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ORIGINAL ARTICLE / ОРИГИНАЛНИ РАД

Analyzing strain in samples with all-ceramic systems using the digital image correlation technique

Ivan Tanasić[1], Aleksandra Mitrović[2], Nenad Mitrović[3], Dušan Šarac[3], Ljiljana Tihaček-Šojić[4], Aleksandra Milić-Lemić[4], Miloš Milošević[2]

[1]Medical College of Applied Studies, Belgrade, Serbia;
[2]University of Belgrade, Innovation Center of the Faculty of Mechanical Engineering, Belgrade, Serbia;
[3]University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia;
[4]University of Belgrade, School of Dental Medicine, Clinic for Prosthodontics, Department for Prosthodontics, Belgrade, Serbia

SUMMARY
Introduction/Objective The study was conducted to identify the maximum strain generated in the samples composed of poly-methyl-methacrylate, Straumann® implants, and three types of ceramic systems.
Methods Three types of experimental models were used, loaded by external load of 100 N, 300 N, and 500 N and analyzed using the digital image correlation method. The models were composed of yttria-stabilized zirconia, e.max lithium disilicate, and Vita Enamic® hybrid ceramics, placed on the Straumann® cylindrical dental implant systems (4 × 10 mm) with straight abutments.
Results Significant differences in strain values between samples with different crown material groups were detected ($p = 0.000$). This suggests that strain values were dependent on the type of crown material. Strain values were also affected by the region of interest ($p = 0.000$). Application of two-way ANOVA enabled testing of the interaction effect between two independent variables, crown material and region of interest, where a significant difference was also found ($p = 0.046$). This indicates that strain values were also influenced by different combinations of material type and region of interest. The highest strain values were found for Z (0.383 ± 0.015) in the apical region, and the lowest for E (0.303 ± 0.015) in the middle region.
Conclusion The study shows maximum strain in the apical and marginal directions. When considered various all-ceramics, we noticed the minimum strain below Vita Enamics®, while the maximum strain was found in samples with yttria-stabilized zirconia crown.
Keywords: all-ceramics; strain; PMMA

INTRODUCTION

The lower fracture toughness in all ceramic systems (full ceramics, metal-free ceramics) can cause crown material breakdown. Hence, it's necessary to create restorative material that could resist possible excessive masticatory forces and satisfy mechanical features due to the irregular shape and size of teeth and dental arches in the restored patients [1]. Still, there is a concern about an impact of currently developed high strength ceramics and their possible influence on underlaying structures, especially considering implant-supported restorations [2]. Thus, additional requirement regarding their biomechanics is to achieve positive effect of all ceramic crowns on the supportive bone tissue that surround teeth or implants. It would be suitable if these materials could be prepared as a mixture composed of restorative dental materials to express their best biomechanical features in a dynamic system of the oral cavity [3]. Furthermore, it is known that the composition of supporting structures may influence stress distribution in all ceramics [4]. Additionally, material properties of all ceramics can cause different strain responses in adjacent structures. The mechanical properties, such as elastic modulus and Poisson's coefficient of each material, should be especially considered in regard to the strain in the supporting tissue [5]. The crown material with lower modulus of elasticity absorbs an increased portion of energy from the applied occlusal load, and transfers less energy to the supporting dental tissue. Therefore, crowns made of acrylic resin/composite showed higher ability to absorb the occlusal stress than crowns made of ceramic material, zirconia, or gold alloy [6]. Considering implant-supported restorations, occlusal materials with high elasticity, like acrylic resin/composite, will mitigate the external occlusal forces and decrease its effect on the bone–implant interface during the occlusal loading conditions [7]. Higher elasticity material reduced the transmitted forces to bone by about 94% compared to zirconia, which improved biocompatibility regarding impacts to adjacent supporting structures [8]. Previous studies investigated the influence of various occlusal materials on stress transferred to implant-supported restorations and supporting structures and found that the type of the restorative material used in implant crown design was a significant factor in the amount and distribution of the stress-loaded structures [9, 10]. The following study was conducted to investigate

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Correspondence to:
Ivan TANASIĆ
Obrenovac Medical Health Center
Vojvode Mišića 231
11500 Belgrade
Serbia
doktorivan@hotmail.com; prosthodontics.clinic@gmail.com

the impact of three usually applied metal-free ceramics on the supporting structure of poly-methyl-methacrylate (PMMA). PMMA was used to substitute the bone due to similar physical characteristics, as previously mentioned [11]. A new classification based on the phase present in the composition of all ceramics included current materials and thus tend to be more suitable for mechanical properties [12]. In accordance with this, all ceramics are divided into three families: glass-matrix ceramics, polycrystalline ceramics, and resin-matrix ceramics. The objective of this study was to determine, evaluate and visualize surface strain generated in samples-models composed of the above mentioned all-ceramics subjected (exposed) to vertical loading conditions. A standardized model for biomechanical investigations was previously proposed [13, 14]. Through the use of the digital image correlation (DIC) method, the authors sought to explain the effect of different all-ceramic crown materials on strain change in peri-implant structures and to indicate which kind of an all-ceramic crown is more suitable for the implant-supported crown. Three sets of null hypotheses were established prior to ANOVA analysis:

1. mean strain values are the same for all samples;
2. mean strain values are the same for all regions of interest;
3. there is no interaction in effect between the ceramic material and the region of interest.

METHODS

The study proposed three groups of experimental models (samples) composed of PMMA, Straumann® implants with three types of all-ceramic posterior crowns (specimens) placed on the Straumann® S Ø 4.1 × 10 mm RN dental implants (Straumann® Cylindrical Dental Implant systems, Basel, Switzerland) with straight abutments. Straumann® RN synOcta® abutments were screwed on a Straumann® dental implant, and tightened using Straumann® SCS screwdriver, ratchet, and torque control device. Abutments were torqued down with 35 Ncm.

All ceramic fully anatomical, contoured crowns were prepared by utilizing computer-aided-design / computer-aided-manufacturing (CAD/CAM) to standardize specimens. The milling was done by a Wieland dental CNC (Ivoclar Vivadent Group, Schaan, Liechtenstein) in a milling unit of a technical dental laboratory. The CAD/CAM milling machine finished ceramic blocks and manufactured all ceramic crowns. The ceramic blocks were processed one by one in the following manner: a block was rotated on its axis while a diamond disk rotated moving up and down around the ceramic block, thus processing it. The movement of the diamond disc was enabled via an electric rail. The precision of milling was in the range of +/- 25 microns. The crowns were polished using polishing sets with a special bur kit for tested all-ceramics, with water cooling. All-ceramic crowns were shaped by milling of the ceramic blocks affixed to a wheel.

The obtained crowns were then placed on abutments using cement and definitively cemented with a special esthetic cement for metal-free ceramics – a self-adhesive Maxcem Elite (Kerr, Orange, CA, USA) dual-cured cement. This research investigated the following materials: IPS e.max Zir-CAD (yttria-stabilized zirconia polycrystal, Y-TZP; Ivoclar Vivadent, Schaan, Liechtenstein), as a high-strength ceramic with high values of flexural strength and fracture toughness thanks to the crystalline structure [15, 16]; E max CAD (lithium disilicate glass-ceramics; Ivoclar Vivadent), which has a needle-like crystal structure that offers excellent strength and durability as well as outstanding optical properties [17]; and Vita Enamic® (VITA Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany), as the first hybrid dental ceramic with a dual-network structure belonging to the polymer-infiltrated ceramic network (PICN) group, where one network is a ceramic material (feldspar, 86 wt%) and the other is a polymer (commonly used methacrylates for dental applications, 14 wt% [18, 19, 20]. Hereinafter, the terms Z-model (Z samples; zirconia), L-model (L samples; e.max), and E-model (E samples; Enamic) will be used due to easier overview. Each group consisted of three different ceramics, thus the total of nine specimens with an implant immersed in the PMMA during the hardening process were manufactured in accordance with the standardized protocol presented in a recently published research [12]. Immediately after initial preparing and spraying (coating), the models were tested on a H10K-S UTM testing machine (Tinius Olsen TMC, Horsham, PA, USA) with a 5 kN load cell, as described in previous studies. The DIC method was used to visualize the strain field in the loaded models. As previously said, the loading speed was 0.1 mm/minute, while the stroke limit was set to 1 mm. We used the force intensities of 100 N, 300 N, and 500 N, respectively, in accordance with the literature data [19]. This was an experimental compressive loading with a gradual increase in the intensity of the applied vertical load. Of the total number of the samples/specimens (n = 9), three representative figures (virtual models) obtained by the software data processing were selected and used to present different stages of the vertically loaded Z, L, and E samples. Strain fields were observed on surfaces 2 mm away from the vertical axis of the implant body. Regions of interest were considered to be surfaces that surrounded the implant body in a projection of the section line, presented in all the figures. In order to facilitate the interpretation of the results, we divided the region of interest into three parts: the cervical region (CR), the middle region (MR), and the apical region (AR).

The following analyses for nine samples (three in each group) were conducted:

- Two-way ANOVA was used in order to examine the differences in the effect of the type of samples, region of interest, and their mutual interaction on the strain values in the sample. The strain values induced by the different ceramic material and strain values within the regions of interest were compared using two-way ANOVA. Significance level (α) was set to 0.05. ($p < 0.05$). All comparisons and calculations were made using the R Stats Package (Software R, Vienna, Austria).
- The post hoc t-test with Bonferroni correction. The post hoc t-test can compare only two strain values at a time.

RESULTS

The relationship between sample type, region of interest, and strain values is displayed in the interaction plot (Figure 1). Comparing all nine samples, the maximum strain (peak) was observed in the ARs and corresponds to the average strain values of 0.30–0.35%, while the minimum strain (0.10–0.15%) was detected in the middle third of the visualized samples (Figure 1). Additionally, the maximum strain was detected in Z samples, while the minimum strain was induced during loading of E samples.

Significant differences in strain values between samples with different specimens were detected (p = 0.000). This suggests that strain values were dependent from the type of crown material. Strain values were also affected by the region of interest (p = 0.000). The application of two-way ANOVA enabled the testing of interaction effect between two independent variables, the crown material and the region of interest, where a significant difference was found (p = 0.046). This indicates that strain values were also influenced by different combinations of material type and region of interest. The highest strain values were found for Z (0.383 ± 0.015) in the AR, and the lowest for E (0.070 ± 0.026) in the MR (Table 1).

The loading of the Z and L samples showed significant differences between all analyzed segments of the region of interest, including the CR, MR, and AR segment (p < 0.001). Statistical significance between the MR and CR was set at p < 0.01 when L samples were loaded (Table 2). Vertically loaded E samples showed significant differences between the CR and AR, and the MR and AR (p < 0.001), while the statistical significance for the MR and CR was set at p < 0.05. In the AR, significant difference was noticed between samples Z and E (p < 0.01, Table 3). The MR showed significant differences in strain between samples Z and E (p < 0.001), Z and L (p < 0.01). In the CR, a significant difference was noticed between samples Z and E, and Z and L (p < 0.01).

Three types of DIC representative virtual models showed surface strain quantitatively determined by the scales within the DIC figures. Sample surface of the representative software models (virtual models) presented in Figures 2, 3, and 4 generated strain fields during axial loading conditions characterized by gradually increasing the intensity of the strain, which was manifested through color changing from dark blue through green to yellow [10]. Experimental strain field was analyzed using vertical section, as shown in Figures 2, 3, and 4. Section length was around 10 mm. Strain of interest was "on" and "around" the section lines, practically around the implant body. As it can be seen in Figures 2, 3, and 4, the maximum strain was detected in the AR and CR. The lowest strain detected in the region of interest was 0.04%, while the highest strain was 0.40 % for the Z-model (Figure 2). Thus, the Z-model showed higher overall strain than the L-model (Figure 3) or the E-model (Figure 4), where an insignificant strain during the first stage related to a load of 100 N was noticed. Section lines showed the maximum strain in the AR (4%), although the E-model reached only 2.8% even when loaded with 500 N

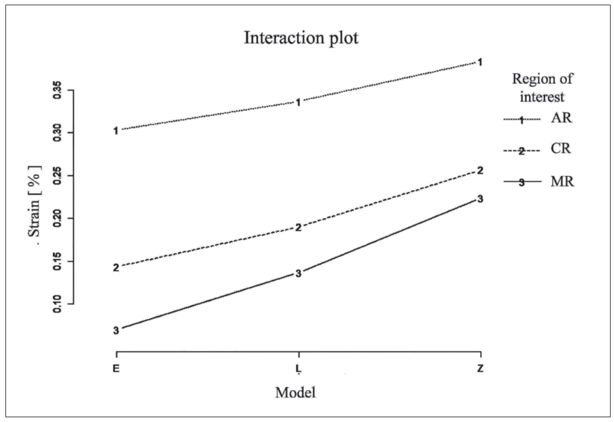

Figure 1. Interaction plot

CR – cervical region; MR – middle region; AR – apical region

Table 1. Means and standard deviations of von Mises strain values for different experimental models (all-ceramics) and regions of interest

Model	Region of interest					
	CR		MR		AR	
	Mean	SD	Mean	SD	Mean	SD
Z	0.257	0.015	0.223	0.015	0.383	0.015
L	0.190	0.010	0.137	0.015	0.337	0.021
E	0.143	0.025	0.070	0.026	0.303	0.015

CR – cervical region; MR – middle region; AR – apical region; Z – Z-model, zirconia; L – L-model, e.max; E – E-model, Enamic

Table 2. Mean values (SD), and significance between locations of interest for identical specimens

Model	Region of interest			p
	CR	MR	AR	
Z	0.26 (0.02)	/	0.38 (0.02)	< 0.001[a]
E	0.14 (0.03)	/	0.3 (0.02)	< 0.001
L	0.19 (0.01)	/	0.37 (0.02)	< 0.001
Z	0.26 (0.02)	0.22 (0.02)	/	> 0.05
E	0.14 (0.03)	0.07 (0.03)	/	< 0.05[b]
L	0.19 (0.01)	0.14 (0.02)	/	< 0.01
Z	/	0.22 (0.02)	0.38 (0.02)	< 0.001
E	/	0.07 (0.03)	0.3 (0.02)	< 0.001
L	/	0.14 (0.02)	0.37 (0.02)	< 0.001[c]

CR – cervical region; MR – middle region; AR – apical region; Z – Z-model, zirconia; L – L-model, e.max; E – E-model, Enamic;
[a]significant difference between CR and AR location of interests, for specimens Z;
[b]significant difference between CR and MR location of interest, for specimens E;
[c]significant difference between MR and AR location of interest, for specimens L

Table 3. Mean values (SD), and significance between specimens and for identical locations of interest

Region of interest	Model			p
	Z	E	L	
CR	0.26 (0.02)	/	0.19 (0.01)	< 0.01[d]
AR	0.38 (0.02)	/	0.37 (0.02)	< 0.05
MR	0.22 (0.02)	/	0.14 (0.02)	< 0.01
CR	0.26 (0.02)	0.14 (0.03)	/	< 0.01
AR	0.38 (0.02)	0.3 (0.02)	/	< 0.01[e]
MR	0.22 (0.02)	0.07 (0.03)	/	< 0.001
CR	/	0.14 (0.03)	0.19 (0.01)	< 0.05
AR	/	0.3 (0.02)	0.37 (0.02)	< 0.05
MR	/	0.07 (0.03)	0.14 (0.02)	> 0.05[f]

CR – cervical region; MR – middle region; AR – apical region; Z – Z-model, zirconia; L – L-model, e.max; E – E-model, Enamic;
[d]significant difference between Z and L specimens, for location of interest CR;
[e]significant difference between Z and E specimens, for location of interest AR;
[f]non-significant difference between E and L specimens, for location of interest MR

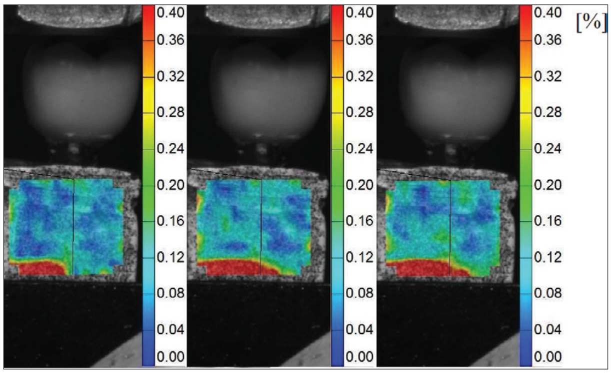

Figure 2. Strain in the Z-model visualized during vertical loading conditions

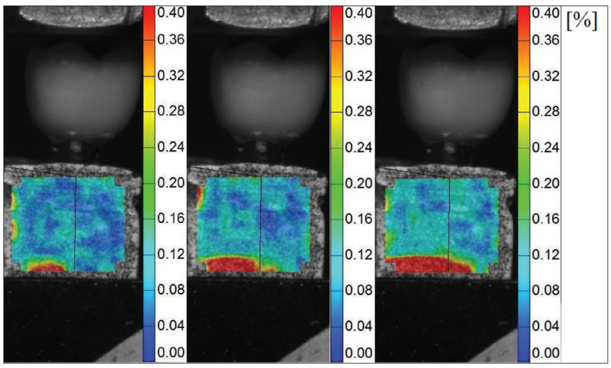

Figure 3. Strain in the L-model visualized during vertical loading conditions

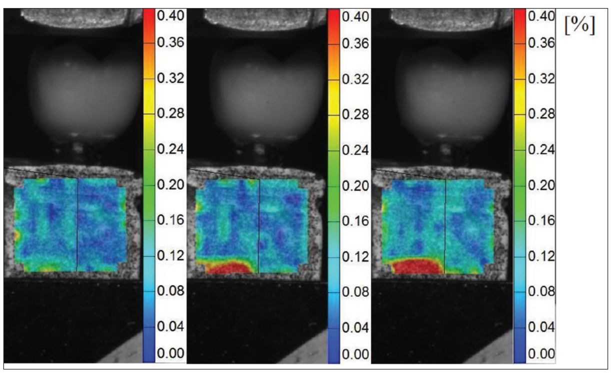

Figure 4. Strain in the E-model visualized during vertical loading conditions

(Figure 4). According to the software data processing, the E-model strained to 0.16%, the L-model to 0.2%, while the Z-model to at least 0.24% in the CR.

DISCUSSION

The study is a preliminary technical report regarding mechanical testing of three types of ceramic systems placed *in situ* on custom-made PMMA samples with immersed dental implants. Actually, all samples were fabricated of the same type of the Straumann® implants/PMMA and the only difference between the samples were different types of all-ceramics. The study was conducted to find which ceramic induced the highest strain in the PMMA block during occlusal loading conditions. It was found that Vita Enamic® (the E-model, Figure 4) induced the lowest strain compared to the others. The presented *in vitro* experiments included a minimum of three identical models of each specimen (Z, L, and E) and showed significant results. Nevertheless, further results will be assessed and argued after examinations on a large number of samples prepared in the same way as presented in this report. DIC showed an ability to measure strain in PMMA induced by the loaded all ceramic crowns. Knowing the fact that the DIC is a surface method and that desirable thickness of bone surrounding an implant is at least 2 mm, strain field was observed on surfaces 2 mm away from the vertical axis of the implant body. This thickness was enough to describe the strain change in PMMA around implant (peri-implant) [20].

The results acquired from the Aramis system (GOM GmbH, Braunschweig, Germany), were sorted in three groups of samples and three groups of interest locations. Ceramics, as the part of the samples and locations of interest within tested models presented factors which caused different values of strain of loaded samples. Their mutual effect on a sample was presented in the interaction plot where the connection between experimental results was visualized. Although strain varied significantly between locations of interest, ceramic-material's effect was also noticed. Namely, samples with zirconia showed the highest strain for every part of interest, including CR, MR, and AR. Enamic samples displayed the lowest strain for all segments of interest. As a hybrid material with PICN, Vita Enamic® includes the best properties of ceramic and composite materials. Additionally, E max CAD crown induced less strain in the L-model than IPS e.max ZirCAD crown induced in the Z-model. The results of this study are consistent with previous findings, where using softer (lower rigidity) crown material reduced the stresses generated on the jaw bone (cortical and spongy). This type of material absorbs more energy from the applied load, and transfers less energy to the following parts of the system (implant–abutment complex and bones) [21]. Particularly, Z specimens had much higher modulus of elasticity (13 GPa) value than E (30 GPa) and/or L specimens (95 ± 5 GPa) [3, 22, 23, 24]. Thus, higher amortization of the vertical loads and lower values of strain in the E model were observed [6, 7, 8].

Strain for different types of samples and different segments of interest was compared using two-way ANOVA, employed to determine whether there was statistical significance in differences between the tested groups. All three ceramic types and locations of interest showed significant influence. Significant differences in strain values existed between three groups of materials, and also in three different regions of interest of the measured surfaces. Although ANOVA revealed statistically significant differences between the type of the strained sample, the region of interest, and the interaction of these two factors, this analysis could not point out the differences between these two factors. Thus, additional post hoc t-test was introduced to reveal a statistical significance between observed variables and to find out where these differences actually occurred.

In order to provide valid comparison and to reduce type I error, the conservative Bonferroni correction was applied. Therefore, all three null hypotheses were rejected and alternative ones were adopted, which state that the strain depended on the ceramic material used and on the location of interest. Also, there was an interaction between ceramics and the region of interest related to strain values. However, the strain values for Z-models were quite similar in the CR and the MR ($p > 0.05$). Furthermore, no significant difference between the E- and the L-model was found considering MR.

The results of this study are consistent with previous reports, where the highest strain was registered in the AR, while the lowest one was observed in the MR [11, 12, 13]. This could lead to the conclusion that the MR of all samples was less sensitive to changes in material composition when compared to CR and AR.

It seems that prosthetic failure was prevented, considering that all ceramics withstood occlusal forces of up to 500 N without breaking, during static loading conditions due to their fracture toughness Z(5.5):L(2.5):E(1.5) MPam [22–25]. Previous researches found that zirconia is the strongest and toughest of all dental ceramics, with superior mechanical properties compared to the glass ceramics (IPS e.max) and hybrid ceramics (Vita Enamic®) [26]. Zirconia belongs to the group of the highest strength ceramics, with outstanding mechanical properties corresponding to its crystalline structure [27]. Flexure strength of zirconia is more than twice as high than that of IPS e.max (glass-ceramics), and even more so when compared to Vita Enamic® [28]. The dominant ceramic network structure supports toughness in Vita Enamic®, while the reinforcing polymer network structure provides viscoelasticity. In this study, a ceramic, like a medium, underwent stress generated by vertical loading with consequent strain detected in the PMMA block. Thus, PMMA indirectly reacted to the implant-supported crown loading. Registered strain actually depends on the strength of the applied ceramics and showed the highest values in the Z-model. Unlike zirconia, Vita Enamic® is, with respect to the elastic modulus, closer to human tooth structure values [6, 7, 8]. As a hybrid material with a PICN, Vita Enamic® includes the best properties of ceramic and composite materials. Composite portion of this material showed higher deformation, which reduces the probability of a spontaneous fracture but it can also reduce the hardness of the ceramic itself and accumulate high percentage of strain in the PICN structure. This has a more beneficial effect on the underlying system of supporting structures, which is actually PMMA in this study.

CONCLUSION

The study determined, evaluated, and visualized surface strain generated in all ceramic samples subjected to vertical loading conditions employing the DIC as a powerful tool for strain analysis. Standardization of the experiment was achieved through using identical PMMA and Straumann® implants for the fabrication of all samples to be tested. Based on the objective of this study and set hypotheses, the following conclusions were derived:

- Mean strain values vary between different types of samples and depend on specimens – all-ceramic crowns. Three viable compositions of all-ceramics transferred different portion of occlusal load over implants, thus generating different strain in PMMA. This fact favors one ceramic over others from the biomechanical viewpoint due to the composition of the ceramic matrix, which may affect potential deterioration of the surrounding supportive structure, in this case PMMA. Furthermore, this gives rise to a possibility of different consequent therapeutic effects on implant-supported restorations.
- A correlation between the mean strain values the and region of interest was registered. Strain was not equally distributed through the region of interest. While an obvious maximum strain was detected in the apical direction, a large portion of strain showed marginal direction.
- Interaction between the specimen and the region of interest was noted. This indicates that all ceramic crowns affect implant–bone interface during vertical loading conditions.

The minimum strain was registered below the Vita Enamic® material, while the maximum strain was found in the samples with zirconia crowns. However, future investigations, with numerous samples will be conducted by employing nondestructive methods, such as the atomic force microscopy, to obtain detailed surface characteristic information and surface quality of tested materials. Also, further clinical studies are necessary to better understand the real biomechanical behavior and interactions of these biomaterials.

Conflict of interest: None declared.

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Анализа деформација у узорцима састављеним од керамичких система применом методе дигиталне корелације слика

Иван Танасић[1], Александра Митровић[2], Ненад Митровић[3], Душан Шарац[3], Љиљана Тихачек-Шојић[4], Александра Милић-Лемић[4], Милош Милошевић[2]

[1]Висока здравствена школа струковних студија, Београд, Србија;
[2]Универзитет у Београду, Иновациони центар Машинског факултета, Београд, Србија;
[3]Универзитет у Београду, Машински факултет, Београд, Србија;
[4]Универзитет у Београду, Стоматолошки факултет, Катедра за стоматолошку протетику, Београд, Србија

САЖЕТАК

Увод/Циљ Студија је спроведена да идентификује максималну деформацију произведену у узорцима састављеним од полиметилметакрилата, Штрауман® имплантата и три врсте керамичких система.

Методе Коришћене су три врсте експерименталних модела изложених спољашњем оптерећењу од 100 *N*, 300 *N* и 500 *N* и анализираних уз помоћ метода корелације дигиталних слика. Модели су били састављени од итријум-цирконије, е. макс. литијум дисиликатне и хибридних керамика Вита енамик®, постављених на цилиндричне денталне имплантантне системе Штрауман® (4 × 10 *mm*) са абатментима под правим углом.

Резултати Значајне разлике су откривене у вредностима деформација између узорака са различитим керамичким круницама ($p = 0,000$). Ово подразумева да су вредности деформација зависне од типа керамичког материјала. Вредности деформација су зависне и од региона интереса ($p = 0,000$). Примена АНОВА теста је омогућила да се уочи интеракција између независних варијабли, метеријала керамичких круна и региона од интереса, где је такође нађена статистички значајна разлика ($p = 0,046$). Ова чињеница указује на то да вредности деформација зависе од различите комбинације типа керамичког материјала и региона интереса. Највеће вредности деформација су нађене на моделу *Z* (0,383 ± 0,015) у апикалном региону, док су најмање вредности деформација нађене на моделу *E* (0,303 ± 0,015) у региону средње трећине.

Закључак Извештај је показао максималне деформације у апикалним и маргиналним правцима. Када се разматрају различите врсте керамика, најмање деформације су примећене испод круна Вита енамик®, док је највећа деформација пронађена у узорцима са крунама итријум-цирконија.

Кључне речи: керамички системи; деформација; ПММА