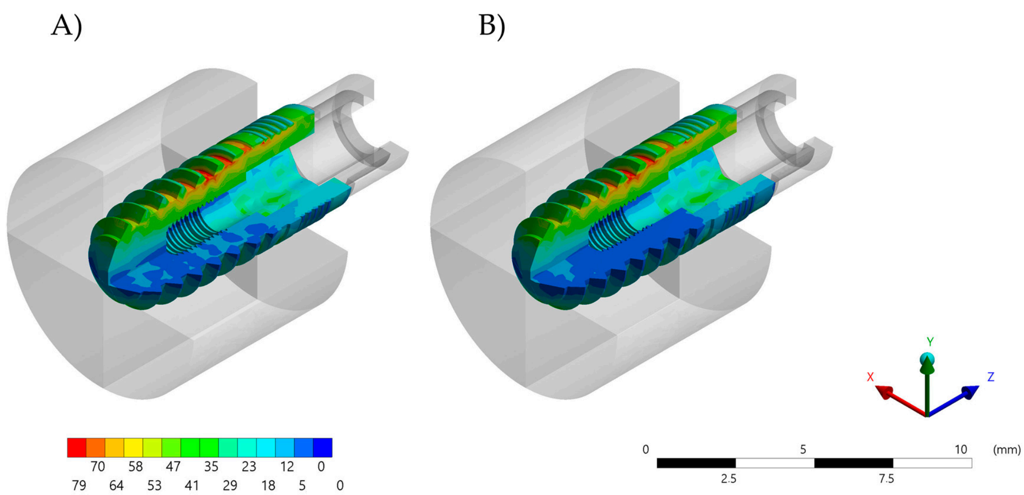

Figure 7. Von-Mises stress maps (MPa) in the implant fixture. (**A**) Zirconia abutment and (**B**) Bio-HPP abutment.

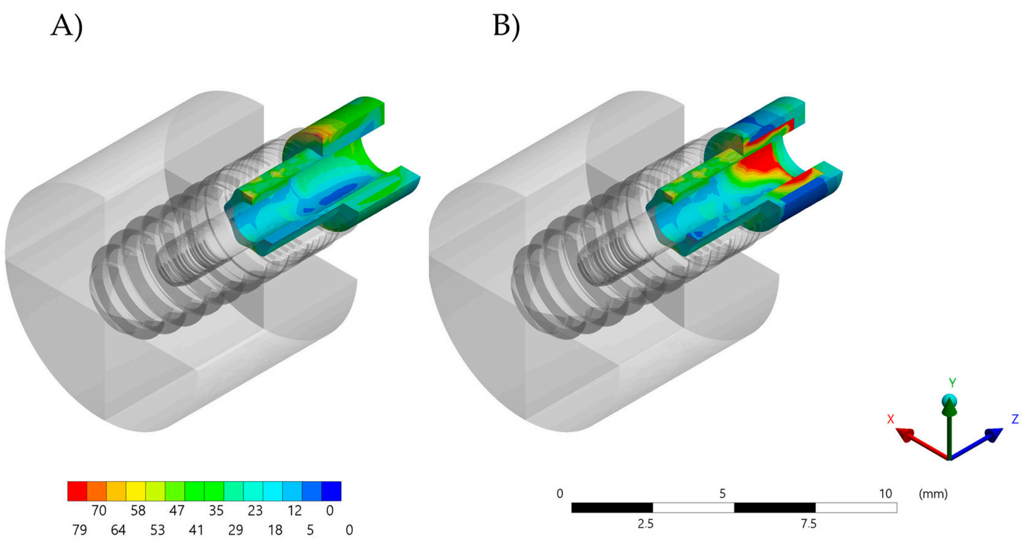

Figure 8. Von-Mises stress maps (MPa) in the abutment. (**A**) Zirconia abutment and (**B**) Bio-HPP abutment.

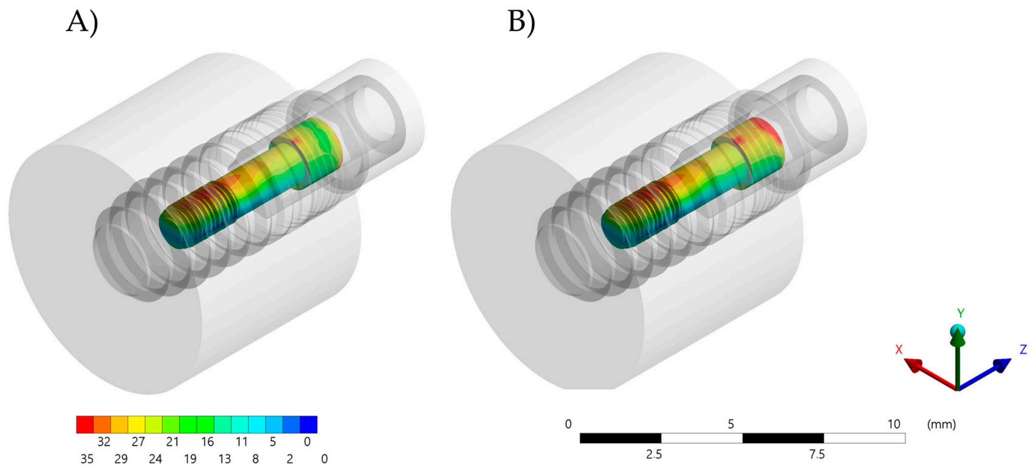

Figure 9. Von-Mises stress maps (MPa) in the screw. (**A**) Zirconia abutment and (**B**) Bio-HPP abutment.

4. Discussion

The present communication aimed to evaluate and compare the surface characteristics and stress of Bio-HPP and zirconia abutments for CAD/CAM. The Bio-HPP was developed as a peculiar Bio-HPP for dental and medical applications [30]. Therefore, it is possible to observe that there is an uniform surface characteristic. This characteristic can be useful when selecting the abutment special positioning in the CAD software.

The mechanical characteristics of this material make it very attractive for many biomedical applications thanks to an elastic modulus of 4000 MPa (value between cortical and cancellous bone tissues elastic modulus), a fracture resistance up to 1200 N, flexural strength higher than 150 MPa, water absorption of 6.5 μg/mm^3, water solubility inferior to 0.3 μg/mm^3, melting range of approx. 340 °C, bond strength higher than 25 MPa and hardness of 110 HV [31,32]. Despite that, it presents higher stress concentration on its structure than zirconia abutment due to the increased flexibility. However, the threshold of 150 MPa was not achieved what means that mechanical failures would not occur.

The biological characteristics of biocompatibility, insolubility in water and low reactivity with other materials make Bio-HPP appropriate even for allergic patients [23,29]. Moreover, excellent chemical stability, resistance to radiation used in sterilization procedures, and transparency to radio waves makes this polymer one of the best alternatives to titanium for orthopedic application [33]. In addition, stain resistance and color stability have been described in the literature [34].

These characteristics makes Bio-HPP suitable for several dental application as fixed prostheses, provisional abutments, dental implant, implant-supported bars and clasps for removable prostheses [35–40] with a surface significant smoother than zirconia (without polishing).

The evaluation of the surfaces characteristics is particularly important thanks to the strong connection to the physical-chemical composition at nanometer scale and the cellular response (adhesion and growth) [38]. The roughness profile appears also to be important for tissue inflammation and cellular behavior. The analysis of the present data shows how this material has a mean Ra of 0.116 ± 0.06 μm and Rz of 0.661 ± 0.274 μm. Therefore, with Ra lower than 0.2 μm, the polishing protocol seems not to be necessary for Bio-HPP abutment samples. However, when bonding is necessary, an adequate surface treatment should be performed to increase the surface roughness.

This data should be evaluated considering the intraoral cavity as a particularly difficult environment to test material characteristics, due to the strong mechanical and chemical stresses to which the materials are subjected and due to the heavy bacterial activity.

Comparing the present data to the literature, it is possible to observe the link between the mucosal inflammation and the material used especially considering the macroscopic design, surface topography or surface manipulation [41,42]. For abutments, the literature reports that zirconia is less prone to plaque retention compared to titanium [43]. Therefore, the present study suggests that Bio-HPP also could be an alternative due to the reduced surface defects.

Not only the different biofilm accumulation but also the quality of soft tissue attachment may play a role in the degree of inflammation. Zirconia (YTZP) has been shown to promote in vitro a higher degree of fibroblasts proliferation when compared to titanium [44]. When comparing the surface roughness values (Ra) of titanium alloy (0.086 ± 0.006 µm) to Bio-HPP and Zirconia, it appears evident how the polymeric abutment has an intermediate behavior between the other materials [45]. However, a direct comparison between these materials should be carried out in similar conditions, even after aging processes.

In addition, it has been indicated that a fibroblast activity is decreased in titanium surfaces smoother than 0.1 µm [46]. Mehl et al. (2016) showed that a higher fibroblast adhesion is present with a surface roughness between 0.1 and 0.2 µm for ceramic and metallic abutment materials [47]. The Ra calculated data suggests that Bio-HPP could induce a better fibroblast behavior and produce an adequate soft tissue sealing than unpolished zirconia abutment.

When compared to scanning electron microscopy (SEM), with confocal surface measurement [48], the data is available as quantitative information of actual height coordinates (X, Y and Z). This makes possible to perform a precise evaluation of 3D parameters. Moreover, no sample preparation was required. Compared to an atomic force microscope (AFM), this method shows several improvements such as a larger measurement range, higher scan speed and non-contact operation.

Bio-HPP based and derived materials could be considered as a reliable group of biomaterials that could find many applications in bone and cartilage replacement as well as in many diverse medical fields [49]. In orthopedics the potential of reducing stress-shielding, weight of the implants and wear during use have been documented, showing favorable biomechanical characteristics, and biological safety [50]. In maxillofacial surgery its use has been documented for maxillofacial reconstruction of patients with facial imbalance with the use of custom implant for mandible and fronto-orbital reconstructions [51,52]. In particular, for the orbital wall reconstruction its use has showed a higher clinical efficacy in comparison to titanium plates, especially in restoring the volume and shape of the damaged orbit [53,54]. For dentistry, it can be properly used even in full-arch rehabilitations [55].

Moreover, in the era of CAD/CAM production these materials have been successfully used in digital workflows that comprehended the elaboration of routine postoperative CT scan in conjunction with a 3D printer for the immediate fabrication of a 3D-printed anatomical cast [56].

A previous study aimed to assess and correlate the stress distribution in an anterior maxillary implant-supported prosthesis with 0°, 15°, and 25° angulated titanium and zirconia abutments using a three-dimensional finite element analysis. According to the authors, when comparing titanium and zirconia straight and angulated abutments, zirconia abutments showed less stress values compared with titanium [57]. The authors recommended that a careful selection of the abutment material combined with a proper loading protocol is strongly suggested to minimize the influence of loading forces on the surrounding bone of a dental implant [57]. The present study corroborates with this statement showing that even when using a titanium-base in the abutment manufacturing, different behavior would be expected depending on the framework material.

Another investigation compared the stresses occurring in the peri-implant bones, implants, crowns, abutments, and screws after loading through finite element analysis using the PEEK as alternative to titanium abutment [58]. It was observed that the use of PEEK abutment increased the stress on the crown, being suggested that screw loosening and screw fracture may be caused by the stresses on screw as consequence of PEEK abutment usage [58]. The present study considered the cement layer and the titanium base as part of the abutment, different from a fully PEEK structure as simulated in the reported study [58]. This difference can explain the absence of effect in the screw as observed in the present study.

Therefore, the titanium base associated with the mesostructured should be mandatory to keep the implant/abutment connection with proper fit and similar hardness.

Three-dimensional models were also used to simulate the clinical situation of replacement of a maxillary central incisor with implants, with a provisional single crown, loaded with 100 N in a perpendicular direction. According to this condition, less rigid abutments (PEEK) showed a trend of higher stress concentration in the implant and at peri-implant bone tissue [59]. Despite that, this mechanical behavior seems to be also associated with the bone level around the peri-implant tissue, since during the present simulation where the ISO 14801 was followed it was not observed.

Simulating in vitro fatigue of dental implants, a previous study inspected the use of PEEK and Zirconia as materials for customized definitive implant-supported hybrid abutments, supporting two types of all-ceramic restorations: translucent zirconia and lithium disilicate monolithic crowns [60]. It was reported that both abutments promoted similar fatigue levels regardless of the crown materials [60]. This assortment corroborates the present findings, since the stress magnitude was similar in the screw, implant, and bone.

Nowadays, the CAD/CAM technologies have improved diagnostics and the clinical/surgical phase of treatment and follow-up [61]; however, aspects of new biomaterials and surface characteristics needs to be evaluated, with a long-term follow-up [62]. In this sense, the present results could be useful to explain the in vivo behavior of Bio-HPP as abutment material and as a biocompatible material in contact with different tissues. As study's limitation the use of quantitative results are not sufficient to provide difference between the samples as well as the absence of the oral environment simulation. Further studies should be carried out to complement the present findings showing if the production processes, aging process, and surface treatment could affect the surface profile of this biomaterial. Experimental animal models [63] and bacteriological evaluation [64] should also be pointed as further studies relevant to the field.

The present study simulated an implant testing with the resinous fixation cylinder to simulate peri-implant tissue. Therefore, this approach simplifies the clinical scenario in which the implant placement occurs in bone with different types. Hence, the present study does not allow the extraction of stress data on the surrounding bone. The crown-implant ratio is not similar to the presence of a crown which could modify the results of this investigation. In addition, to implant-abutment connection joint presented interfaces considered ideal without vertical or horizontal misfit. The roughness was analyzed in a controlled condition, but polishing, grinding or different milling parameters can modify the average roughness calculated herein. Further in vitro investigations are required to provide additional data and validate the limitations of the present numerical study.

5. Conclusions

Based in the present data, it is suggested that CAD/CAM High Performance Polymer abutments present an adequate surface roughness and acceptable values of stress. The mechanical behavior of implant fixture and screw were not affected by the abutment material, however Bio-HPP showed the highest stress magnitude for the abutment region in comparison to Zirconia.

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