Influence of material thickness on fractural strength of CAD/CAM fabricated ceramic crowns

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DOI: https://doi.org/10.4012/dmj.2016-296

TITLE

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RUNNING TITLE

Minimum Thickness Ceramic

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Category:

Original research article

Keywords:

feldspathic ceramic VITA Mark II, lithium disilicate ceramic e.max CAD, zirconia-reinforced lithium silicate ceramic Celtra Duo and VITA Suprinity, hybrid ceramic VITA Enamic, CEREC

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Conflict of interest:

The authors declare that there is no conflict of interest.

ABSTRACT

The fracture behavior of CAD/CAM fabricated crowns was investigated as a function of material thickness for six silicate ceramic materials: Mark II, e.max CAD, Celtra Duo milled, Celtra Duo fired, Suprinity, Enamic. Crowns with thicknesses 0.5/1.0/1.5 mm were fabricated with CEREC and adhesively seated to dies fabricated with stereolithography technology (n=144). Thermomechanical loading and fractural loading was performed. Statistical analysis was done with one-way ANOVA and post-hoc Scheffé test. For 1.5 mm, all crowns survived fatigue testing, for 1.0 mm, survival was 100% only for materials e.max CAD and Suprinity. For 0.5 mm, best survival rate was 37.5% for Suprinity. Maximum fractural loading significantly varied among the groups. For 0.5 mm, highest value was found for Suprinity (660.1 N). Mark II showed lowest values for 1.0 mm (482.0 N), and 1.5 mm groups (634.8 N). e.max CAD showed highest values for 1.0 mm (774.2 N), and 1.5 mm groups (1240.8 N).

INTRODUCTION

Ceramic materials are often selected for the fabrication of CAD/CAM restorations because of their advantageous characteristics[1-2)]. Compared to composite resin materials, ceramic materials are more brittle and more susceptible to fracture, if overload or inappropriate load is performed[3)]. The material characteristics of ceramics have been shown to significantly depend on prior thermal and mechanical fatigue loading[4)]. Four factors have been identified to mainly influence the fracture resistance of all-ceramic restorations: restoration design, tooth preparation, cementation and material thickness[5-9)]. The fracture resistance can be increased by an ideal combination of these four factors, however, the factors restoration material and material thickness have been reported to be of primary importance[10)].

CAD/CAM milling procedures are highly promising, as ceramics can be milled out of homogenous, industrial preformed blocks bearing less risk of artificial material weaknesses. Several ceramic material classes are currently available for CAD/CAM manufacturing, such as feldspathic and lithium disilicate ceramics. The clinical success of these materials could be demonstrated in several studies[11,12)]. New trends in terms of material development either tend to reinforce the ceramic´s glassmatrix by embedding stronger particles, such as zirconia, or to create compound material, e.g. by infiltrating the ceramic matrix. The zirconia-reinforced lithium silicate ceramic (ZLS) Celtra Duo (Dentsply Sirona, Corporation, York, PA, USA) and VITA Suprinity (VITA Zahnfabrik, GmbH & Co. KG, Bad Säckingen, Germany) are examples for this development. Zirconia-reinforced lithium silicate ceramics contain ten percent by weight of dispersed zirconia particles embedded in a fine-grained glass matrix with a size of 500 - 800 nm[13]. VITA Enamic (VITA Zahnfabrik, GmbH & Co. KG, Bad Säckingen, Germany) is a compound hybrid ceramic material. The ceramic network makes up about 86% share of the material and is reinforced by a polymer network[13]. Restorative patient treatment might be performed more conservative with these two type of material as the extent of tooth preparation may be reduced. First studies demonstrate that the fracture resistance of CAD/CAM fabricated monolithic zirconia molar crowns might be sufficient with material thicknesses of 0.5 mm[14]. However, no sufficient data is available for the new material classes zirconia-reinforced lithium silicate ceramics and hybrid ceramic.

The aim of this study was to evaluate the maximum fractural load of new CAD/CAM ceramic materials depending on different material thicknesses. The null hypothesis was that there are no differences for the fractural loading of different silicate ceramic CAD/CAM materials ($p<0.05$).

MATERIALS AND METHODS

This study involved fractural loading of single molar CAD/CAM crowns after previous fatigue testing in a chewing simulation machine. Four different types of silicate ceramic CAD/CAM material were investigated: feldspathic ceramic (group A), lithium disilicate ceramic (group B), zirconia-reinforced lithium silicate ceramic (ZLS) (group C,D,E) and hybrid ceramic (group F). Two different zirconia-reinforced lithium silicate ceramic materials with three different post-processing protocols were investigated. At a total, there were six different groups: VITA Mark II (group A), e.max CAD (group B), Celtra Duo milled (group C), Celtra Duo fired (group D), VITA Suprinity (group E) and VITA Enamic (group F). For each group, molar crowns with minimum thicknesses of 0.5 mm, 1.0 mm and 1.5 mm (with each group n=8) were fabricated using a CAD/CAM system (CEREC Bluecam and CEREC MCXL milling unit, Dentsply Sirona, Corporation, York, PA, USA). Crowns were adhesively seated to specially designed dies. A total of 144 specimens was investigated in this study. All groups are shown in **Table 1**.

Fabrication of SLA dies and CAD/CAM restorations

Dies were fabricated with stereolithography (SLA) technique (Viper Si2, 3D Systems, Corporation, Rock Hill, SC, USA). The z-axis solution was 100 µm for the base of the die and 50 µm for the body. A special methacrylate resin was used as SLA material (E-Modulus 2.5 GPa, fractural strength 110-130 MPa, shore hardness 80-84 Shore D). Dies were designed in respect of guidelines for all-ceramic preparation with special CAD Software (Pro Engineer Wildfire 4.0, PTC, corporation, Needham, MA, USA) for each 0.5 mm, 1.0 mm and

1.5 mm groups. The parameters for a 1.5 mm crown were: occlusal reduction 1.5 mm (deepest fissure), 4-degree axial taper, 1.5 mm shoulder finish line placed 0.5 mm occlusal to the cementoenamel junction (CEJ), vertical height of stump 5 mm and 140-degree flat occlusal plateau. Based on the design for the 1.5 mm die, dies for material thicknesses 1.0 mm and 0.5 mm were anatomically up-scaled to ensure a homogenous wall thickness of the restorations. The die for a 0.5 mm restoration is shown in **Figure 1.**

Crowns with thicknesses of 0.5 mm, 1.0 mm and 1.5 mm (n=8) were fabricated for each type of material using a CAD/CAM system (CEREC MCXL milling unit, Dentsply Sirona, Corporation, York, PA, USA). First, a 0.5 mm crown was individually designed on a 0.5 mm SLA die with CEREC Software (v.4.0). The CAD design parameter spacer was set to 80 µm, all other parameters were set to 0 µm. Using the design option "show minimum thickness" and "cursor details", exact material thickness could be ensured at all areas of the crown (**Figure 2)**. The CEREC CAD mode "biocopy" was used for CAD design of 1.0 mm and 1.5 mm crowns. First, an adhesively luted 0.5 mm crown was slightly dusted (VITA Powder Scan Spray, VITA Zahnfabrik, GmbH & Co. KG, Bad Säckingen, Germany) and then scanned with the intraoral scanner CEREC Bluecam. Five single images were taken (occlusal, 30 degrees distal, 30 degrees mesial, 30 degrees buccal and 30 degrees lingual). CAD design with thicknesses of exactly 1.0 mm and 1.5 mm could be done on the respective SLA dies using this template, without the need for any further manual manipulation. CAM fabrication of the ceramic crowns was performed with the 3+1 axis milling unit CEREC MCXL equipped with the milling instruments cylinder pointed bur 12s and step bur 12. Milling mode was set to "standard". New milling instruments were selected for each group. After the milling process, no manipulation was done to the sprue. Additional post-processing protocols were required for restorations of group B,D and E. Lithium disilicate crowns (group B) were crystallized according to manufacturer´s recommendations (Programat CS, Ivoclar Vivadent, AG, Schaan, Liechtenstein). Zirconia-reinforced lithium silicate ceramic Celtra Duo crowns of group D were fire glazed using Celtra Duo glaze paste (Dentsply Sirona, Corporation, York, PA, USA) and zirconia-reinforced lithium silicate ceramic Suprinity crowns of group E were crystallized using VITA glaze paste (VITA Zahnfabrik, GmbH & Co. KG, Bad Säckingen, Germany), according to manufacturer´s recommendations (Programat CS, Ivoclar Vivadent, AG, Schaan, Liechtenstein).

Adhesive luting of CAD/CAM restorations

SLA fabricated dies were prepared prior to adhesive luting of the restorations. First, dies were airborne-particle abraded with Si-coated aluminum oxide (Cojet, 3M ESPE, 3M Corporation, St. Paul, MN, USA) (diameter ≤ 50 µm, 200 kPa). Silane (Monobond Plus, Ivoclar Vivadent, AG, Schaan, Liechtenstein) was applied to the die´s surface for at least 60 seconds. Heliobond was used as adhesive bonding agent. All restorations were cleaned with ultrasonic and degreased with ethanol after milling. A 5% HF acid was used for acid etching of the restoration´s luting surface (VITA Mark II 60 sec; e.max CAD 20 sec; Celtra Duo 40 sec; VITA Suprinity 40 sec). Silanisation (Monobond Plus, Ivoclar Vivadent, AG, Schaan, Liechtenstein) for at least 60 sec and application of bond (Heliobond, Ivoclar Vivadent, AG, Schaan, Liechtenstein) was performed for all restorations. A dual-polymerizing composite resin system (Variolink II high viscosity; Ivoclar Vivadent, AG, Schaan, Liechtenstein) was used for adhesive luting of all restorations. After removing excess, an oxygen layer inhibitor material was applied to the area of the cementation interface (Oxyguard, Kuraray, Corporation, Chiyoda, Japan). Luting composite resin was polymerized with a polymerization lamp (Satelec MiniLED, KaVo Dental, Danaher Corporation, Biberach, Germany), using 1600 mW/cm^2 from the occlusal, mesial, distal, buccal, and lingual aspects for 60 seconds each. The radiant exposure was ensured by prior calibration of the light curing device.

Fatigue testing and fractural loading

The adhesively seated restorations were embedded with methacrylate (Paladur; Heraeus Kulzer, Mitsui Chemicals Group, Hanau, Germany) in special test blocks. Centric fixation of all restorations was ensured. Specimens were stored in distilled water at 37 degrees in a heating cabinet. Fatigue loading was performed using a special mastication simulator[15)]. Thermomechanical loading was performed (1.2 million cycles, 1.7 Hz, invariable occlusal load 49 N $\pm$ 0.7 N, thermal cycling 5 - 55 degrees, dwell time 120 sec, 12 000 cycles, water change time 10 sec)[15)]. Load was exerted exactly to the central fissure by the antagonistic cusp of a natural molar. After fatigue testing, specimens were examined under a stereomicroscope at 14x magnification with transmitted light (Wild Leitz/M1B; Walter Products, Windsor, ON, Canada). If modes of failure, such as cracks, were visible, specimens were eliminated. For those specimens survived fatigue testing, fractural loading in a universal testing machine (Allround Line z010, Zwick, GmbH % Co. KG, Ulm, Germany) was performed with a standardized protocol (crosshead speed 1 mm/min, ball diameter 5 mm). The maximum load at failure was registered. Statistical analysis was done using SPSS 22 (IBM, Corporation, Armonk, NY, USA) and one-way ANOVA with following post-hoc Scheffé test was performed. The significance level was set to p=0.05. Homogenous subset groups for groups with no statistical significant difference were calculated.

RESULTS

Results for survival after fatigue testing and fractural loading are shown in **Table 2**. For material thickness 0.5 mm, one lithium disilicate (e.max CAD; group B), one zirconia-reinforced lithium silicate ceramic fired (Celtra Duo; group D) and three zirconia-reinforced lithium silicate ceramic crystallized (VITA Suprinity; group E) CAD/CAM crowns survived fatigue testing. All other restorations did not survive fatigue testing, due to fracture and were not included in fractural load testing. For material thickness 1.0 mm, one feldspathic (VITA Mark II; group A), seven zirconia-reinforced lithium silicate ceramic milled (Celtra Duo; group C), eight zirconia-reinforced lithium silicate ceramic fired (Celtra Duo, group D) and two zirconia-reinfored lithium silicate ceramic crystallized (VITA Suprinity; group F) CAD/CAM restoration did not survive fatigue testing. All restorations with minimum thickness 1.5 mm survived fatigue testing. Feldspathic ceramic restorations (VITA Mark II; group A) showed lowest values both for 1.0 mm (482.0 N) and 1.5 mm (634.8 N) material thickness group. Lithium disilicate ceramic restorations (e.max CAD; group B) showed highest values for 1.0 mm (774.2 N) and 1.5 mm (1240.8 N) material thickness group. The maximum fractural load significantly varied among the groups tested. Results for statistical analysis with one-way ANOVA and post-hoc Scheffé test are shown in **Table 3**.

DISCUSSION

In this study, the fracture behavior of CAD/CAM fabricated silicate ceramic CAD/CAM crowns was investigated as a function of material thickness. Molar crowns with minimum thicknesses of 0.5 mm, 1.0 mm and 1.5 mm were fabricated for each type of material using a CAD/CAM system. Assuming a maximum chewing force of 600 - 800 N, all silicate ceramic CAD/CAM materials with a thickness of 1.5 mm may be appropriate for clinical use. For material thicknesses of 0.5 mm, 1.0 mm and 1.5 mm, there are significant differences depending on the respective CAD/CAM material. Standard deviations for the fractural load was relatively high among all groups tested. Several aspects of this study need to be discussed.

The material characteristics of the dies may influence the maximum fractural loading forces of the restorations. In this study, dies with an E-Modulus of 2.5 GPa were fabricated with SLA technology. Compared to the E-Modulus of human dentine, reported to be between 7 and 13 GPa, these values are very low[16)]. There is one study in literature showing the fracture resistance of all-ceramic crowns depending on the E-Modulus of the underlying supporting structure[17)]. The fracture load significantly increased with an increase of the elastic modulus[17)]. In this study, dies with relatively low E-Modulus were selected, thus representing a worst-case scenario for the CAD/CAM material tested. If CAD/CAM restorations tested in this study would have been adhesively luted to human dentine dies, results for fractural loading might have been higher. It might be interesting to see, how results for fractural loading would change, if the E-Modulus of the dies would be altered.

The cement used for adhesive luting of restorations may be another relevant component of the supporting structure. There are several studies reporting about the influence of the material thickness of luting composite resins[18-20)]. There are studies reporting that the higher the cement's E-Modulus, the lower the distribution of the tension within the restoration will be[21)]. In addition, the E-Modulus is reported to be more decisive than the cement layer thickness[6)]. In this study, spacer parameter was set to 80 μm, which is in good accordance with recommendations reported in literature[21)]. The adhesive resin cement Variolink II used in this study has an E-Modulus of 8.3 GPa, which is relatively high.

In this study, fatigue testing with a special masticator simulator was performed prior to fractural loading[15)]. The protocol for this study was a thermomechanical loading with 1.2 million cycles and an invariable occlusal load of 49 N ± 0.7 N. For the interpretation of the results found in this study, fatigue testing has to be considered. There are several studies reporting that fatigue loading weakens the ceramic structure[22-23)]. The values found for fractural loading in this study thus may be lower than those found in studies without fatigue loading.

There are several factors influencing the fracture resistance of ceramic restorations[5,8-10)]. The fracture resistance of all-ceramic restorations can be increased by an ideal combination of these factors. The E-Modulus of the restorations in relation to the supporting material may be highly decisive. In this study, maximum loading force for 1.5 mm hybrid ceramic restorations (VITA Enamic; group F) was 1063.6 N. The E-Modulus of VITA Enamic is reported to be 30 GPa[3)]. The maximum loading force for 1.5 mm feldspathic restorations (VITA Mark II; group A) was 634.8 N. The E-Modulus of VITA Mark II is reported to be 63 GPa[3)]. There may be the conclusion that the less mismatch there is between the restoration and the supporting material E-Modulus, the higher the fractural load will be. However, these findings are not valid for materials with a very high E-Modulus such as lithium diliscate. The E-Modulus for e.max CAD is 90 GPa and the maximum loading force for 1.5 mm restorations was 1240.8 N. If the restoration material´s E-Modulus is very high, there seems to be less influence of the supporting structure and a more predominant impact of the intrinsic stiffness of the materials. It may be interesting to investigate new CAD/CAM materials such as particle filled composite resins that might have higher fractural loading forces than the ceramics used in this study. The findings of this study are in good accordance with studies recently described comparing high E-Modulus ProCAD and low E-Modulus Paradigm MZ 100 restorations[24)].

One of the drawbacks of this study might be that only one parameter, minimum thickness, was evaluated. It may be interesting to evaluate the potential influence of more parameters on the fractural strength than only the minimum thickness. New test methods such as finite element analysis (FEA) methods might be additionally needed besides fatigue and fractural loading tests to elucidate the specific role of the system supporting material, cementum and restoration material and even occlusion in future. Another shortcoming of this study may be the sample size of n=8 for each group.

CONCLUSION

Assuming a maximum chewing force of 600 - 800 N, all silicate ceramic CAD/CAM materials with a thickness of 1.5 mm may be appropriate for clinical use. For material thicknesses of 0.5 mm, 1.0 mm and 1.5 mm, there are statistically significant differences for the maximum fractural load depending on the respective CAD/CAM material.

LEGENDS

Table 1: Overview groups and material classes for CAD/CAM crowns investigated; groups A-F were composed of each three subgroups (n=8) with 0.5 mm, 1.0 mm and 1.5 mm material thickness; totally 144 specimens were fabricated

group	material class	material label	post-procesing	E-Modulus
A	feldspathic ceramic	VITA Mark II	after milling	45 ± 0.5 GPa
B	lithium disilicate ceramic	e.max CAD	crystallized	95 ± 5 GPa
C	zirconia-reinforced lithium silicate ceramic (ZLS)	Celtra Duo	after milling	70 GPa
D	zirconia-reinforced lithium silicate ceramic (ZLS)	Celtra Duo	fired	70 GPa
E	zirconia-reinforced lithium silicate ceramic (ZLS)	VITA Suprinity	crystallized	70 GPa
F	hybrid ceramic	VITA Enamic	after milling	30 GPa

Table 2: Results for maximum fractural loading of CAD/CAM restorations (in Newton); (n) representing total quantity of specimens having survived fatigue loading and having been forwarded to fractural loading

							95% confidence intervall	
	thick.	**n**	**mean**	**SD**	**Min**	**Max**	**lower**	**upper**
A	0.5	-	-	-	-	-	-	-
	1.0	7	482.0	85.1	331.0	552.2	403.3	560.7
	1.5	8	634.8	76.4	536.8	773.7	571.0	698.72
B	0.5	1	636.1	-	-	-	-	-
	1.0	8	774.2	107.8	635.2	948.1	684.1	864.3
	1.5	8	1240.8	116.2	1104.2	1432.2	1143.6	1337.9
C	0.5	-	-	-	-	-	-	-
	1.0	1	533.6	-	-	-	-	-
	1.5	8	702.8	130.5	522.6	911.42	593.7	811.9
D	0.5	1	600.1	-	-	-	-	-
	1.0	-	-	-	-	-	-	-
	1.5	8	755.6	163.8	502.4	987.8	618.6	892.5
E	0.5	3	660.1	-	-	-	-	-
	1.0	6	615.0	158.4	471.6	917.4	448.8	781.2
	1.5	8	1092.5	396.8	865.4	1944.9	760.7	1424.2
F	0.5	-	-	-	-		-	-
	1.0	8	771.7	156.9	548.5	1009.6	640.5	902.9
	1.5	8	1063.6	151.1	902.3	1302.9	937.3	1189.9

Table 3 Homogenous subset groups as a result of statistical analysis of maximum fractural loading with one-way ANOVA and post-hoc Scheffé test; significance level p=0.05; values within one subset group show no statistical significant difference (p>0.05) meaning that the null hypothesis can be accepted for these groups

Material and thickness	n	Subsets for alpha=0.05			
		1	2	3	4
Mark II, 1.0mm	7	482.0			
Suprinity, 1.0mm	6	615.0			
Mark II, 1.5mm	8	634.8			
Suprinity, 0.5mm	3	660.1	660.1		
Celtra, 1.5mm	8	702.8	702.8	702.8	
Celtra fired, 1.5mm	8	755.6	755.6	755.6	
Enamic, 1.0mm	8		771.7	771.7	
e.max CAD, 1.0mm	8		774.2	774.2	
Enamic, 1.5mm	8		1063.6	1063.6	1063.6
Suprinity, 1.5mm	8			1092.5	1092.5
e.max CAD, 1.5	8				1240.8
Sig.		.514	.083	.112	.967

Figure 1: Exact specifications of SLA fabricated die for CAD/CAM ceramic crown with 0.5 mm material thickness; view from buccal and mesial aspect; (unit in millimeters and degrees)

Figure 2: CAD Design with CEREC chairside CAD software for CAD/CAM crown restoration with 0.5 mm, 1.0 mm and 1.5 mm thickness; slices show view from mesial and buccal aspect

REFERENCES

1. Brown D. The status of indirect restorative dental materials. Dent Update 1998; 25: 23-32.
2. Thompson VP, Rekow DE. Dental ceramics and the molar crown testing ground. J Appl Oral Sci 2004; 12: 26-26
3. Mormann WH, Stawarczyk B, Ender A, Sener B, Attin T, Mehl A. Wear characteristics of current aesthetic dental restorative CAD/CAM materials: two-body wear, gloss retention, roughness and Martens hardness. J Mech Behav Biomed Mater 2013; 20: 113-25.
4. Quinn GD, Hoffman K, Quinn JB. Strength and fracture origins of a feldspathic porcelain. Dent Mater 2012; 28: 502-11.
5. Burke FJ. Maximising the fracture resistance of dentine-bonded all-ceramic crowns. J Dent 1999; 27: 169-73.
6. Shahrbaf S, vanNoort R, Mirzakouchaki B, Ghassemieh E, Martin N. Effect of the crown design and interface lute parameters on the stress-state of a machined crown-tooth system: a finite element analysis. Dent Mater 2013; 29: 123-31.
7. Ahlers MO, Morig G, Blunck U, Hajto J, Probster L, Frankenberger R. Guidelines for the preparation of CAD/CAM ceramic inlays and partial crowns. Int J Comput Dent 2009; 12: 309-25.
8. Federlin M, Krifka S, Herpich M, Hiller KA, Schmalz G. Partial ceramic crowns: influence of ceramic thickness, preparation design and luting material on fracture resistance and marginal integrity in vitro. Oper Dent 2007; 32: 251-60.
9. Guess PC, Schultheis S, Wolkewitz M, Zhang Y, Strub JR. Influence of preparation design and ceramic thicknesses on fracture resistance and failure modes of premolar partial coverage restorations. J Prosthet Dent 2013; 110: 264-73.
10. Rekow ED, Harsono M, Janal M, Thompson VP, Zhang G. Factorial analysis of variables influencing stress in all-ceramic crowns. Dent Mater 2006; 22:125-32.
11. Otto T, Mormann WH. Clinical performance of chairside CAD/CAM feldspathic ceramic posterior shoulder crowns and endocrowns up to 12 years. Int J Comput Dent 2015; 18:147-61.
12. Reich S, Schierz O. Chair-side generated posterior lithium disilicate crowns after 4 years. Clin Oral Investig 2013; 17: 1765-72.
13. Zimmermann M, Mehl A, Reich S. New CAD/CAM materials and blocks for chairside procedures. Int Journal Comput Dent 2013; 16:173-81.
14. Nakamura K, Harada A, Inagaki R, Kanno T, Niwano Y, Milleding P, et al. Fracture resistance of monolithic zirconia molar crowns with reduced thickness. Acta Odontol Scand 2015: 1-7.
15. Krejci I, Reich T, Lutz F, Albertoni M. An in vitro test procedure for evaluating dental restoration systems. 1. A computer-controlled mastication simulator. Schweiz Monatsschr Zahnmed 1990; 100: 953-60.
16. Kinney JH, Marshall SJ, Marshall GW. The mechanical properties of human dentin: a critical review and re-evaluation of the dental literature. Crit Rev Oral Biol Med 2003; 14: 13-29.
17. Scherrer SS, de Rijk WG. The fracture resistance of all-ceramic crowns on supporting structures with different elastic moduli. Int J Prosthodont 1993; 6: 462-7.
18. D'Arcangelo C, De Angelis F, Vadini M, Carluccio F, Vitalone LM, D'Amario M. Influence of curing time, overlay material and thickness on three light-curing composites used for luting indirect composite restorations. J Adhes Dent 2012; 14: 377-84.
19. Ilie N, Stawarczyk B. Quantification of the amount of light passing through zirconia: the effect of material shade, thickness, and curing conditions. J Dent 2014; 42: 684-90.
20. Lee JW, Cha HS, Lee JH. Curing efficiency of various resin-based materials polymerized through different ceramic thicknesses and curing time. J Adv Prosthodont 2011; 3: 126-31.
21. Liu B, Lu C, Wu Y, Zhang X, Arola D, Zhang D. The effects of adhesive type and thickness on stress distribution in molars restored with all-ceramic crowns. J Prosthodont 2011; 20: 35-44.
22. Sobrinho LC, Cattell MJ, Glover RH, Knowles JC. Investigation of the dry and wet fatigue properties of three all-ceramic crown systems. Int J Prosthodont 1998; 11: 255-62.
23. Attia A, Kern M. Influence of cyclic loading and luting agents on the fracture load of two all-ceramic crown systems. J Prosthet Dent 2004; 92: 551-6.
24. Tsitrou EA, Helvatjoglu-Antoniades M, van Noort R. A preliminary evaluation of the structural integrity and fracture mode of minimally prepared resin bonded CAD/CAM crowns. J Dent 2010; 38: 16-22.