СРПСКИ АРХИВ
ЗА ЦЕЛОКУПНО ЛЕКАРСТВО
SERBIAN ARCHIVES
OF MEDICINE

Address: 1 Kraljice Natalije Street, Belgrade 11000, Serbia
☎ +381 11 4092 776, Fax: +381 11 3348 653
E-mail: office@srpskiarhiv.rs, Web address: www.srpskiarhiv.rs

---

Paper Accepted[*] **ISSN Online 2406-0895**

Original Article / Оригинални рад

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

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

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

[1]Obrenovac Medical Health Center, Belgrade, Serbia;
[2]University of Belgrade, Faculty of Mechanical Engineering, Innovation Center, 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

Received: October 30, 2017
Revised: March 6, 2018
Accepted: July 23, 2019
Online First: July 31, 2019
DOI: https://doi.org/10.2298/SARH171030085T

---

[*] **Accepted papers** are articles in press that have gone through due peer review process and have been accepted for publication by the Editorial Board of the *Serbian Archives of Medicine*. They have not yet been copy-edited and/or formatted in the publication house style, and the text may be changed before the final publication.
Although accepted papers do not yet have all the accompanying bibliographic details available, they can already be cited using the year of online publication and the DOI, as follows: the author's last name and initial of the first name, article title, journal title, online first publication month and year, and the DOI; e.g.: Petrović P, Jovanović J. The title of the article. Srp Arh Celok Lek. Online First, February 2017.
When the final article is assigned to volumes/issues of the journal, the Article in Press version will be removed and the final version will appear in the associated published volumes/issues of the journal. The date the article was made available online first will be carried over.

[†] **Correspondence to:**
Ivan TANASIĆ
Obrenovac Medical Health Center, 11000 Belgrade, Serbia
E-mail: **doktorivan@hotmail.com; prosthodontics.clinic@gmail.com**

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

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

SUMMARY

Introduction/Objective The study was conducted to identify the maximum strain generated in the samples composed of poly-methyl-methacrylate (PMMA), Straumann implants and three types of ceramic systems.

Methods Three types of experimental models, loaded by external load of 100 N, 300 N and 500 N and analyzed using the Digital Image Correlation Method were used. The models were composed of ytrium zirconia, e.max lithium disilicate and vita enamic hybrid ceramics, placed on the Straumann® cylindrical dental implant systems (4 mm x10 mm) with straight abutments.

Results Significant differences in strain values between samples with different crown materials groups were detected (p = 0.000). This suggests that strain values were dependent from the type of crown material. Strain values were also affected by region of interest (p = 0.000). Application of two-way ANOVA enabled testing of interaction effect between two independent variables, crown material and region of interest, where 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 report showed 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 a samples with ytrium zirconia crown.

Keywords: all-ceramics; strain; PMMA

САЖЕТАК

Увод/Циљ Студија је спроведена да идентификује максималну деформацију произведену у узорцима састављеним од полиметилмет акрилата (ПММА), 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 вита енамик хибридних керамика, постављених на Штрауман® цилиндричне денталне имплантантне системе (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 варијабла, материјала 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 вита енамик круна док је највећа деформација пронађена у узорцима са итријум цирконија крунама.

Кључне речи: керамички системи; деформација; ПММА

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 to 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 eligible 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 composition of supporting structures may influence on stress distribution in all ceramics[4]. Additionally, the material properties of all ceramics can cause different strain response in adjacent structures. The mechanical properties, such as elastic modulus and Poisson's coefficient of each material should be especially considered when argued about strain in supporting tissue[5]. The crown material with the lower modulus of elasticity, absorbs increased portion of energy from the applied occlusal load, and transfers less energy to the supporting dental tissue. Therefore, crowns made from 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 a high elasticity, like acrylic resin/composte, will mitigate the external occlusal forces and decreases its effect on the bone-implant interface during occlusal loading condition[7]. Higher elasticity material reduced the transmitted forces to bone by about 94% compared to Zirconia which improves biocompatibility considering an impact 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 type of the restorative material used in implant crown design was significant factor in the amount and distribution of the stress loaded structures[9, 10]. Following study was conducted to investigate the impact of three usually applied metal-free ceramics on supporting structure of the 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 devided into three families: glass-matrix ceramics, polycrystalline ceramics, and resin-matrix ceramics. This report **aimed 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 DIC properties the authors want to explain the effect of different all-ceramic-crown-materials on the strain change in peri-implant structure and to indicate which kind of 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 ceramic material and region of interest.

METHODS

The study proposed 3 groups of experimental models (samples) composed of PMMA, Straumann implants with 3 types of all-ceramic posterior crowns (specimens) placed on the Strauman S Ø 4.1 mm × 10 mm RN dental implants (Straumann® cylindrical dental implant systems, Basel, Switzerland) with straight abutments. Strauman Abutments RN synOcta (Basel, Switzerland) were screwed on Strauman dental implant, and tightened using Strauman 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-Manufacture (CAD/CAM) to standardize specimens. A model with an intact dental arch, obtained after lower jaw imprint, was served for the preparation of tooth for placing all ceramic crowns. After grinding the tooth, which was carried out by dentist, model was scanned using an extraoral scanner (3 Shape D 800 scanner, 3Shape A/S, Copenhagen Denmark). The design was carried out using CAD software (Dental System Premium 2014, 3Shape A/S, Copenhagen Denmark). The milling was done in a milling unit Wieland dental CNC (Ivoclar Wieland Group) dental technical laboratory. The milling CAD/CAM machine finished ceramic blocks and manufactured all ceramic crowns. The ceramic blocks (one by one) was processed by turning on its axis, a diamond disk rotates, moves up and down around the ceramic block and processes it. The movement of the diamond disc is enabled via electric rail. Precision of milling was moving 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 produced by milling of the ceramic blocks fixed on the wheel that allows block to be inserted.

The obtained crowns were then placed on abutments using cement and definitively cemented with special aesthetic cement for metal-free ceramics, self-adhesive, dual cured cement Maxcem Elite (Kerr, Orange, CA, USA). This research investigated: IPS e.max ZirCAD (yttria-stabilized zirconia polycrystal, Y-TZP; Ivoclar Vivadent, Schaan, Liechtenstein), as a high-strength ceramic with a high values of flexular strength and fracture toughness thanks to the crystalline structure[15, 16]; E max CAD (lithium disilicate glass-ceramics; Ivoclar Vivadent) 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, Germany), as the first hybrid dental ceramic with a dual-network structure and belongs to PICN (polymer infiltrated ceramic network) 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% [18–20]. In the further text, it will be used the terms Z-model (Z samples; zirconia), L-model (L samples; e.max) and E-model (E samples; enamic) due to easy overview. Namely, each group consisted of three different ceramics, thus the total of nine specimens with implant immersed in PMMA during his hardening process were manufactured in accordance with the standardized protocol presented in recently published research[12]. Immediately after initial preparing and spraying (coating), models were tested on a H10K-S UTM Testing machine (by manufacturer Tinius Olsen, USA) with 5 kN load cell, as described in previous studies. The digital image correlation method (DIC) was used to visualize the strain field in the loaded models. As previously said, loading speed was 0.1 mm/min, while stroke limit was set to 1 mm. We used the force intensities of 100 N, 300 N and 500 N, respectively, in accordance with literature data[19]. This was an experimental compressive loading with gradual increase the intensity of the applied vertical load. Of the total number (N=9) of the samples/specimens (N=9), 3 representative figures (virtual models) obtained by Software data processing were selected and used to present different stages of the vertically loaded Z, L and E samples. Strain field was observed on the surfaces distanced 2 mm from the vertical axis of the implant body. A region of interest was considered to be a surface that surrounded implant body in a projection of the section line, presented in all figures. In order to facilitate the interpretation of the results we divided region of interest into three parts: the cervical (CR), the middle one (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 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 different kind of 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 in package “stats” (Software R, Vienna, Austria).
- The Post Hoc t-test with Bonferroni correction. The Post Hoc t test can compare only two strain values at the time.

RESULTS

The relationship between sample type, region of interest and strain values were displayed in the interaction plot (Fig. 1). Comparing all 9 samples, the maximum strain (peak) was observed in the apical regions and corresponds to average strain values between 0.30 % and 0.35 %, while the minimum strain (0.10 %-0.15 %) was detected in the middle third of the visualized samples (Fig.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 region of interest ($p = 0.000$). Application of two-way ANOVA enabled testing of interaction effect between two independent variables, crown material and region of interest, where 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 apical region (AR), and the lowest for E (0.070 ± 0.026) in the middle region (**Error! Reference source not found.**).

Loading of the Z and L samples showed significant differences observed between all analyzed segments of the region of interest, including CR, MR and AR segment ($P<0.001$). Statistical significance between middle and cervical was assumed for $P<0.01$ when loaded L samples (Table 2). Vertically loaded E samples showed significant differences between CR and AR, and MR and AR ($P<0.001$), while the statistical significance for MR and CR was assumed to be $P<0.05$. In apical region significant difference was noticed between samples Z and E ($P<0.01$, Table 3). Middle region showed significant differences in strain between samples Z and E ($P<0.001$), Z and L ($P<0.01$). In the cervical region, significant difference was noticed between samples Z and E, and Z and L ($P<0.01$).

Three types of the 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 Figs. 2, 3 and 4 generated strain fields during axial loading conditions characterized by gradually increasing the intensity of 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 Figs. 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, the presented figures (Figs. 2-4), maximum strain was detected in AR and CR. The lowest strain detected in the region of interest was 0.04 %, while the highest strain was 0.40 % for Z-model (Fig. 2). Thus, Z-model showed higher overall strain than L-model (Fig. 3) or E-model (Fig. 4), where an insignificant strain during the first stage related to load of 100 N was noticed. Section lines showed the maximum strain in AR (4.0 %), although the E-model reached only 2.8 % even when loaded with 500 N (Fig. 4). According to the software data processing, E-model strained to 0.16 %, L-model to 0.20 %, while Z-model to at least 0.24 % in CR.

DISCUSSION

The study is a preliminary technical report regarding mechanical testing of three types of ceramic systems placed “in situ” on custom made poly-methyl-methacrylate (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 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 (E-model, Fig.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 the large number of samples prepared in the same way as presented in this report. DIC showed 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 implant is at least 2 mm, strain field was observed on the surfaces distanced 2 mm 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, 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 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 highest strain for every part of interest, including CR, MR and AR. Enamic samples displayed lowest strain for all segments of interest. As a hybrid material with a polymer infiltrated ceramic network (PICN) Vita Enamic includes the best properties of ceramic and composite materials. Additionally, E max CAD crown induced less strain in L-model than IPS e.max ZirCAD crown induced in 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]. Particulary, Z specimens has much higher modulus of elasticity (13 GPa)[22] value than E (30 GPa)[3, 23] and/or L specimens (95±5 GPa)[24]. Thus higher amortization of the vertical loads and less values of strain in E model was observed[6, 7, 8].

Strain for different types of samples and different segments of interest was compared using two-way ANOVA. Two-way ANOVA was employed to determine whether there was statistical significance in differences between the tested groups. All three ceramic types and location 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, region of interest and interaction in these two factors, this analysis could not point out differences between these two factors. Thus, additional Post Hoc t test was introduced to reveal 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 strain depended on the ceramic material used and location of interest. Also, there was an interaction between ceramics and region of interest related to strain values. However, the strain values for Z-models were quite similar in CR and MR ($p>0.05$). Furthermore, no significant difference between E- and L-model was found considering MR.

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

It seems that prosthetic failure was prevented considering that all ceramics withstood occlusal forces 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 highest strength ceramics with outstanding mechanical properties corresponding to its crystalline structure[27]. Flexure strength (FS) of zirconia is more than twice as high than FS of IPS e.max (glass-ceramics), and even more when compared to Vita Enamic[28]. The dominant ceramic network structure support toughness in vita enamic while the reinforcing polymer network structure provides visco-elasticity. In this study, ceramic, like a medium, undergoes from stress generated by vertical loading with consequent strain detected in 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 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 polymer infiltrated ceramic network (PICN) Vita Enamic®

includes the best properties of ceramic and composite materials. Composite in this material showed the higher deformation of the material, which reduces the eventual spontaneous fracture probability, but also can reduce the hardness of ceramic itself and accumulate high percentage of strain in the structure PICN. This has better effect on the underlying system of supporting structures, 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 powerfull tool for strain analysis. Standardization of the experiment was achieved through using identical PMMA and Strauman implants for fabrication of all samples to be tested. Based on the aim of this study and set hipostheses following conclusions are derived:

- Mean strain values vary between different types of samples and depend on specimens- all ceramic crowns. Three viable compositions of all ceramics transfered different portion of occlusal load over implants thus generated different strain in PMMA. This fact favours one ceramic over others from the biomechanical viewpoint due to composition of ceramic matrix which may affect on potential detoriation of surrounding supportive structure, in this case PMMA. Furthermore, this arises a possibility of the consequent different therapeutic effects on implant supported restorations.

- Correlation between mean strain values and region of interest was registered. Strain is not equally distributed through region of interest. While an obvious maximum strain was detected in apical direction, a large portion of strain showed marginal direction.

- Interaction in effect, between specimen and region of interest was noticed. This indicates that all ceramic crowns affect implant–bone interface during vertical loading conditions.

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

Conflict of interest: None declared.

REFERENCES

1. Tim F, Zesewitz TF, Knauber AW, Nothdurft FP. Fracture Resistance of a Selection of Full-Contour All-Ceramic Crowns: An In Vitro Study. Int J Prosthodont. 2014; 27(3):264–6. PMID: 24905268 DOI: 10.11607/IJP.3815
2. Koyano K, Esaki D. Occlusion on oral implants: Current clinical guidelines. J Oral Rehabil. 2015; 42:153–61. PMID: 25284468 DOI: 10.1111/joor.12239
3. Della Bona A, Kelly JR. The clinical success of all-ceramic restorations. J Am Dent Assoc. 2008; 139(9):8S–13S. PMID: 18768903
4. Dittmer MP, Kohorst P, Borchers L, Stiesch M (2010). Influence of the supporting structure on stress distribution in all-ceramic FPDs. Int J Prosthodont. 2010; 23:63-8.
5. Pérez-Pevida E, Brizuela-Velasco A, Chávarri-Prado D, Jimenez-Garrudo A, Sanches-Lacheras F, Solaberrieta-Mendez E, et al. Biomechanical Consequences of the Elastic Properties of Dental Implant Alloys on the Supporting Bone: Finite Element Analysis. BioMed Research International. 2016; 2016:1850401. DOI:10.1155/2016/1850401.
6. Menini M, Conserva E, Tealdo T, Bevilacqua M, Pera F, Signori A, et al. Shock absorption capacity of restorative materials for dental implant prostheses: an in vitro study. Int J Prosthodont. 2013; 26: 549-556. DOI: 10.11607/ijp.3241.
7. El-Anwar MI, El-Mofty MS, Awad AH, El-Sheikh SA, El-Zawahry MM. The effect of using different crown and implant materials on bone stress distribution: a finite element study EJOMS. 2014; 5(2):58-4.
8. Menini M, Conserva E, Tealdo T, Bevilacqua M, Pera F, Ravera G, Pera P. The use of a masticatory robot to analyze the shock absorption capacity of different restorative materials for implant prosthesis. J Biol Res (Thessalon). 2011; 84(1):118-19. DOI: https://doi.org/10.4081/jbr.2011.4636.
9. Stegaroiu R, Khraisat A, Nomura S, Miyakawa O. Influence of superstructure materials on strain around an implant under 2 loading conditions: a technical investigation. JOMI. 2004; 19(5):735–42.
10. Tanasić I, Tihaček Šojić Lj, Milić-Lemić A. Biomechanical interactions between bone and metal-ceramic bridges composed of different types of non-noble alloys under vertical loading conditions. MIT. 2014; 48(3):337–41. DOI: mit.imt.si/Revija/izvodi/mit143/tanasic.pdf
11. Tiossi R, de Torres EM, Rodrigues RCS, Conrad HJ, de Mattos M da GC, Fok ASL, et al. Comparison of the correlation of photoelasticity and digital imaging to characterize the load transfer of implant-supported restorations. J Prosthet Dent. 2014; 112(2):276–84. PMID: 24461947 DOI: 10.1016/j.prosdent.2013.09.029
12. Gracis S, Thompson Van P, Ferencz JL, Silva-Nelson RFA. Bonfante-Estevam A. A New Classification System for All-Ceramic and Ceramic-like Restorative Materials. Int J Prosthodont 2015; 28(3):227-235. PMID:25965634 DOI:10.11607/ijp.4244
13. Tanasić I, Tihaček-Šojić Lj, Mitrović M, Milić-Lemić A, Vukadinović M, Marković A, et al. An attempt to create a standardized (reference) model for experimental investigations on implant's sample. Measurement. 2015; 72:37–2. DOI: https://doi.org/10.1016/j.measurement.2015.04.029
14. Tanasić I, Šarac D, Mitrović N, Tihaček-Šojić Lj, Mišković Ž, Milić-Lemić A, et al. Digital Image Correlation Analysis of Vertically Loaded Cylindrical Ti-Implants With Straight and Angled Abutments. Exp Techn. 2015; 40(4):1227–33. DOI: 10.1111/ext.12156
15. Denry I, Kelly JR. Emerging Ceramic-based Materials for Dentistry. J Dent Res. 2014; 93(12):1235–42. PMID: 25274751 DOI: 10.1177/0022034514553627
16. Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: Basic properties and clinical applications. J Dent. 2007; 35(11): 819–26. PMID: 17825465 DOI: 10.1016/j.jdent.2007.07.008
17. Mclaren EA, Cao PT. Ceramics in Dentistry—Part I: Classes of Materials. Insid Dent. 2009; 5(9):94–03.
18. Coldea A, Swain MV, Thiel N. Mechanical properties of polymer-infiltrated-ceramic network materials. Dent Mater. 2013; 29(4):419–26. PMID: 23410552 DOI: 10.1016/j.dental.2013.01.002
19. Tortopidis D, Lyons MF, Baxendale RH, Gilmour WH. Thevariability of bite force measurement between sessions, indifferent positions within the dental arch. J Oral Rehabil. 1998;25:681–6.

20. Spray JR, Black CG, Morris HF, Ochi S. The influence of bone thickness on facial marginal bone response: stage 1 placement through stage 2 uncovering. Ann Periodontol. 2000; 5(1):119–28. PMID: 11885170 DOI: 10.1902/annals.2000.5.1.119
21. Soliman TA, Tamam RA, Yousief SA, El-Anwar MI. Assessment of stress distribution around implant fixture with three different crown materials.Tanta Dent J. 2015; 12(4):249-8. DOI: https://doi.org/10.1016/j.tdj.2015.08.001
22. Scientific Report Ivoclar Vivadent, “IPS e.max ® ZirCAD Scientific Documentation,” 2013.
23. Shembish FA, Tong H, Kaizer M, Janal MN, Thompson VP, Opdam NJ, Zhang Y. Fatigue resistance of CAD/CAM resin composite molar crowns. Dent Mater. 2016; 32(4):499–09. PMID: 26777092 DOI: 10.1016/j.dental.2015.12.005
24. Scientific Report Ivoclar Vivadent, “IPS e.max ® CAD Scientific Documentation,” 2011.
25. Harada K, Shinya A, Yokoyama D, Shinya A. Effect of loading conditions on the fracture toughness of zirconia. J Prosthodont Res. 2013; 57(2):82–7. PMID: 23498598 DOI: 10.1016/j.jpor.2013.01.005
26. Guazzato M, Albakry M, Ringer SP, Swain MV. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part I. Zirconia-based dental ceramics. Dent Mater. 2004; 20(5):449–56. PMID: 15081551 DOI: 10.1016/j.dental.2003.05.002
27. Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: Basic properties and clinical applications. J Dent. 2007; 35(11):819–26. PMID: 17825465 DOI: 10.1016/j.jdent.2007.07.008
28. Denry I, Kelly JR. Emerging Ceramic-based Materials for Dentistry. J Dent Res. 2014; 93:1235–42. PMID: 25274751 DOI: 10.1177/0022034514553627

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

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

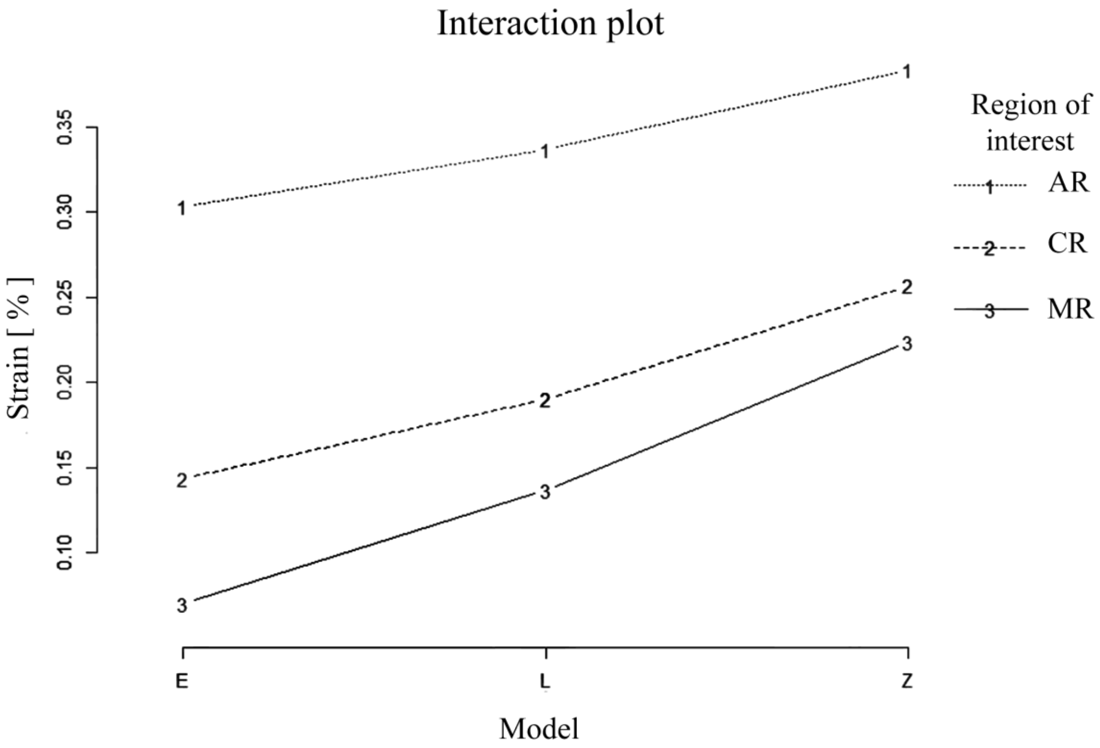

Figure 1. Interaction plot

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

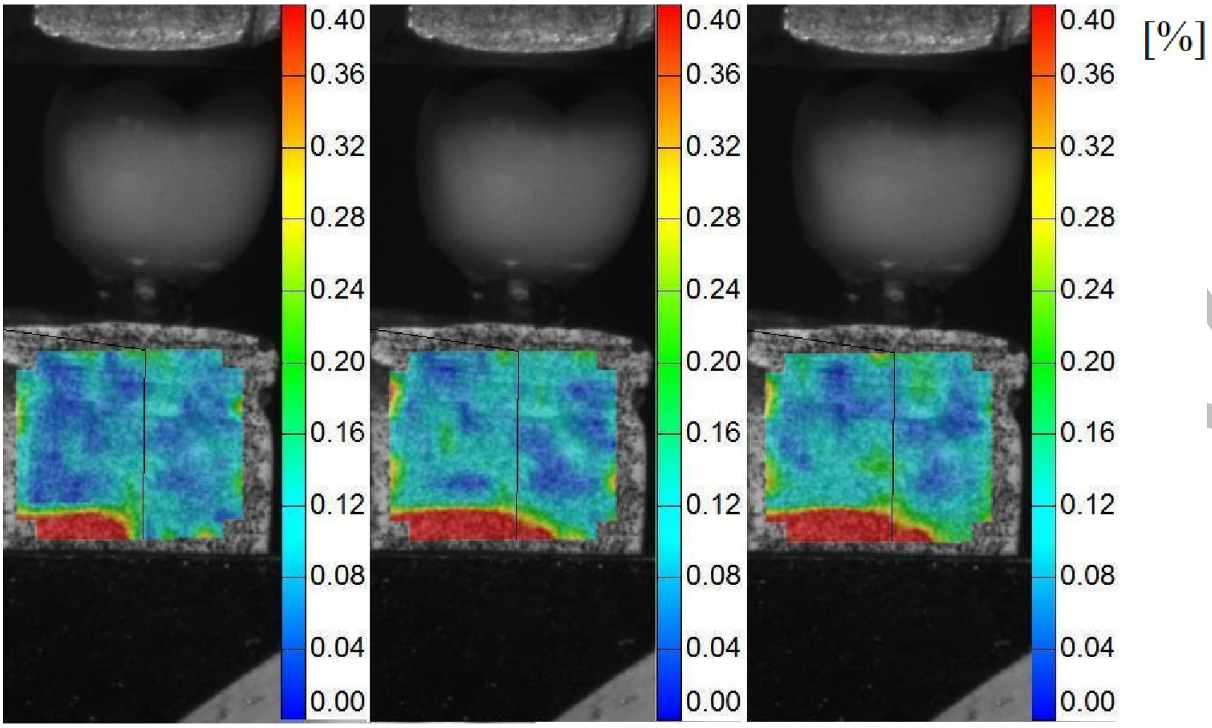

Figure 2. Strain in Z model visualized during vertical loading conditions

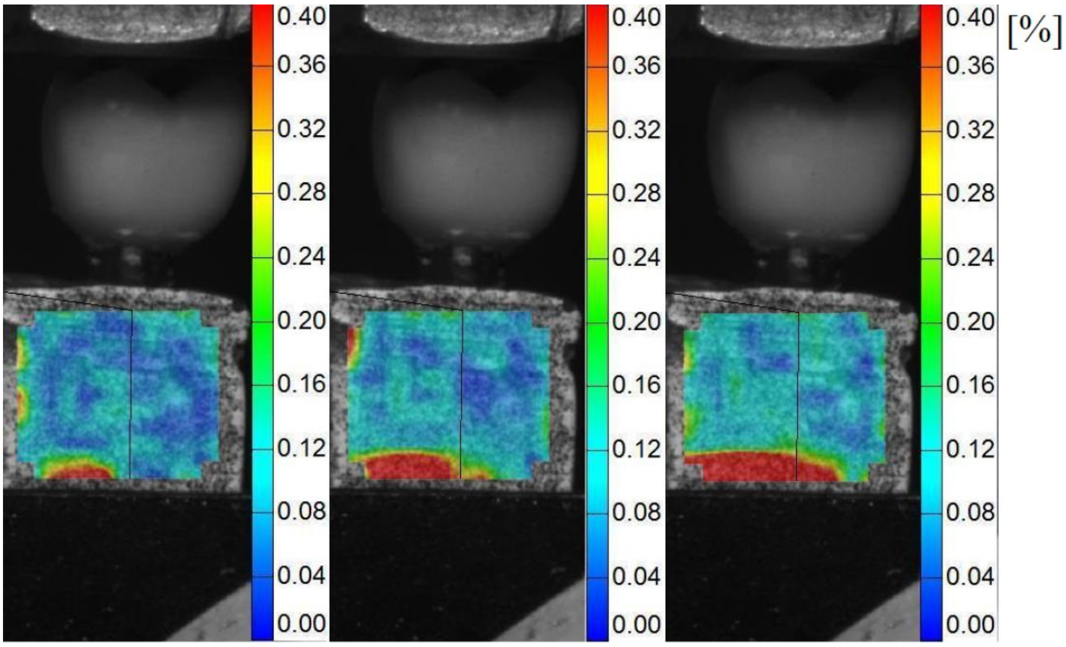

Figure 3. Strain in L model visualized during vertical loading conditions

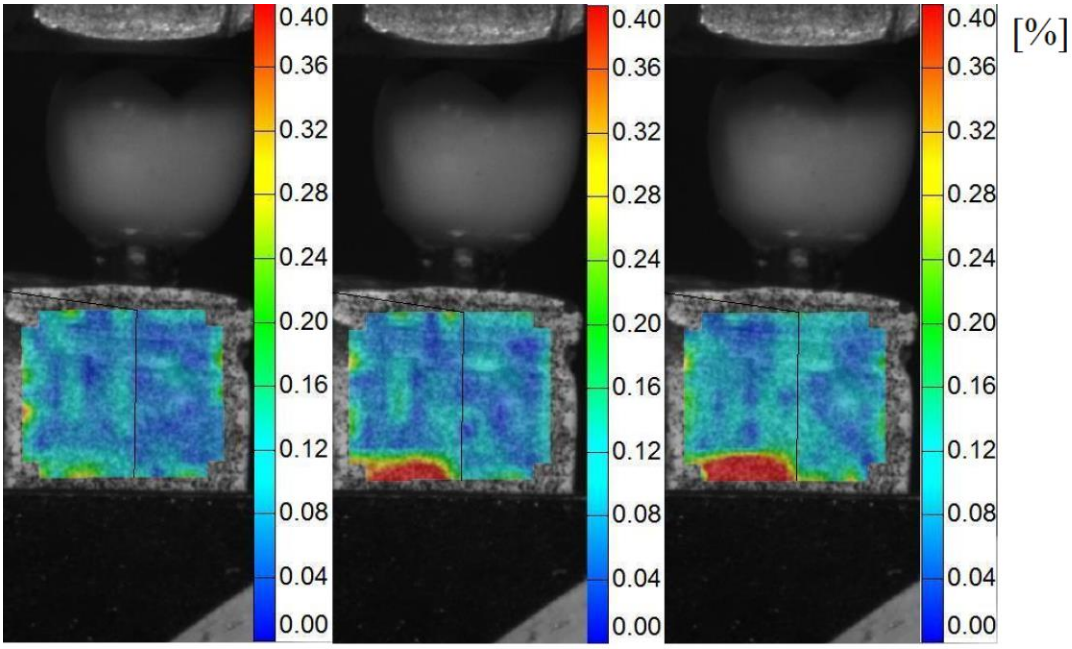

Figure 4. Strain in E model visualized during vertical loading conditions