Fracture resistance of bonded CAD/CAM restorations with standard or extended preparations

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The purpose of this study was to evaluate the fracture resistance of teeth with standard or extended mesio-occlusodistal (MOD) preparations after restoration with bonded computer-aided design/computer-aided manufacturing (CAD/CAM) materials. Standard or extended MOD cavities were prepared in 60 of 70 extracted, caries-free third molars. In the standard MOD preparations (n = 30), 4.5-mm buccal and lingual/palatal wall thickness remained, and proximal boxes extended 1.0 mm coronal to the cementoenamel junction. In the extended MOD preparations (n = 30), the buccal and lingual/palatal walls were reduced to a thickness of 3.0 mm. A CAD/CAM acquisition unit was used to scan 20 standard and 20 extended preparations. Subsequently, 10 standard and 10 extended preparations were restored with milled lithium disilicate, and 10 of each type were restored with resin nanoceramic. Ten of each preparation type were left unrestored (negative control). An additional 10 third molars were neither prepared nor restored (positive control). After thermocycling and cyclic loading, specimens were fractured in a material testing device. Although bonded CAD/CAM restorations reinforced the tooth structure, the mean fracture loads were significantly lower ($P < 0.05$) in teeth with restored extended preparations (2642.4 [SD 479.4] N) than in teeth with restored standard preparations (3376.6 [SD 817.9] N). The type of CAD/CAM restorative material did not significantly affect the fracture load. Practitioners should consider covering the cusps with a CAD/CAM restorative material to reduce the potential for fracture in preparations with reduced cuspal thickness, especially in patients with heavier occlusion or functional loads.

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The introduction of computer-aided design/computer-aided manufacturing (CAD/CAM) has drastically changed the landscape of dentistry. CAD/CAM technology was initially developed to make tooth restoration easier, faster, and more accurate.[1] Using CAD/CAM, practitioners are most often able to provide patients with a definitive restoration on the same day as tooth preparation. Among other things, same-day delivery eliminates perhaps the most difficult component of conventional inlay and onlay procedures—the provisional restoration—normally challenging due to the nonretentive design of the preparations.[2] Accuracy has also been significantly improved by this modern technology. It has been reported that marginal adaptation values of 9-15 µm have been achieved in milled restorations.[3] Additionally, CAD/CAM restorations eliminate the porosities inherent in hand-fabricated porcelain restorations.[4]

Since its introduction in the mid-1980s, CAD/CAM technology has been used with a multitude of restorative materials. Early material options, such as feldspathic and leucite-reinforced porcelains, demonstrated reduced flexural strength and fracture toughness.[4] Moderate gains in strength were gained with the advent of a lithium disilicate–based CAD/CAM material (IPS e.max CAD, Ivoclar Vivadent).[5] These lithium disilicate glass ceramic blocks are machined in a partial crystallization phase (also known as the *blue phase*) and then tempered to reach their final state. During this process, lithium disilicate crystals are formed, giving the ceramic the desired final shade and high flexural strengths, reported by the manufacturer to be as high as 500 MPa.[6] Additionally, the modulus of elasticity in the fully crystalized state has been reported to be 95 GPa.[7,8] Unfortunately, the additional laboratory procedures required for tempering and any necessary correction firings further increase chair time and delay restoration delivery.

Unlike ceramic blocks, millable composite resin blocks possess properties that allow the material to be more easily adjusted, polished, and repaired.[5] Lava Ultimate (3M ESPE) is a resin nanoceramic that contains approximately 80% (by weight) nanoceramic particles bound in a resin matrix.[9] The filler particles consist of both nanoclusters and nanomer particles. Specifically, the nanoclusters are made from nanomer particles—silica (20 nm) and zirconia (4-11 nm)—that mass to form aggregates. According to the manufacturer, the nanotechnology and resin achieve a combination of exceptional flexural strength (204 MPa) and esthetics with shorter milling times and more desirable marginal edge quality, and the material can be easily repaired with traditional composite resin restorative materials.[9] Additionally, Lava Ultimate has a flexural modulus of 12.8 MPa, which is similar to that of human dentin (17.5).[9,10]

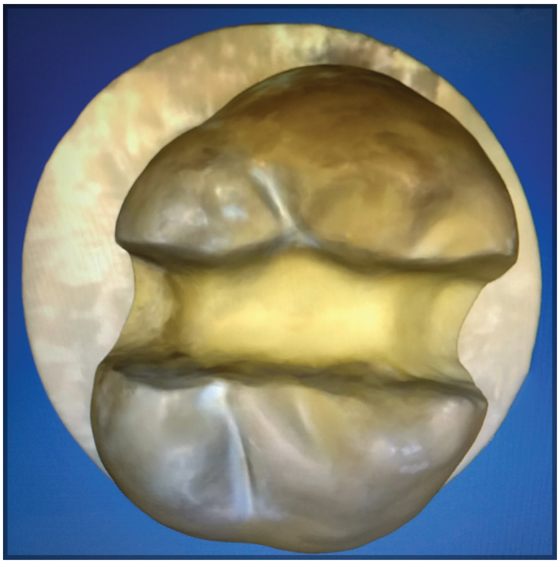


Fig 1. Standard preparation scanned with a CAD/CAM acquisition unit.

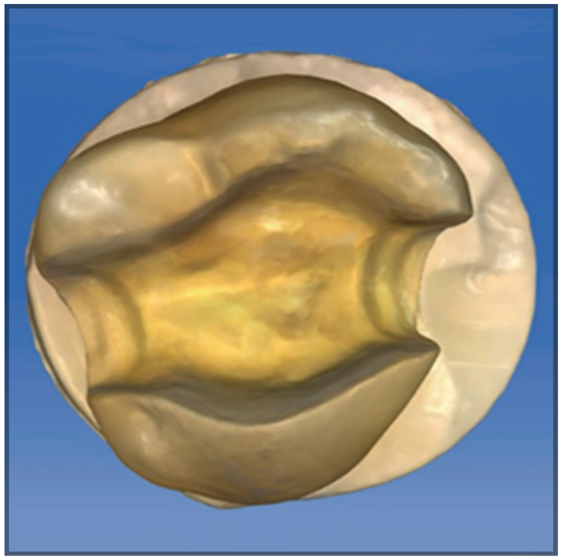


Fig 2. Extended preparation scanned with a CAD/CAM acquisition unit.

Lava Ultimate restorative material is indicated for inlays, onlays, and veneers.[9]

Conventional inlay preparation guidelines apply to CAD/CAM preparations, but there is greater emphasis on well-defined cavosurface margins and rounded internal line angles, both of which are necessary for accurate image acquisition. The occlusal aspect of the preparation should be at least 1.0-1.5 mm thick in the central fissure (depending on material) and have a 90-degree butt-joint configuration at the cavosurface margins.[2] Additionally, cavity walls of proximal boxes should have at least 6-8 degrees of taper.[11] However, the extent to which wider preparations may be restored with inlay restorations is controversial.[5,12-14] Anecdotal observations reported at dental conventions and in the continuing education circuits include a multitude of millable restorative materials used to restore teeth with extended preparations. Additionally, anecdotal conversations in both educational and private practice settings suggest that bonded CAD/CAM restorations reinforce teeth with wide preparations.

Mehl et al evaluated the reinforcing effects of a milled feldspathic ceramic inlay (Vita Mark II) and an indirect composite inlay made from a direct composite restorative material (Tetric) in various extended mesio-occlusodistal (MOD) inlay cavities.[15] Preparations with different isthmus widths were restored and loaded in a chewing simulator, and fracture resistance was established. The study determined that the milled ceramic provided significantly greater reinforcement than the indirect composite inlay. Nevertheless, this reinforcing effect was reduced in the case of extremely extended preparations (eg, 1.3 mm or less of remaining cuspal thickness).[15] Although the study had significant clinical implications, newer materials, such as lithium disilicate and resin nanoceramic, have since been introduced. However, no research evaluating the ability of these newer materials to reinforce tooth structures with wide preparations has been published.

The objective of the present study was to examine and compare the extent to which CAD/CAM lithium disilicate glass ceramic (IPS e.max CAD) and resin nanoceramic (Lava Ultimate) inlays can predictably reinforce extended Class II preparations. To accomplish this, the fracture resistance of different preparation designs was determined in vitro after mechanical fatigue loading. The null hypotheses were that there would be no differences in fracture load between (1) the standard and extended preparation types; (2) the lithium disilicate glass ceramic and resin nanoceramic restorative materials; or (3) any of the test groups and an unprepared control group.

Materials and methods

Seventy extracted, caries-free mandibular third molars of similar size were used in this study. Each tooth was embedded in self-cured bisacrylic resin (Integrity, Dentsply Sirona) to 2.0 mm below the cementoenamel junction in a custom cylindrical block. In 30 teeth, standard MOD preparations were completed so that 4.5-mm buccal and lingual/palatal wall thicknesses remained and proximal boxes extended 1.0 mm coronal to the cementoenamel junction (Fig 1). In another 30 teeth, extended MOD preparations were completed so that the buccal and lingual/palatal walls were reduced to a thickness of 3.0 mm (Fig 2). The molars were divided in 7 groups of 10 teeth each according to restorative material and preparation: lithium disilicate (IPS e.max CAD) in a standard preparation; resin nanoceramic (Lava Ultimate) in a standard preparation; lithium disilicate in an extended preparation; resin nanoceramic in an extended preparation; unrestored standard preparation (negative control group 1); unrestored extended preparation (negative control group 2); and unprepared teeth (positive control).

A CAD/CAM acquisition unit (CEREC Omnicam Acquisition Unit, Dentsply Sirona) was used to scan 20 standard and 20 extended preparations. Following completion of the digital design with CEREC software (version 4.4, Dentsply Sirona), 20 IPS e.max CAD and 20 Lava Ultimate inlay restorations were milled from their respective blocks (size C14, shade A2) using

Table. Mean (SD) fracture loads (in N) of lithium disilicate and resin nanoceramic CAD/CAM restorations (n = 10 per group).

	Preparation type		
Group	Standard	Extended	Both types
Lithium disilicate	3248.2 (781.2)^{Aa}	2547.9 (468.7)^{Ab}	2898.1 (736.0)^{A}
Resin nanoceramic	3504.9 (916.4)^{Aa}	2736.9 (524.6)^{Ab}	3120.9 (826.7)^{A}
Unrestored	1586.6 (436.8)^{Ba}	731.0 (290.2)^{Bb}	1158.8 (568.2)^{B}
Unprepared		4475.3 (797.4)^{C}	

Abbreviation: CAD/CAM, computer-aided design/computer-aided manufacturing.

Groups with the same superscript uppercase letter within columns or lowercase letter within rows are not significantly different ($P > 0.05$).

a milling unit (MCXL, Dentsply Sirona). After all inlays were fitted, the restorations were cemented according to their respective manufacturer's recommendations.

The intaglio surfaces of the IPS e.max CAD inlays were etched with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 seconds, rinsed, and thoroughly dried. Next, Monobond Plus (Ivoclar Vivadent) was applied to the etched surface, allowed to react for 60 seconds, and dried. On the prepared teeth, a mixture of Multilink primers A and B (Ivoclar Vivadent) was applied to enamel and dentin. Next, Multilink Automix resin cement (Ivoclar Vivadent) was applied directly to the etched and silanated restorations. The restorations were seated and tack cured for 1 second with a curing light (Bluephase G2, Ivoclar Vivadent), and excess cement was removed with a sharp instrument. The restorations were light cured for 20 seconds on each surface. Irradiance was recorded with a power meter (PowerMax, Coherent) and considered acceptable if greater than 1000 mW/cm^2. After removal of excess cement, the specimens were polished according to the manufacturer's recommendations. The surfaces of the restorations were polished with Dialite LD Extra-Oral Polishing System (Brasseler).

For the Lava Ultimate restorations, the intaglio surfaces of the inlays were sandblasted with 50-µm aluminum oxide at 2 bars (30 psi) (Basic Quattro IS, Renfert) and then steam cleaned (i700B, Reliable). Scotchbond Universal adhesive (3M ESPE) was applied for 20 seconds and then air dried for 5 seconds using a 3-way syringe. Enamel was selectively etched with 37.5% phosphoric acid (Scotchbond etchant, 3M ESPE) for 15 seconds, rinsed, and lightly air dried. Scotchbond Universal adhesive was applied to the enamel and dentin. Next, a uniform layer of RelyX Ultimate adhesive resin cement (3M ESPE) was mixed according to the manufacturer's recommendations and applied to the restorations. The restorations were seated and tack cured for 1 second with the curing light. After excess cement was removed with a sharp instrument, the restorations were light cured for 20 seconds on each surface. The surfaces of the restoration were finished and polished with Sof-Lex Spiral finishing and polishing wheels (3M ESPE).

All teeth in the 7 groups were stored in distilled water solution at 37°C for 24 hours in an incubator (model 20 GC, Quincy Labs). After storage in distilled water, each tooth specimen was thermocycled in distilled water for 2000 cycles at 5°C and 55°C with a dwell time of 30 seconds at each temperature (Sabri Dental Enterprises). All teeth were then mechanically loaded in a chewing simulator (Sabri Dental Enterprises) to simulate clinical loading. The machine subjected the mounted teeth, still submerged in distilled water, to a cycling force of 10-150 N at a rate of 1 cycle per second (1 Hz) for 100,000 cycles. The force was applied parallel to the occlusal surface via a 12.7-mm-diameter, flat-ended cylindrical piston resting on the cusp tips. Each group (consisting of 10 teeth) was loaded separately from the other groups. The load was verified with a digital force meter (Infinity CS, Cooper Instruments) before each load sequence.

Static fracture loading was initiated subsequent to fatigue loading. The teeth were removed from the water and oriented so that a 6-mm-diameter, round-ended probe applied the load to the center and long axis of the molars; the edges of the probe rested on the occlusal inclines of the buccal and lingual cusps of the natural tooth. Loading was performed in a universal testing machine (Instron) at a crosshead speed of 1 mm/min until the first fracture occurred. The fracture force was recorded in Newtons, and a mean and standard deviation were determined for each group.

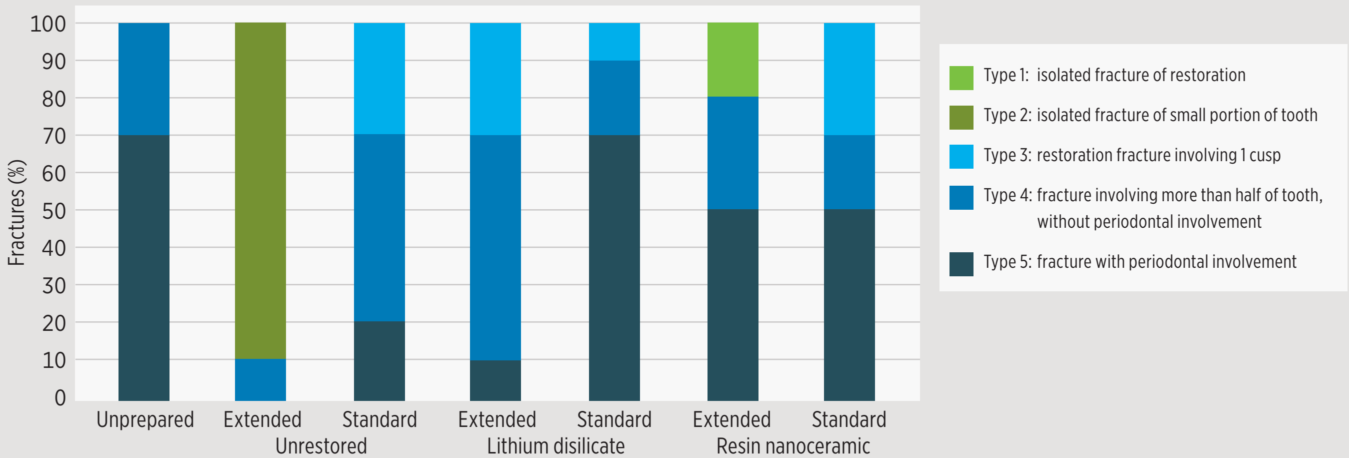
The data were analyzed with a 2-way analysis of variance and Tukey post hoc test to evaluate the effect of preparation type (2 levels) or material/no material (3 levels) on fracture load ($\alpha = 0.05$). The data were also analyzed with the Dunnett test to compare the fracture load of all groups to that of the unprepared control ($\alpha = 0.05$). Unpaired t tests were used to compare differences between extended and standard preparations and between material types in the restored groups ($\alpha = 0.05$).

The fracture mode of each specimen was analyzed visually and categorized according to the following criteria, modified from those used by Burke et al: type 1, isolated fracture of the restoration; type 2, isolated fracture of a small portion of the tooth; type 3, restoration fracture involving 1 cusp; type 4, fracture involving more than half of the tooth, without periodontal involvement; and type 5, fracture with periodontal involvement.[16]

Results

The mean fracture loads are reported in the Table. The extended preparations resulted in significantly lower fracture loads than the standard preparations ($P < 0.05$) in both material groups as well as in the unrestored groups. In addition, when the lithium disilicate and resin nanoceramic preparation groups were combined, the mean (SD) fracture load was 2642.4 (479.4) N in the

Chart. Fracture modes of lithium disilicate and resin nanoceramic CAD/CAM restorations (n = 10 per group).



Abbreviation: CAD/CAM, computer-aided design/computer-aided manufacturing.

extended preparations and 3376.6 (817.9) N in the standard preparations ($P < 0.05$). The unrestored teeth had significantly lower mean fracture loads than the restored teeth ($P < 0.05$), which were not significantly different from each other ($P = 0.623$). Fracture loads in all groups were significantly less than those in the unprepared group ($P < 0.007$).

The mode of fracture of the specimens for each material is presented in the Chart. In general, all of the restored teeth had a large number of type 4 or 5 fractures (fracture of more than half the tooth and fracture involving the periodontium, respectively). Among the restored teeth, the extended preparations restored with IPS e.max CAD lithium disilicate inlays had the fewest type 5 (catastrophic) failures. Overall, the restored standard preparation groups demonstrated a greater number of unfavorable fractures than did the restored extended preparation groups. The unrestored extended preparation group (negative control group 2) demonstrated the most favorable fracture mode. The positive control group (unprepared teeth) demonstrated the greatest number of catastrophic, nonrestorable fractures (type 5).

Discussion

The purpose of this in vitro study was to evaluate the fracture resistance of teeth with or without extended tooth preparations after they were restored with lithium disilicate or resin nanoceramic inlays. The first null hypothesis, based on the preparation type, was rejected. There was a statistically significant difference in fracture load based on preparation type. Extended preparations with reduced cuspal thickness resulted in significantly lower fracture loads than did standard preparations for each of the material groups separately as well as for unrestored groups. In addition, when the material groups were combined, the mean (SD) fracture load was 2642.4 (479.4) N for the restored extended preparations and 3376.6 (817.9) N for the restored standard preparations ($P < 0.05$). Furthermore, the mean fracture load in each of the preparation groups was significantly less than that of the unprepared group, which demonstrated a mean (SD) fracture load of 4475.3 (797.4) N ($P < 0.007$), so the third null hypothesis was also rejected.

These findings were consistent with results reported by Mehl et al, who found a significant reduction in the fracture loads of feldspathic ceramic and composite inlays in teeth with extended preparations.[15] However, the results of the present study contradicted the findings of Morimoto et al, who reported that the fracture load of teeth restored with ceramic inlays was similar to that of intact teeth.[17] However, their study involved only 1 material (feldspathic porcelain) and only 1 type of inlay preparation, defined as an isthmus width of half of the intercuspal distance. Overall, the findings of the present study suggest that the evaluated restorative materials reinforce teeth but to a far lesser extent if cuspal thickness is extensively reduced.

This study failed to reject the second null hypothesis, based on type of restorative material. The type of material did not affect the fracture load, despite the fact that 2 very different materials with very different properties were used. As stated previously, lithium disilicate has a reported flexural strength as high as 500 MPa compared to a reported value of 204 MPa for the resin nanoceramic.[6,9] Conversely, the resin nanoceramic material has a much lower modulus of elasticity (12.8 GPa) than lithium disilicate (95 GPa).[7,9] Compared to lithium disilicate, the resin nanoceramic material used in this study is more similar to human dentin in terms of flexibility under function, which may help compensate for the lower flexural strength. Moreover, the design of this study and the design of other fracture studies in teeth ultimately test the physical properties of not just the materials in question but the teeth as well. Thermal and mechanical loading of the restored tooth creates a more dynamic process than simple physical property tests of the materials. For example, the 6-mm-diameter, round-ended probe engaged the natural tooth structure on the occlusal inclines of the buccal and lingual cusps, perhaps allowing the lower modulus resin nanoceramic material to flex with the tooth prior to fracture of the tooth and/or restoration.

Some general observations can be made concerning fracture modes. The unrestored extended preparations had the most favorable fractures. Without the bonded restorative material, the extended preparations withstood a significantly lower fracture load but exhibited a more favorable fracture mode. Conversely, the unprepared teeth required the greatest amount of force to fracture but displayed the most catastrophic type of fracture, involving the periodontium. In general, the force applied to the tooth structure resulted in less favorable fracture modes in the restored extended preparation groups than in the unrestored extended preparation group but better failure modes than in the restored standard preparation groups. The extended preparations restored with IPS e.max CAD had the fewest catastrophic fractures but achieved the lowest fracture load of the restored groups. However, the fracture loads reported in this study are well above the forces that normally occur in the oral cavity. The mean force during mastication reported in humans is approximately 40 N, while the average maximum posterior masticatory force varies from 200 to 540 N.[18]

Static fracture tests may screen for the durability of restorative materials. Repeated stresses of cyclic loading can predispose restorations to fail under fatigue. The present study subjected the specimens to thermal (2000 cycles) and mechanical (100,000 cycles) loading before application of a static load. Studies demonstrate that mean fracture resistance decreases significantly when the number of cycles exceeds 1 million. However, fatigue loading decreases the load to failure, regardless of the number of cycles.[19]

The purpose of this study was to evaluate anecdotal claims that CAD/CAM restorations reinforce teeth with wide preparations and reduced cuspal thickness. Few in vitro studies and, to the authors' knowledge, no in vivo studies have addressed this practice. Additional research should evaluate additional preparation designs, such as inlay preparations with further extended preparations, along with other types of CAD/CAM restorative material (eg, leucite-reinforced, polycrystalline ceramics). A limitation of the present study is that the force was only applied along the long axis of the tooth.

The results of this study suggest that bonded CAD/CAM restorations reinforce tooth structure compared to unrestored prepared teeth. However, the effectiveness of this reinforcement decreases as the remaining cusp width decreases. Although extended preparations demonstrated more favorable fracture modes, standard preparations achieved significantly higher loads to failure. Practitioners should consider covering the cusps with a CAD/CAM restorative material to reduce the potential for fracture in teeth with reduced cuspal thickness, especially in patients with heavier occlusion or functional loads.

Conclusion

Within the limitations of this study, the results confirmed that the type of CAD/CAM restorative material did not significantly affect the fracture load. However, although bonded CAD/CAM restorations reinforced the tooth structure, the load to fracture was significantly lower in teeth that had extended preparations.

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References

1. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. *Dent Clin North Am.* 2011;55(3):559-570.
2. Fasbinder DJ, Neiva G, Robbins JW. Esthetic inlays and onlays. In: Hilton TJ, Ferracane JL, Broome JC (eds). *Summitt's Fundamentals of Operative Dentistry: A Contemporary Approach*. 4th ed. Hanover Park, IL: Quintessence Publishing; 2013:501-523.
3. Beuer F, Naumann M, Gernet W, Sorensen JA. Precision of fit: zirconia three-unit fixed dental prostheses. *Clin Oral Investig*. 2009;13(3):343-349.
4. Tinschert J, Zwez D, Marx R, Anusavice KJ. Structural reliability of alumina-, feldspar-, leucite, mica-, and zirconia-based ceramics. *J Dent.* 2000;28(7):529-535.
5. Fasbinder DJ, Neiva GF, Dennison JB, Heys DR. Clinical performance of CAD/CAM-generated composite inlays after 10 years. *J Cosmetic Dent*. 2013;28(4):134-145.
6. Ivoclar Vivadent. *IPS e.max CAD/IPS e.max Press. Adhesive 1 mm Crown* [product information]. November 14, 2016. https://www.ivoclarvivadent.com/zoolu-website/media/document/38982/IPS+e-max+CAD-IPS+e-max+Press+-+Adhesive+1mm+crown. Accessed April 3, 2018.
7. Ivoclar Vivadent. *IPS e.max CAD* [scientific documentation]. March 2011. http://www.ivoclarvivadent.com/zoolu-website/media/document/9793/IPS+e-max+CAD. Accessed April 3, 2018.
8. Lien W, Roberts HW, Platt JA, Vandewalle KS, Hill TJ, Chu TM. Microstructural evolution and physical behavior of a lithium disilicate glass-ceramic. *Dent Mater*. 2015;31(8):928-940.
9. 3M ESPE. *Lava Ultimate* [technical product profile]. 2011. http://www.d-way.cz/data/product/13/23/files/Lava_Ult_TPP.pdf. Accessed April 3, 2018.
10. Plotino G, Grande NM, Bedini R, Pameijer CH, Somma F. Flexural properties of endodontic posts and human root dentin. *Dent Mater*. 2007;23(9):1129-1135.
11. Poticny DJ, Klim J. CAD/CAM in-office technology: innovations after 25 years for predictable, esthetic outcomes. *J Am Dent Assoc*. 2010;141(Suppl 2):5S-9S.
12. Hickel R, Manhart J. Longevity of restorations in posterior teeth and reasons for failure. *J Adhes Dent*. 2001;3(1):45-64.
13. Thordrup M, Isidor F, Hörsted-Bindslev P. A 5-year clinical study of indirect and direct resin composite and ceramic inlays. *Quintessence Int.* 2001;32(3):199-205.
14. Otto T, Schneider D. Long-term clinical results of chairside CEREC CAD/CAM inlays and onlays: a case series. *Int J Prosthodont.* 2008;21(1):53-59.
15. Mehl A, Kunzelmann KH, Folwaczny M, Hickel R. Stabilization effects of CAD/CAM ceramic restorations in extended MOD cavities. *J Adhes Dent*. 2004;6(3):239-245.
16. Burke FJ, Wilson NH, Watts DC. The effect of cavity wall taper on fracture resistance of teeth restored with resin composite inlays. *Oper Dent.* 1993;18(6):230-236.
17. Morimoto S, Vieira GF, Agra CM, Sesma N, Gil C. Fracture strength of teeth restored with ceramic inlays and overlays. *Braz Dent J.* 2009;20(2):143-148.
18. Jung YG, Peterson IM, Kim DK, Lawn BR. Lifetime limiting strength degradation from contact fatigue in dental ceramics. *J Dent Res*. 2000;79(2):722-731.
19. Coray R, Zeltner M, Ozcan M. Fracture strength of implant abutments after fatigue testing: a systematic review and meta-analysis. *J Mech Behav Biomed Mater*. 2016;62:333-346.