Effect of finishing condition on fracture strength of monolithic zirconia crowns

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INTRODUCTION

Restorative materials are used for replacing missing teeth, either individually or in groups1. New manufacturing processes for porcelain and all-ceramic materials have been intensively studied in recent years because of the growing demand for esthetically pleasing products2-6. One of the most recent dental ceramic materials is yttria-stabilized zirconium oxide polycrystals (Y-TZP), which are used for endodontic posts and orthodontic brackets, and as an implant material and abutment for implant prosthetics, encouraged by the use of computer-aided design/computer-aided manufacturing (CAD/CAM) technology7-10.

Zirconia is one of the most promising restorative materials, especially for the posterior region, because of its good appearance compared with other materials11, high flexural strength12 and good biocompatibility. A previous study has demonstrated that a zirconia collar between the adjacent areas of two teeth can significantly reduce the risk of cervical fracture13. Zirconia crystallized in zirconium dioxide has a color similar to that of natural teeth, as well as similar mechanical properties compared with the stainless steel used for implants. It has a significantly higher fracture strength that can reach 900–1,200 MPa14, and a compression force of about 2,000 MPa and flexural strength of up to 900–1,200 MPa15,16. Therefore, zirconia has been found to be a very satisfactory dental restorative material in recent years17.

In the oral clinical application, monolithic zirconia crowns are directly exposed to the humid oral environment and support the chewing function; therefore, surface treatment is necessary after CAD/CAM production and sintering of zirconia. A rough zirconia surface has been shown to increase the dentin abrasion rate18,19 and decrease the flexural strength, which will compromise the long-term prognosis of the restoration20. Several studies have shown that rough ceramic surfaces produced by insufficient polishing lead to increased adhesion of bacteria and that rough surfaces are insufficiently cleanable by patients21-24. A well-polished zirconia surface is reported to exhibit not only low abrasivity to antagonists, but also superior biocompatibility to reduce bacterial and plaque apposition25-29. Thus, reduction or prevention of dentin wear can be achieved by a good polishing procedure using polishing kits30,31.

After CAD/CAM manufacturing and polishing, the zirconia crown should be placed in the patient’s mouth in a position that is compatible with the adjacent teeth and the opposite jaw teeth. Clinically, to fit the crowns, the dentist needs to adjust the occlusal height by removing excess tooth tissue of the higher point to achieve a comfortable occlusal position with the opposite tooth, this chairside occlusal adjustments involve roughening of the zirconia surface by diamond rotary instruments, thus we call this process “adjustment of occlusal contact”. Usually, it will be followed by subsequent polishing to restore surface smoothness. Few reports have focused on whether there are obvious differences between the occlusal adjustments alone and adjustments combined with polishing.

Although the surface polishing procedure can reduce the surface roughness to provide a better clinical results, prior research has shown that the phase transformation.
of zirconia is directly related to the damage caused by the surface treatment. Areas with surface defects act as potential sites for crack initiation and expansion into areas of stress concentration. Therefore, the phase transformation of zirconia should also be considered during the polishing process.

Consequently, in this study, we designed two experiments. Firstly, we performed different degrees of polishing on zirconia plate specimens using the same polishing kit. Based on the results of the roughness tests and zirconia phase transformations, we chose the most effective polishing procedure for use in the next experiment. Then, the second experiment investigated two different surface treatments (adjustment of occlusal contact only or occlusal adjustment followed by polishing as per the first experiment) by field emission scanning electron microscopy (FE-SEM) and assessment of fracture strength. Thus, an improved zirconia polishing method with superior efficacy could be developed.

MATERIALS AND METHODS

Material preparation and treatment of zirconia plates

In order to compare the effects of different grades of polishing on the surface of zirconia using the same polishing kit, the following experiment was performed.

Thirty-five zirconia plate specimens (15×15×2 mm) were prepared using a pre-sintered zirconia disk block (A3 12T, Liaoning Upcera, Benxi, China). The specimens were gradually polished using sandpaper from #600 to #2000, and finally sintered at 1,550°C for 2 h according to the manufacturer's instructions.

All the specimens were randomly divided into five groups, composed of seven specimens per group. The purpose of dividing the experiment into five groups is to observe the effect of polishing by using from the basic polishing bur to the smooth polishing bur and the superposition of polishing bur, whether the different polishing procedures are statistically different by the changes in surface roughness and phase transformation.

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Table 1  The information about the polishing burs

| Bur Type       | Manufacturer/Location                  | Diameter/Length | Description                      |
|---------------|----------------------------------------|-----------------|----------------------------------|
| High-speed bur| FG 881016, Komet, Lemgo, Germany       | Supercoarse Grit, Round End Cylinder, Single Use Diamond Bur. |
| Green bur     | ZIRCO MASTER, SEICHONG, Seoul, Korea   | Φ5.5 mm*16 mm extra-coarse 105104XC |
| Red bur       | ZIRCO MASTER, SEICHONG                | Φ5.5 mm*16 mm medium 105104M    |
| Yellow bur    | ZIRCO MASTER, SEICHONG                | Φ5.5 mm*16 mm fine 105104F     |

Table 2  The surface treatment process of each group

| Group No | The surface treatment process                      |
|----------|-----------------------------------------------------|
| 0        | Removing using high speed bur                       |
| 1        | Polished with Green bur after removing using high speed bur |
| 2        | Polished with Red bur after removing using high speed bur |
| 3        | Polished with Yellow bur after removing using high speed bur |
| 4        | Polished with Green+Red+Yellow bur after removing using high speed bur |
by the high temperature. The burs were replaced after polishing every fifth specimen to maintain a consistent amount of grit.

Surface analysis of the zirconia plates
The centerline average roughness ($R_a$) of the treated surface of each specimen was measured by a profilometer (SURFTEST SV-3000, Mitutoyo, Kawasaki, Japan). Seven different readings were taken with a traveling distance of 2 mm across the treated surface. After completing the measurements, the maximum and minimum values were removed, and the remaining five values were used to calculate the $R_a$ of the specimen. A lower $R_a$ value indicates a smoother surface.

The phase composition of the specimens was investigated by a multi-purpose high-performance X-ray diffractometer (X'pert Powder, PANalytical, Almelo, the Netherlands) using Cu Kα radiation, tube voltage 40 kV, and tube current 30 mA. In the range of $20\leq2\theta\leq40$ with a step size of 0.033° and a measuring time of 5 s at each step.

Material preparation and treatment of the zirconia crowns
In some oral clinical cases, to fit the crowns, the dentist needs to adjust the occlusion (remove excess tooth tissue using a high-speed bur to achieve a comfortable occlusal position with the opposite tooth). From the previous experiment, the optimum polishing process (Polished with Green+Red+Yellow bur after removing using high speed bur) was determined, selected based on maximizing the difference between the adjustments alone and adjustments combined with polishing, as well as the relationship between occlusal thickness and fracture strength.

A stainless steel master die (Fig. 1) and zirconia crown restoration of the mandibular first molar was used. To fabricate the master die, a design was prepared with an occlusal-gingival height of 6.5 mm, a convergence angle of 6° on each side and a margin shoulder width of 1.0 mm. Then, 28 master dies were duplicated without the zirconia crown and cast from stainless steel. The master die preparation with standardized occlusal position was then scanned with a three-dimensional (3D) digital scanner (IDENTICA, MEDIT, Seoul, Korea) for CAD use.

On the basis of the data in the CAD software (EXO CAD, Darmstadt, Germany), the monolithic crown model was designed to adapt to every master die. In order to determine the relationship between occlusal thickness and fracture strength, two standardized occlusal thickness were chosen; namely, 0.5 and 1.0 mm. Finally, the designed data was output to the CAM milling machine (DeG-5X100, ARUM, Seoul, Korea) to fabricate the zirconia crowns ($n=28$). The fabricated crowns were classified into 2 groups according to the different occlusal thicknesses (1.0 and 0.5 mm), with 14 specimens per group.

Mechanical properties of the zirconia crowns
Each crown was cemented to a master die using resin cement (GC FujiCEM, GC, Tokyo, Japan) at room temperature of 25°C, in accordance with the manufacturer's instructions. The cement was subjected to a constant static load of 7 kg for 5 min. Prior to mechanical testing, the specimens were stored in distilled water at 37°C for at least 24 h to assure hydration and prevent dimensional expansion after crown cementation.

Each group was treated by two surface treatment methods: the excellent polishing treatment already described in the previous experiment (Polished with Green+Red+Yellow bur after removing using high speed bur), or only adjustment of occlusal contact (Removing using high speed bur). The crown conditions and surface treatment processes are listed in Table 3.

Before the fracture test, each specimen was immobilized on a fatigue-testing machine (Model 8871, 

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Table 3  The condition of groups classified by different occlusal thickness and surface treatment

| The occlusal thickness (mm) | Surface treatment |
|-----------------------------|-------------------|
| Group A 1.0 | Polishing treatment using diamond polishing kit (Green+Red+Yellow bur after removing using high speed bur) |
| Group B 1.0 | Adjustment of occlusal contact (Removing using high speed bur) |
| Group C 0.5 | Polishing treatment using diamond polishing kit (Green+Red+Yellow bur after removing using high speed bur) |
| Group D 0.5 | Adjustment of occlusal contact (Removing using high speed bur) |
Intron, Berkhamsted, UK) to simulate mouth-chewing movement. Each crown specimen was subjected to cyclic loads of between 2 and 300 N, at a rate of 1 Hz. The crown specimens were designed to hold a stainless steel ball (3.0 mm in diameter) placed on the middle of the occlusal surface to ensure an even loading force was applied to the crowns. This maximum load is higher than the average masticatory force in the posterior area of the mouth, and the frequency was chosen to be equivalent to the average masticatory cycle time of 0.8–10 s. The total loading time corresponded to 100,000 cycles.

Each specimen was immobilized on a fracture-testing machine (GB 4201, Instron), and the load-to-fracture test was performed by applying a stainless steel ball (3.0 mm in diameter) in three-point contact with the crown, transferring the force evenly to the crowns during loading (Fig.2). All specimens were loaded at a crosshead speed of 1.0 mm/min until a fracture occurred. The fracture load was recorded by the testing machine. The highest and lowest values from each of the seven specimens were removed, the mean and standard deviation (SD) of the fracture strength were calculated.

Two typical surface morphologies resulting from different surface treatments were observed by FE-SEM (SUPRA40VP, Carl Zeiss, Oberkochen, Germany), secondary electron imaging was performed using FE-SEM at an accelerating voltage of 15 kV to investigate surface geometry.

The statistical significance between the groups was analyzed by one-way analysis of variance (ANOVA). The $R_a$ and fracture load results were expressed as the mean±SD. A $p$ value of $<0.05$ between groups was considered statistically significant.

RESULTS

Table 4 summarizes the surface roughness values after different surface polishing treatments. Compared to specimens polished with the green bur only (group 1), the $R_a$ values are reduced in all tested groups apart from group 0. Three groups exhibit significantly lower surface roughness values than 2 of the groups (groups 0 and 1). However, no significant differences are observed among these three groups. Group 1 specimens, which exhibit a $R_a$ value almost five times greater than that of the smoothest group (group 4). Since higher roughness values indicate a rougher surface, we can conclude that specimens from group 4 that were polished with the green bur, smoothing with the red bur, and polishing with the yellow bur after removing with the high-speed bur produced the most highly polished, smooth surface.

The X-ray diffraction (XRD) patterns of the different zirconia surface-treated groups are shown in Fig. 3, wherein it can be observed that the presence of a monoclinic phase could still be detected in groups 0, 1, and 2; however, the monoclinic phase is not detectable in groups 3 or 4. Groups 1 and 2 used the green and red burs, respectively, which are the most primitive polishing burs; these results prove that using only the primary polishing bur cannot effectively eliminate the monoclinic phase. With regard to group 3, we used the yellow bur that is for high-brightness super-fine polishing; therefore, the monoclinic phase is not detected. Among all the groups, group 4, which was polished with the green, red and yellow burs after adjustment with the high-speed bur, shows the most stable phase.

Typical FE-SEM images before and after polishing the crowns are shown in Fig. 4. The surface of the
specimen after occlusal adjustment without any polishing treatment is rough and irregular. After the polishing treatment, the surface of the specimen is significantly smoother and flatter, and consists of homogeneous grains.

The mean and SD of the fracture strength of each crown type are provided in Fig. 5. The data show that, for groups with the same occlusal thickness, the groups after polishing have higher fracture strengths than after adjustment of occlusal contact; however, the data are not significantly different, which may be a result of the tetragonal to monoclinic phase transformation. For specimens with the same surface treatment, the fracture strength depends on the occlusal thickness; specimens with larger occlusal thicknesses have higher fracture strengths (p<0.05).

DISCUSSION

External stress during polishing, adjustment of the occlusal thickness, and tens of thousands of chewing cycles can trigger the tetragonal to monoclinic (t→m) phase transformation\(^{34,35}\). Therefore, in this study, we examined the effect of different degrees of polishing on the zirconia surface, and the influence of different surface treatments on the fracture strengths of the
zirconia is composed of two kinds of crystals namely, the tetragonal and monoclinic phases. From the XRD results, we can see that the surface crystalline composition in each group of specimens is different after varying polishing treatments. In groups 0, 1, and 2, we can clearly observe the existence of a monoclinic peak, while in groups 3 and 4, we could not observe a monoclinic peak. From this, we can infer that the green bur does not provide a good surface treatment, nor can it remove the monoclinic phase on the surface. Also, the use of the red bur alone does not completely eliminate the monoclinic phase; some additional burs are required, followed by polishing in order to achieve good results. The yellow bur was used for groups 3 and 4, and we did not detect the presence of a monoclinic phase in either of these two groups. Group 3 was polished using only the yellow bur, and good results were obtained. In the case of group 4, polishing with a high-speed bur after using the green, red, and yellow burs, produced the most delicate and smooth surfaces among all the groups. Although neither the group 3 nor the group 4 detected the existence of the monoclinic phase, in combination with the results of the surface roughness, we think that the group 4 has a much better effect. This suggests that the monoclinic phase can be eliminated by optimizing the polishing process.

Zirconia is becoming a favorable material for restorative dentistry. In the clinic, chairside modifications and adjustments of zirconia restorations are sometimes required to achieve optimal interproximal contact and occlusal relationships. It is important to study whether the polishing procedure after adjustment is clinically statistically significant. Based on the results of the surface roughness and XRD analyses of the zirconia plates, we selected the best group to compare the effect of different occlusal thicknesses. With regard to the SEM results, comparative observations show very clearly that the surface without polishing is uneven; however, the surface after polishing is smoother and more regular. This demonstrates that the polishing process has a large influence on the roughness of the zirconia surface.

Strength is an important mechanical property that helps to determine the functionality of a frangible material. In the present study, external pressure was applied to the samples for 100,000 cycles, which is equivalent to about six months of chewing in a typical human mouth. The cycling load was 300 N, which is lower than the maximum occlusal bite force in the molar area, but still higher than the average chewing force. Statistical analysis showed that the differences among groups with the same occlusal thicknesses in terms of fracture strength were not statistically significant in this study. However, we believe that this result is due to rapid zirconia phase transformation; therefore, this study still has practical significance. It has been reported that cyclic external mechanical forces, such as cyclic loading, sandblasting, grinding, impact and thermal aging can cause tetragonal to monoclinic phase transformation. Stress built up at the tip of the crack will trigger phase transformation. At the same time, this process is accompanied by a volume expansion of 3–4%, as the monoclinic phase is larger in size than the tetragonal phase. This phenomenon will generate a compressive force at the tip of the crack, which increases the work of the fracture; at the same time, the energy is dissipated, thereby closing the crack tip and leading to deeper crack propagation and dissemination. Thus, in a short time, the zirconia volume expands and the cracks extend into the bulk; however, the fracture strength increases. This could explain why our occlusal thickness results are not statistically significant. However, the practical lifetime of zirconia crowns in the mouth can be up to 10 years, which far exceeds the duration of our experimental study. Crowns in the mouth experience cycles of chewing that will lead to the formation of micro-cracks, ultimately reducing the fracture strength. Therefore, changing the number of cycles or increasing the cyclic loading strength can also produce different effects on the fracture strength of a monolithic zirconia crown. Therefore, we think that, from a long-term perspective, this study is still meaningful.

The occlusal bite force of healthy young adults in the posterior area has been reported to be 597 N in females and 847 N in males, with a maximum force reaching 900 N. Ferrario et al. reported an average bite force.
of about 700 N. According to the experimental data in the present study, we can see that the fracture strength in all groups is higher than the average bite force in the posterior area. In the present study, a steel wheel was inserted between the crown and the indenter to avoid impact damage. However, our experiment cannot be representative of all relevant clinical trials because we only used a vertical cycling loading force. In order to gain a better understanding of the effects of different surface treatments on the fracture strength of zirconia crowns, other factors such as lateral force, thermal cycling, and unexpected circumstances should also be taken into account.

Within the limitations of the present study, we can still conclude that a thicker zirconia collar will have higher fracture strength. For a given occlusal thickness, the average value of the fracture strength in a zirconia crown after polishing was higher than in a zirconia crown after only occlusal adjustment. Consequently, the clinical significance of this finding is that, after adjusting the zirconia crowns in the patient’s mouth, it is preferable to carry out a polishing treatment. In order to better understand the dependence of fracture strength on different surface treatments of zirconia crowns, we should do more in-depth, long-term, clinical follow-up experiments.

CONCLUSION

Within the limitations of this study, the following conclusions were drawn. It is suggested that the monoclinic phase can be eliminated by optimizing the polishing process. The fracture strength of the zirconia crowns increased with increasing occlusal thickness ($p<0.05$). Polishing treatment had a better effect than roughness adjustment on the zirconia monolithic crowns ($p>0.05$).

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REFERENCES

1) Shirakura A, Lee H, Geminiani A, Ercoli C, Feng C. The influence of veneering porcelain thickness of all-ceramic and metal ceramic crowns on failure resistance after cyclic loading. J Prosthet Dent 2009; 101: 119-127.
2) Yilmaz H, Aydin C, Gul BE. Flexural strength and fracture toughness of dental core ceramics. J Prosthet Dent 2007; 98: 129-128.
3) Bachhav VC, Aras MA. Zirconia-based fixed partial dentures: a clinical review. Quintessence Int 2011; 42: 173-182.
4) Thurmond JW, Barkmeier WW, Wilwerding TM. Effect of porcelain surface treatments on bond strengths of composite resin bonded to porcelain. J Prosthet Dent 1994; 72: 355-359.
5) Rosenblum MA, Schulman A. A review of all-ceramic restorations. J Am Dent Assoc 1997; 128: 297-307.
6) Hobo S, Shillingburg HT. Porcelain fused to metal: Tooth preparation and coping design. J Prosthet Dent 1973; 30: 28-36.
7) Ohno M, Gjerde NR, Tvinneireim HM. The firing procedure influences properties of a zirconia core ceramic. Dent Mater 2008; 24: 471-475.
8) Akagawa Y, Ichikawa Y, Nikai H, Tsuru H. Interface histology of unloaded and early loaded partially stabilized zirconia endosseous implant in initial bone healing. J Prosthet Dent 1993; 69: 599-604.
9) Paul SJ, Werder P. Clinical success of zirconium oxide posts with resin composite or glass-ceramic cores in endodontically treated teeth: a 4-year retrospective study. Int J Prosthodont 2004; 17: 524-528.
10) Lurtherd R, Sandkühler O, Reitz B. Zirconia-TZP and aluminia—advanced technologies for the manufacturing of single crowns. Eur J Prosthodont Restor Dent 1999; 7: 113-119.
11) Tan PLB, Dunne JT. Anesthetic comparison of a metal ceramic crown and cast metal abutment with an all-ceramic crown and zirconia abutment: a clinical report. J Prosthet Dent 2004; 91: 215-218.
12) Kosmać T, Oblak C, Jevnikar F, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. Dent Mater 1999; 15: 426-433.
13) Pogoncheff CM, Duff RE. Use of zirconia collar to prevent interproximal porcelain fracture: a clinical report. J Prosthet Dent 2010; 104: 77-79.
14) Deng Y, Lawn BR, Lloyd IK. Characterization of damage modes in dental ceramic bilayer structures. J Biomed Mater Res Part A 2002; 63: 137-145.
15) Christel P, Meunier A, Heller M, Torre JP, Peillé CN. Mechanical properties and short-term in vivo evaluation of yttrium-oxide-partially-stabilized zirconia. J Biomed Mater Res 1989; 23: 45-61.
16) Chai J, Chu FCS, Chow TW, Liang BMH. Chemical solubility and flexural strength of zirconia-based ceramics. Int J Prosthodont 2007; 20: 587-595.
17) Sailer I, Gottner J, Kanellis B, Hammerle CHF. Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: a 3-year follow-up. Int J Prosthodont 2009; 22: 553-560.
18) Happe A, Röling N, Schäfer A, Rothamel D. Effects of different polishing protocols on the surface roughness of Y-TZP surfaces used for custom-made implant abutments: A controlled morphologic SEM and profilometric pilot study. J Prosthet Dent 2015; 113: 440-447.
19) Hallmann L, Ulmer P, Wille S, Polonsky O, Köbel S, Trottenberg T, Bornholdt S, Haase F, Kersten H, Kern M. Effect of surface treatments on the properties and morphological change of dental zirconia. J Prosthet Dent 2016; 115: 341-349.
20) Nakamura T, Hojo S, Sato H. The effect of surface roughness on the Weibull distribution of porcelain strength. Dent Mater J 2010; 29: 30-34.
21) Anami LC, Pereira CA, Guerra E, Souza RO de A, Jorge AO, Bottino MA. Morphology and bacterial colonisation of tooth/ceramic restoration interface after different cement excess removal techniques. J Dent 2012; 40: 742-749.
22) Akyent F, Yondem I, Ozyesil AG, Gunal SK, Avunduk MC, Ozkan S. Effect of different finishing techniques for restorative materials on surface roughness and bacterial adhesion. J Prosthet Dent 2010; 103: 221-227.
23) Brentel AS, Kantorski RZ, Valandro LF, Fúcio SB, Puppini-Rontani RM, Bottino MA. Confocal laser microscopic analysis of biofilm on new feldspar ceramic. Oper Dent 2011; 36: 43-51.
24) Haralur SB. Evaluation of efficiency of manual polishing over autoglazed and overglazed porcelain and its effect on plaque accumulation. J Adv Prosthodont 2012; 4: 179.
25) Zhang M, Zhang Z, Ding N, Zheng D. Effect of airborne-particle abrasion of presintered zirconia on surface roughness and bacterial adhesion. J Prosthet Dent 2015; 113: 448-452.
26) Kim HY, Yeo IS, Lee JB, Kim SH, Kim DJ, Han JS. Initial in vitro bacterial adhesion on dental restorative materials. Int J Artif Organs 2012; 35: 773-779.
27) Scotti R, Kantorski KZ, Monaco C, Valandro LF, Ciocca L, Bottino MA. SEM evaluation of in situ early bacterial colonization on a Y-TZP ceramic: a pilot study. Int J Prosthodont 2007; 20: 419-422.
28) Salihoglu U, Boynegeir D, Engin D, Duman AN, Gokalp P, Balos K. Bacterial adhesion and colonization differences between zirconium oxide and titanium alloys: an in vivo human study. Int J Oral Maxillofac Implants 2010; 26: 101-107.
29) Bollen CML, Lambrechts P, Quirynen M. Comparison of surface roughness of oral hard materials to the threshold surface roughness for bacterial plaque retention: A review of the literature. Dent Mater 1997; 13: 258-269.
30) Janyavula S, Lawson N, Cakir D, Beck P, Ramp LC, Burgess JO. The wear of polished and glazed zirconia against enamel. J Prosthet Dent 2013; 109: 22-29.
31) Preis V, Behr M, Handel G, Handel G, Schneider-Feyrer S, Hahnel S, Rosentritt M. Wear performance of dental ceramics after grinding and polishing treatments. J Mech Behav Biomed Mater 2012; 10: 13-22.
32) Karakoca S, Yilmaz H. Influence of surface treatments on surface roughness, phase transformation, and biaxial flexural strength of Y-TZP ceramics. J Biomed Mater Res B Appl Biomater 2009; 91: 930-937.
33) Wang C, Zhao Y, Zheng S, Xue J, Zhou J, Dan H, Azuma T, Karita K. Effects of sample hardness on human chewing force: A model study using silicone rubber. Arch Oral Biol 2004; 49: 805-816.
34) Bilt A van der. Assessment of mastication with implications for oral rehabilitation: A review. J Oral Rehabil 2011; 38: 754-780.
35) Kobayama K, Hatakeyama E, Sasaki T, Dan H, Azuma T, Karita K. Effects of surface roughness on bacterial plaque accumulation. Int J Prosthodont 2006; 19: 68-71.
36) Luthardt RG, Holzhüter MS, Rudolph H, Herold V, Walter MH. CAD/CAM-machining effects on Y-TZP zirconia. Dent Mater 2004; 20: 655-662.
37) Luthardt RG, Holzhüter M, Sandkuhl O, Herold V, Schnapp JD, Kuhlisch E, Walter M. Reliability and properties of ground Y-TZP-zirconia ceramics. J Dent Res 2002; 81: 487-491.
38) Kosmač T, Oblak Č, Jevnikar P, Funduk N, Marion L. Influence of surface roughness, phase transformation, and biaxial flexural strength on adhesion of bacteria and their synthesizing glucans. J Prosthodont 2000; 83: 646-667.
39) Subbarao EC. Zirconia —An Overview. In: Advances in Ceramics, Vol. 3, Science and technology of zirconia, ed. A. H. Heuer and LW Hobbs, The American Cer. Soc, Inc, Columbus, Ohio, 1981. p. 1-24.
40) Denny I, Kelly JR. State of the art of zirconia for dental applications. Dent Mater 2008; 24: 299-307.
41) Chevalier J, Cales B, Drouin JM. Low-temperature aging of Y-TZP ceramics. J Am Ceram Soc 1999; 82: 2150-2154.
42) Rashid H. The effect of surface roughness on ceramics used in dentistry: A review of literature. Eur J Dent 2014; 8: 571-579.
43) Rosentritt M, Plein T, Kolbeck C, Behr M, Handel G. In vitro fracture force and marginal adaptation of ceramic crowns fixed on natural and artificial teeth. Int J Prosthodont 2000; 13: 387-391.
44) Bilt A van der. Assessment of mastication with implications for oral rehabilitation: A review. J Oral Rehabil 2011; 38: 754-780.
45) Kobayama K, Hatakeyama E, Sasaki T, Dan H, Azuma T, Karita K. Effects of sample hardness on human chewing force: A model study using silicone rubber. Arch Oral Biol 2004; 49: 805-816.
46) Luthardt RG, Holzhüter MS, Rudolph H, Herold V, Walter MH. CAD/CAM-machining effects on Y-TZP zirconia. Dent Mater 2004; 20: 655-662.
47) Luthardt RG, Holzhüter M, Sandkuhl O, Herold V, Schnapp JD, Kuhlisch E, Walter M. Reliability and properties of ground Y-TZP-zirconia ceramics. J Dent Res 2002; 81: 487-491.
48) Kosmač T, Oblak Č, Jevnikar P, Funduk N, Marion L. Influence of surface roughness, phase transformation, and biaxial flexural strength on adhesion of bacteria and their synthesizing glucans. J Prosthodont 2000; 83: 646-667.