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Evaluation of Fracture Resistance in Aqueous Environment of Four Restorative Systems for Posterior Applications. Part 1

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Keywords
Ceramic; fracture resistance; lithium disilicate; posterior crown; press-on metal; thin zirconia core.

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This study was funded in part by the Greater New York Academy of Prosthodontics Research grant.

The authors deny any conflicts of interest.

Accepted August 26, 2012

doi: 10.1111/j.1532-849X.2012.00948.x

Abstract

Purpose: The goals of this study were to: (1) establish a range of the performance of four restorative systems for posterior single-tooth crowns under single load to fracture submerged in an aqueous environment, (2) identify restorative system(s) of interest to be examined in the second study phase under sliding contact step-stress fatigue as full-contour anatomically appropriate single posterior tooth restoration(s), (3) establish a range for loading/testing for phase 2.
Materials and Methods: Forty specimens (n = 10/group) of 2 mm uniform thickness were tested. Group 1: monolithic lithium disilicate IPS e.max Press; group 2: IPS e.max ZirPress, 0.8 mm zirconia core with 1.2 mm pressed veneering porcelain; group 3: IPS e.max ZirPress, 0.4 mm zirconia core with 1.6 mm pressed veneering porcelain; group 4: IPS InLine PoM. Specimens were bonded to a block of polycast acrylic resin on a 30° sloped surface with resin cement. Specimens were axially single loaded to failure while submerged under water.
Results: There was a statistically significant difference ($p < 0.001$) in failure load among the four restorative systems. Lithium disilicate showed a mean failure load similar to mean maximum posterior bite forces (743.1 ± 114.3 N). IPS e.max Zirpress with a 0.4 mm zirconia core exhibited the lowest mean failure load (371.4 ± 123.0 N).
Conclusion: Fracture resistance of monolithic lithium disilicate in an aqueous environment is promising and requires second phase testing to evaluate the potential of various thicknesses appropriate for posterior single tooth applications. Doubling the IPS e.max Zirpress zirconia core from 0.4 mm to 0.8 mm increased the fracture resistance of this restorative system threefold.

Despite numerous all-ceramic and metal ceramic systems presently available, there is not a universally applicable material for all single-tooth restorations. Evaluation of the use of different restorative systems for single posterior teeth includes consideration of the properties of available materials. The strength of all-ceramic restorations is not only dependent on the type of ceramic material used, but also on several other factors including the core-veneer strength, crown thickness, cementation method, and restoration design.[1-5] Quite a wide range of mean maximum masticatory forces (216–847 N) has been reported, with suggestions that restorations for posterior teeth bear a mean load of 500 N.[6-9]

Current technology and scanning capabilities allow for fabrication of full-coverage single restorations for posterior teeth with various restorative systems and designs. These include ceramic materials with or without a porcelain veneering layer and a polycrystalline or metal substructure with a veneering layer (pressed or manually layered). Fracture and delamination in the porcelain veneering layer has been shown to be the most common mode of failure in layered restorations.[5,10,11] Monolithic full-coverage restorations have demonstrated higher in vitro fracture loads when compared to hand-layered porcelain-veneered restorations with a zirconia or metal core.[12] In vitro studies have also shown significantly higher failure loads under mouth motion fatigue for metal ceramic crowns than hand layered porcelain veneered crowns with a zirconia core.[13] In vitro performance of monolithic 1.0 mm and 2.0 mm lithium disilicate crowns has also shown significantly higher failure loads than veneered zirconia restorations under sliding-contact step-stress fatigue.[14]

Fracture loads in wet in vitro testing are more applicable to clinical conditions and show significantly smaller loads required to fracture the material than dry environment testing.[15] These differences in failure modes and loads seen in laboratory and clinical conditions with ceramic materials often make it challenging to correlate in vitro and clinical findings. Despite this, the laboratory environment aids in assessing the potential of these materials for clinical applications. Some of the recommendations made to allow for a better correlation between laboratory and clinical behavior of ceramic materials include testing in a wet environment, a simulated dentin material with similar or higher elastic modulus, a wide diameter ball indenter, and use of standard luting cements.[16,17]

In this multi-part study, an in vitro and a clinical evaluation of various restorative systems for single-tooth posterior applications were undertaken. The laboratory-based assessment consisted of two phases that: (1) gave a range of failure loads for different ceramic systems and (2) varied design of the most load-resistant system. The clinical evaluation focused on the clinical survival of various ceramic restorations for posterior teeth that have been in service for a minimum of 5 years at the Mayo Clinic (Rochester, MN).

Part one of the in vitro study is presented here. The findings of part two and the clinical assessment follow in separate manuscripts. The hypothesis of part one of the study was that there is no difference in resistance to fracture between layered and monolithic restorative systems for single-tooth posterior applications. The goals of part one of the study were to (1) establish a range of the performance of monolithic lithium disilicate, a 0.4-mm zirconia core with pressed veneering layer, 0.8 mm zirconia core with pressed veneering layer, and press-on-metal, all with a uniform thickness of 2 mm under single load to fracture while submerged in a wet environment; (2) identify behavior of the most load-resistant system in the second study phase under sliding contact step-stress fatigue. This was explored as full contour anatomically appropriate single posterior tooth restoration(s) with different tooth preparation reductions (0.8 mm, 1.0 mm, 1.5 mm, 2.0 mm); (3) establish a range for loading/testing for phase 2.

Materials and methods

Four restorative systems with a 2-mm uniform thickness were selected. Forty square wafer specimens were tested. Each group contained 10 specimens:

Group 1: monolithic lithium disilicate (IPS e.max Press; Ivoclar Vivadent, Amherst, NY);
Group 2: zirconia core (0.8 mm thick) with pressed veneering porcelain (IPS e.max ZirPress);
Group 3: zirconia core (0.4 mm thick) with pressed veneering porcelain (IPS e.max ZirPress);
Group 4: press-on-metal with a metal core of 0.8 mm with pressed veneering porcelain (IPS InLine PoM; Ivoclar Vivadent).

Forty specimen-supporting blocks were fabricated with the same machined design. Each block was designed as a $1.0 \times 1.0 \times 1.0$ cm^3 polycast acrylic resin block (Spartech Ind. Clayton, MO). Each specimen-supporting block was machine milled (Fig 1) to an occlusal surface with a 30° slope. Using a drill press milling machine (Frasgerat F1, GB Dental, Degussa, Hanau, Germany), two 2.0-mm deep grooves were machine milled at opposite corners of each block to allow for securing of the specimens to avoid rotational movement during testing on the sloped surface.

The restorative testing specimens were fabricated as follows. Monolithic lithium disilicate specimens were fabricated indirectly by waxing a 2.0-mm uniformly thick specimen to conform to the sloped surface of the blocks. Consistent thickness of all specimens was confirmed with an electronic digital caliper. Wax patterns were then invested and pressed (Programat EP-5000, Ivoclar) with IPS e.max Press LT ingots (Ivoclar Vivadent, Amherst, NY) following manufacturer's recommendations. The intaglio surface of group 1 specimens was etched with 5% hydrofluoric acid (IPS ceramic hydrofluoric acid, Ivoclar Vivadent) for 20 seconds, rinsed with deionized water for 60 seconds, and force air dried.

Groups 2 and 3 consisted of IPS e.max ZirPress specimens with a 0.8-mm zirconia core for group 2 and a 0.4 mm zirconia core for group 3. Specimens were fabricated by first scanning the sloped surface of the block (Nobel Procera, Nobel Biocare, Yorba Linda, CA). The computer design obtained from the scanning was used for milling of the zirconia cores for group 2. Multiple attempts at scanning the sloped surface of the block for group 3 specimens resulted in specimens that did not have a uniform thickness of 0.4 mm and did not replicate the required 2 mm extensions of the specimens for proper orientation on the blocks. As a result, group 3 zirconia core specimens of 0.4 mm were milled by scanning a 0.4 mm wax pattern waxed to conform to the sloped surface. Thickness were verified with an electronic digital caliper. Zirliner (Ivoclar Vivadent) was applied to specimens following manufacturer's recommendations. The corresponding veneering layer for the zirconia cores in groups 2 and 3 was fabricated indirectly by waxing the pattern for the veneering layer on each zirconia core and Zirliner to a total individual specimen thickness of 2 mm. Thicknesses of zirconia cores, veneering layer wax pattern, and completed specimens were confirmed with an electronic digital caliper. Each specimen of groups 2 and 3 consisting of the zirconia core (group 2: 0.8 mm, group 3: 0.4 mm), Zirliner, and wax pattern for corresponding veneering layer (group 2: 1.2 mm, group 3: 1.6 mm) were invested and pressed (Programat EP-5000) using IPS e.max ZirPress (nanofluorapatite) ingots following manufacturer's recommendations. Group 4 press-on-metal IPS

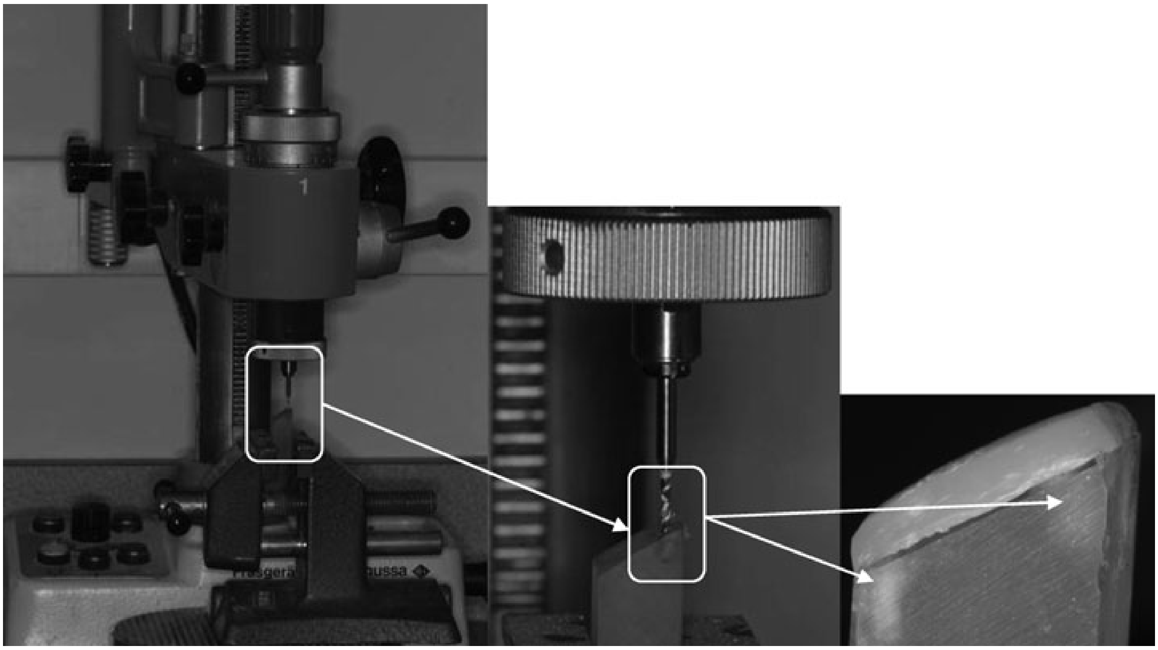

Figure 1 Machine milling of specimen-supporting blocks to fabricate a 1.0 × 1.0 × 1.0 cm^3, a 30° slope of the occlusal surface, and two grooves 2.0 mm deep at opposite corners for securing specimens to avoid rotational movement during testing.

InLine PoM specimens were fabricated indirectly by waxing a 0.8 mm uniform thickness specimen to conform to the sloped occlusal surface. The metal core was fabricated by the lost-wax technique as the substructure following manufacturer's recommendations (Collegiate, Jelenko, Armonk, NY). Three layers of opaquer (Ivoclar Vivadent) were applied to each specimen. The corresponding veneering layer was fabricated indirectly by waxing the pattern to a total uniform specimen thickness of 2.0 mm. Metal core thickness, veneering layer wax pattern, and completed specimens were confirmed with an electronic digital caliper. Each press-on-metal specimen for group 4 with the metal core, opaquer, and corresponding wax pattern was invested and pressed (Programat EP-5000) using IPS InLine PoM ingots and following manufacturer's recommendations.

All 40 specimens were bonded to the supporting blocks with resin cement (RelyX, 3M ESPE, St. Paul, MN) with constant force and light polymerization (Translux PowerBlue, Heraeus Kulzer, Hanau, Germany) using four 60-second intervals around each block surface. Specimens were then stored at room temperature in deionized water for 64 days prior to testing.

All specimens were completely submerged in deionized water during testing (Fig 2). All specimens were axially loaded under water to failure in the middle of the 30° sloped surface with a stainless steel ball of 4.25 mm diameter (MTS Mini-Bionix, MTS Corp., Eden Prairie, MN) with 50 N/sec delivered until catastrophic failure was detected acoustically, together with in-time load data (MPT Software, MTS Corp.).

Failure loads were summarized with means, standard deviation (SD), minimum, 25th percentile, median, 75th percentile, and maximum values. Pairwise comparisons were applied to assess differences among groups. Statistical significance was set at $\alpha = 0.05$.

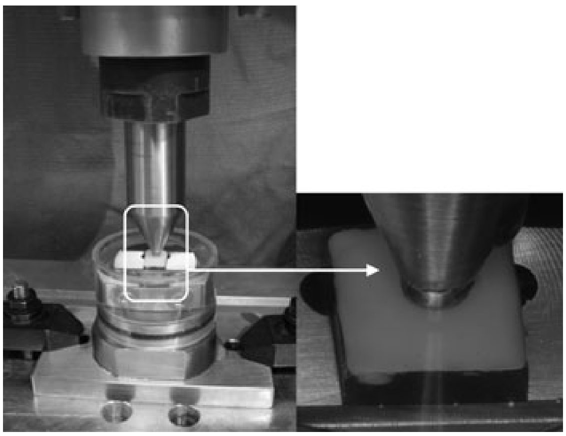

Figure 2 Testing unit with specimens completely submerged in water during testing.

Results

Failure loads for each of the four groups are summarized in Table 1. Press-on-Metal IPS InLine PoM specimens exhibited the highest mean failure load. IPS e.max ZirPress with a zirconia core of 0.4 mm showed the lowest mean failure load. Doubling of the IPS e.max ZirPress zirconia core from 0.4 mm (group 3) to 0.8 mm (group 2) resulted in a threefold increase in mean failure load.

Overall, there was a statistically significant difference in failure load among the four groups ($p < 0.001$; Kruskal-Wallis test). Wilcoxon rank sum tests for pairwise comparisons showed a statistically significant difference in failure loads between all

Table 1 Single load-to-failure characteristics

Restorative systems	Failure loads Mean + SD (minimum, median, maximum) (N)
Group 1. Monolithic lithium disilicate IPS e.max Press	743.1 ± 114.3 (536, 785.5, 861)
Group 2. 0.8 mm zirconia core IPS e.max ZirPress	1106.9 ± 296.5 (716, 1101.5, 1381)
Group 3. 0.4 mm zirconia core IPS e.max ZirPress	371.4 ± 123.0 (232, 355.5, 665)
Group 4. Press-on-metal IPS InLine PoM	3207.1 ± 450.9 (2628, 3079.5, 4021)

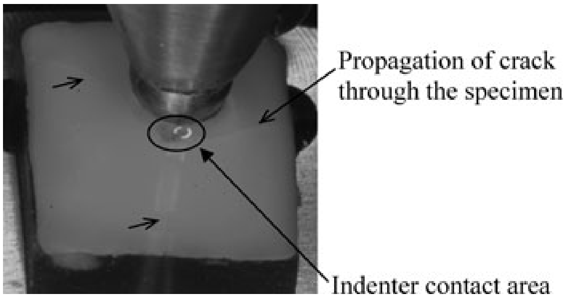

Figure 3 Monolithic lithium disilicate specimen demonstrating Hertzian cracks as the mode of failure. In addition to the characteristic concentric Hertzian crack pattern surrounding the contact zone, the sloped surface of the specimens allows observation of a more radial crack propagation pattern due to the introduction of tangential forces resulting from the sloped surface of the specimens.

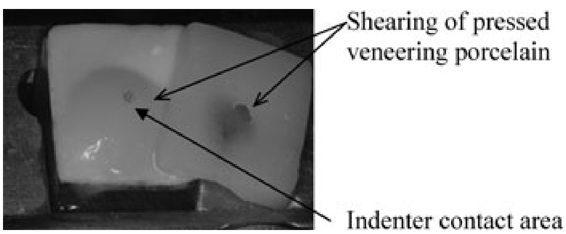

Figure 4 Shearing of the veneering pressed porcelain layer and adhesive failure of a zirconia core specimen with pressed veneering porcelain layer (Zirpress® specimen failure).

possible two-group comparisons ($p < 0.001$ for all comparisons except comparison of group 1 and group 3 where $p = 0.006$).

In the monolithic lithium disilicate group, Hertzian cracks were the characteristic mode of failure (Fig 3). The characteristic failure mode of the IPS e.max Zirpress specimens was shearing of the pressed veneering layer (Fig 4). The failure mode of the press-on-metal specimens was characterized by adhesive failures (Fig 5). Due to the small range and standard deviation of results, monolithic lithium disilicate was identified as the restorative system of interest to be examined in the second study phase under sliding contact step-stress fatigue as a full-contour anatomically appropriate single posterior tooth restoration.

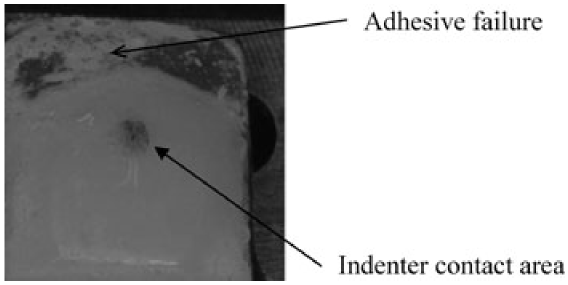

Figure 5 Adhesive failure of the press-on-metal specimens.

Discussion

The hypothesis that there is no difference in resistance to fracture between layered and monolithic restorative systems for single-tooth posterior applications was rejected. Storage of specimens in deionized water for 64 days has several implications on the study's findings. It has been shown that whether testing statically or dynamically, the presence of water enhances degradation of ceramics.[16] Testing in a wet environment has also been recommended as a standard for testing ceramics in the laboratory because its ability to degrade ceramics closely mimics the oral environment.[15] In the present study, testing of ceramics in water not only resulted in lower mean failure forces than those reported for dry testing, the failure modes also more closely resembled failures seen clinically.

The mean static failure load of the monolithic lithium disilicate material in this study was 743.1 ± 114.3 N, which is lower than other reported values in the literature.[1,12] Despite this result, the mean failure load of monolithic lithium disilicate was still greater than average posterior masticatory forces (150–340 N).[9] When comparing these findings with previous ones, the laboratory study designs vary considerably, especially when it comes to the dry or wet testing environment. This is an important factor to consider. It also makes it difficult to extrapolate to other study findings. A consensus on standardizing basic laboratory design parameters such as testing in a wet environment, step-stress fatigue, and fractography interpretation is beneficial for future testing, along with comparison of data and correlation with clinical findings.

The failure loads of the press-on-metal IPS InLine PoM exhibited very high mean failure loads (3207.1 ± 450.9 N). It is difficult to establish a clinical correlation of this finding, as the metallic cores of most restorations have complex geometries and are not typically thick. This is also consistent with well documented literature that clinical failure of metal ceramic restorations is mostly associated with biological failures (caries/necrotic pulp) rather than mechanical/technical failures.[9] Certainly, metal ceramic restorations continue to be the gold standard in comparison to contemporary ceramic restorative materials. But, with recent developments in scanning and milling technology, application of ceramic restorative systems for single teeth are becoming easier, faster, more accurate, and more esthetic than metal ceramic restorations.

A threefold increase in the failure load noted when the IPS Zirpress core thickness doubled from 0.4 mm to 0.8 mm suggests that a 0.4-mm core for this restorative system may be unpredictable for posterior single-tooth restorations. This is further supported by a mean failure load for the 0.4-mm zirconia core of 371.4 N, which is below the reported average 500 N of posterior masticatory forces. Further investigation of anatomically appropriate specimens of the IPS Zirpress specimens showed a mean failure load of the 0.8-mm zirconia core specimens to be higher than average posterior masticatory forces. This finding is consistent with other reports of high failure loads associated with zirconia cores.[13] Scanning of the wax pattern instead of the supporting blocks (done for the 0.8-mm zirconia core specimens) for the 0.4-mm zirconia core specimens did not have any bearing on the study findings since (1) this method allowed for consistency among the specimens fabricated and (2) allowed for uniform thickness of the 0.4-mm specimens and replicated the required 2 mm extensions of the specimens for proper orientation on the supporting blocks. This method of specimen fabrication for the 0.4-mm zirconia core group was applied once it was identified that scanning of the supporting blocks did not allow for uniform thickness of the specimens and did not replicate the required extensions.

In this study, monolithic lithium disilicate IPS e.max Press of a 2-mm uniform thickness showed a mean failure load of 743.1 N, which is within the range if not above the reported mean maximum masticatory forces.[7–9] This finding makes monolithic lithium disilicate of increased interest since fabrication is more simplistic and potentially more resistant to failure fatigue than layered zirconia restorations.

The specimens in this group exhibited failure loads close to reported mean posterior masticatory forces.[9] The clinical dilemma faced in the everyday practice is whether the strongest available restorative system and design is appropriate. Consideration of a margin of safety in the restorative system and design may be more clinically appropriate due to unclear force requirements and our inability to control force applications by patients.

Lithium disilicate has been popularly chosen for its simplicity of production, esthetic potential, and high resistance to fracture. Although tooth reduction guidelines have been established for its use, these are empiric, and varying thicknesses of this bonded material have not been shown to behave differently. This prompted a further phase of study to best facilitate the use of this material while conserving tooth structure. Based on the lithium disilicate sample standard deviation (114.3), and statistical significance set at 0.05, appropriate specimen size to detect differences among four restoration thicknesses was determined to be 40 with 10 specimens per group.

Conclusions

(1) Fracture resistance of monolithic lithium disilicate while submerged in a wet environment appears promising and prompts second-phase testing to evaluate the potential of various thicknesses appropriate for posterior single-tooth applications.

(2) Doubling the IPS e.max Zirpress zirconia core from 0.4 mm to 0.8 mm increases the fracture resistance of this restorative system threefold.

Acknowledgments

The authors would like to acknowledge the Mayo Clinic Biomechanics Laboratory.

References

1. Tinschert J, Schulze KA, Natt G, et al: Clinical behavior of zirconia-based fixed partial dentures made of DC-Zirkon: 3-year results. Int J Prosthodont 2008;21:217-222
2. Jalalian E, Atashkar B, Rostami R: The effect of preparation design on the fracture resistance of zirconia crown copings (computer associated design/computer associated machine, CAD/CAM system). J Dent 2011;8:123-129
3. Pallis K, Griggs JA, Woody RD, et al: Fracture resistance of three all-ceramic restorative systems for posterior applications. J Prosthet Dent 2004;91:561-569
4. Bindl A, Luthy H, Mormann WH: Thin-wall ceramic CAD/CAM crown copings: strength and fracture pattern. J Oral Rehabil 2006;33:520-528
5. Guess PC, Zavanelli RA, Silva NR, et al: Monolithic CAD/CAM lithium disilicate versus veneered Y-TZP crowns: comparison of failure modes and reliability after fatigue. Int J Prosthodont 2010;23:434-442
6. Linderholm H, Wennstrom A: Isometric bite force and its relation to general muscle forge and body build. Acta Odontol Scand 1970;28:679-689
7. Waltimo A, Kononen M: A novel bite force recorder and maximal isometric bite force values for healthy young adults. Scand J Dent Res 1993;101:171-175
8. Ringqvist M: Isometric bite force and its relation to dimensions of the facial skeleton. Acta Odontol Scand 1973;31:35-42
9. Korber KH, Ludwig K, Dunner P. [Experimental studies of the abrasion effect between dental enamel and dental ceramic]. Deutsche Zahnarztl Z 1984;39:2-11
10. Sailer I, Gottnerb J, Kanelb S, et al: 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
11. Silva NR, Bonfante EA, Rafferty BT, et al: Modified Y-TZP core design improves all-ceramic crown reliability. J Dent Res 2011;90:104-108
12. Silva NRFA, Thompson V, Valverde GB, et al: Comparative reliability analyses of zirconium oxide and lithium disilicate restorations in vitro and in vivo. J Am Dent Assoc 2011;142: 4S-9S
13. Silva NR, Bonfante EA, Zavanelli RA, et al: Reliability of metalloceramic and zirconia-based ceramic crowns. J Dent Res 2010;89:1051-1056
14. Silva NR, Bonfante EA, Martins LM, et al: Reliability of reduced-thickness and thinly veneered lithium disilicate crowns. J Dent Res 2012;91:305-310