CAD/CAM lithium disilicate ceramic crowns: Effect of occlusal thickness on fracture resistance and fractographic analysis

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This study uses fracture tests and fractographical analysis to compare computer-aided design and computer-aided manufacturing (CAD/CAM) lithium disilicate molar crowns with the previous occlusal thickness recommendation of 1.5-mm, the new recommendation of 1.0-mm, and a less invasive thickness of 0.8-mm. After fatigue application, fracture tests and fractographic analysis were conducted. The fracture resistance of CAD/CAM lithium disilicate molar crowns was different depending on the occlusal thickness of the restoration, and decreased with lower the thickness. However, the fracture resistance of crowns of all three thicknesses exceeded the reported maximum bite force in the first molar region after the fatigue process, and can be considered acceptable for use in the clinic.

Keywords: Dental prosthesis, Dental restoration failure, Dental stress analysis, Bite force

INTRODUCTION

The development of chairside computer-aided design and computer-aided manufacture (CAD/CAM) technology has provided clinicians with the opportunity to fabricate final restorations in single appointments1. Instruction in chairside CAD/CAM restorations become established in most of US dental school in the 2010s, and the restorations have become a common treatment option in public and private settings providing dental care2. This technology is popular because it does not require traditional technique sensitive laboratory procedures or shipping of the restoration, and it improves the patient’s comfort3.

Although, nowadays, many kinds of CAD/CAM materials are available on the market, lithium disilicate ceramic block has become very popular choice for the fabrication of onlays and crowns4. Lithium disilicate ceramic blocks have proven to have greater fracture toughness than leucite reinforced ceramic and resin composite blocks, combined with good esthetic properties5. In addition, a systematic review has shown that survival rates of all ceramic posterior crowns are excellent and similar to metal ceramic restorations6. Furthermore, a previous study demonstrated that monolithic CAD/CAM lithium disilicate crowns have better fracture resistance when compared to veneered zirconia crowns7.

IPS e.max CAD (Ivoclar Vivadent, Sheaan, Liechtenstein) was the first CAD/CAM lithium disilicate ceramic blocks on the market, launched in 20068. A minimal thickness of 1.5-mm for occlusal surface and width of the shoulder/chamfer of at least 1.0-mm for molar crown was initially recommended. This recommendation was maintained until mid 2017 when the company has decided to modify the occlusal thickness but maintain the chamfer width; the new recommendation is 1.0-mm for occlusal thickness of posterior crowns. Unfortunately, no independent data was provided by the company in order to justify the reduction of the occlusal thickness recommendation. Therefore, the objective of this study was to compare the fracture resistance and fractographical analysis of CAD/CAM lithium disilicate molar crowns with the previous recommendation thickness of 1.5-mm, the recent thickness recommendation of 1.0-mm and a lower thickness 0.8-mm as a less-invasive possibility. The null hypothesis was that there would be no difference in the fracture resistance measured by load at crack initiation, load for complete fracture and time for crack propagation, of CAD/CAM lithium disilicate crowns for mandibular first molars with different thicknesses.

MATERIALS AND METHODS

Study design of fracture resistance test
A manufacturer provided three typodont teeth based on tooth #46 (1560 Dentoform, Columbia Dentoform,
Lancaster, PA, USA) with 1.5-, 1.0- and 0.8-mm occlusal clearance, and detail designs were indicated (Fig. 1). The three teeth were imaged with a CEREC system (Primescan, Dentsply Sirona, Charlotte, NC, USA) and built-in software (CEREC SW 5.1, Dentsply Sirona) to create patterns for the restorations. Thirty CAD/CAM lithium disilicate crowns were milled out (MCXL, Dentsply Sirona), 10 for each of the three different occlusal thicknesses of the restorations: 1.5-, 1.0- and 0.8-mm. Milled crowns were crystalized and finished with glazing and sintering under the manufacturer's recommendations. An in-lab scan system (Degree of Freedom HD, DOF, Seoul, Korea) was used to scan the three typodont teeth and to digitally design dies matching the preparations. Thirty dies were printed out of resin for model (Model Resin, FormLabs, Somerville, MA, USA), with an in-lab 3D printer (FormLabs 3, FormLabs). The crowns were treated following the manufacturer's recommendation: 1) hydrofluoric acid etching (IPS Ceramic Etching Gel, Ivoclar Vivadent) for 20 s, 2) rinsing with water for 20 s and 3) primer application (Monobond Plus, Ivoclar Vivadent) for 60 s. All the crowns were seated to printed dies with conventional resin luting cement (Multilink Automix, Ivoclar Vivadent) and photo-cured (Elipar 2500, 3M Oral Care, St. Paul, MN, USA) from 5 different angles for 20 s. All the bonded specimens were immersed in 37°C distilled water for 24 h.

Prepared crowns were subjected to cycling load in 23°C distilled water using 5 million cycles at 1 Hz with 275 N force (Fig. 2). All the specimens were fixed within a steel jig and exposed the fatigue loading force beside a polyoxymethylene ball (Delrin 6.28 mm, Dupont, Wilmington, DE, USA) that simulated the mastication cycles to the restorations. After the fatigue process, the crowns were evaluated and any that had already fractured to an extent that made it impossible to perform fracture tests were discarded. The surviving crowns were fixed on a jig and then exposed to compressive loading force until fracture in a universal testing machine (Instron 4204, Norwood, MA, USA). In the fracture test, the load at crack initiation, load for complete fracture and time for crack propagation were recorded.

Fractographic analysis
Fractographic analysis of fractured specimen of each the crowns on the 3D printed teeth were conducted with tabletop scanning electron microscope (TM3000, Hitachi-High Technology, Tokyo, USA). The fractured surfaces of the crowns were treated using sputter coater with gold-palladium alloys (Emitech SC7620 Mini Sputter Coater, Quorum Technologies, East Sussex, UK) and were observed using an accelerating voltage at 10 kV.

Statistical analyses
The number of crowns used was determined using G* Power Data Analysis (https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.html). The results suggested that a total of 30 were required for the investigations.

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Independent-Sample Kruskal-Wallis test was carried out using a statistical system (SPSS Statistics 25, IBM, Armonk, NY, USA) to analyze the gathered data for the influence of crown thickness ($\alpha=0.05$).

RESULTS

Fracture resistance

The fracture resistance of the CAD/CAM lithium disilicate crowns with different thickness that survived the fatigue process are shown in Table 1. The survived crowns showed significantly different in load at crack initiation ($p=0.001$), load for complete fracture ($p=0.001$) and time for crack propagation ($p=0.011$), and those are dependent on the thickness of the crown. The crowns that survived the fatigue process showed 1,486.8 N for 1.5-mm, 1,024.6 N for 1.0-mm and 927.4 N for 0.8-mm crowns in the load at crack initiation, and 1,540.2 N for 1.5 mm, 1,162.5 N for 1.0-mm and 980.0 N for 0.8 mm in the load for complete fracture. The load at crack initiation and load for complete fracture of the 0.8-mm crown did not show statistically significant differences from 1.0-mm, unlike the 1.5-mm crowns. The load for complete fracture of the 1.0-mm crowns was statistically similar to the 1.5-mm crowns, but the load at crack initiation showed a significant difference.

The survived crowns showed significantly different in time for crack propagation ($p=0.011$), and it was dependent on the thickness of the crown. The time for crack propagation until fracture was 70.7 ms for 1.5-mm, 55.5 ms for 1.0-mm and 52.1 ms for 0.8 mm crowns in the survived crowns. The elapsed time of the 0.8-mm crown did not show statistically significant differences from 1.0-mm, unlike the 1.5-mm crowns. There elapsed time of the 1.0 mm crowns was statistically similar to the 1.5-mm crowns.

Fractographic analysis

Fractographic images of the crowns on printed teeth are shown in Figs. 3–5. Note that the varying fracture pattern in the crown can obscure the differences between the different thickness. Fracture surfaces of the 0.8- and 1.0-mm crowns and printed teeth were much cleaner, more defined and had fewer cracks vertically and horizontally than 1.5-mm crowns and printed teeth. The defects in crown margin in 1.5-mm crowns was much clearly observed than 0.8- and 1.0-mm crowns.

Fractographic images of lithium disilicate ceramic crown with 1.5-mm occlusal thickness.

Fractographic images of lithium disilicate ceramic crown with 1.0-mm occlusal thickness.

Fractographic images of lithium disilicate ceramic crown with 0.8-mm occlusal thickness.

Table 1 Fracture resistance of the CAD/CAM lithium disilicate crowns with different thickness that survived the fatigue process

<table>
<thead>
<tr>
<th>Occlusal thickness</th>
<th>Number of survived crowns</th>
<th>Load at crack initiation (N)</th>
<th>Load for complete fracture (N)</th>
<th>Time for crack propagation (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-mm crowns</td>
<td>9</td>
<td>1,486.8 (307.5)$^a$</td>
<td>1,540.2 (357.7)$^a$</td>
<td>70.7 (12.8)$^a$</td>
</tr>
<tr>
<td>1.0-mm crowns</td>
<td>8</td>
<td>1,024.6 (90.6)$^b$</td>
<td>1,162.5 (105.8)$^{a,b}$</td>
<td>55.5 (5.0)$^{a,b}$</td>
</tr>
<tr>
<td>0.8-mm crowns</td>
<td>8</td>
<td>927.4 (118.9)$^b$</td>
<td>980.0 (121.0)$^b$</td>
<td>52.1 (7.2)$^b$</td>
</tr>
</tbody>
</table>

Values in parenthesis are standard deviations. The same lowercase letter in the same vertical column indicates no significant difference ($p>0.05$).
DISCUSSION

CAD/CAM lithium disilicate ceramic restorations have become a common option in dentistry, and a recent practice-based study indicated that lithium disilicate ceramic material was the second most common used for single restorations\[^{8}\]. Interestingly, the company has recently changed its guidelines for posterior crown preparation from 1.5-mm thickness to recommend 1.0-mm occlusal thickness for the crowns. Thus, the present study compared the fracture resistance of the previous recommendation of 1.5 mm, the new occlusal thickness recommendation of 1.0 mm, and a less invasive thickness of 0.8 mm. A thickness of 0.8 mm was chosen as this is a standard thickness for tests of dental crowns, and is close enough to the 1.0 mm recommendation to provide useful comparison data.

The choice of 275 N for the fatigue force was based on reported values for maximum biting force. A previous study reported that the maximum bite force measured at the first molar region was 649.6 N for men and 539.4 N for women\[^{10}\]. A different study revealed that a maximum biting force in the first molar region of 777.7 N for men and 481.6 N for women\[^{11}\]. People do not apply maximum biting force every time they chew, so the fatigue force should clearly be lower. In work on the fatigue resistance of dental bonds, the fatigue force that causes bond failure is of the order of half of the static force that does so, which suggests that using a value of half of the maximum force when applying fatigue may be a reasonable approximation to intra-oral conditions.

In this study, the fatigue process was applied to the crown specimens using 5 million cycles. Tsujimoto et al.\[^{12}\] previously indicated that an individual makes around 2,700 mastication cycles per day, which is equal to around 1 million cycles per year. In addition, Ogthiemssak et al.\[^{13}\] reported that 5 million cycles of a fatigue process simulate 5 years of clinical service, thus at least 5 years of clinical service can be considered to be simulated with this fatigue process. A period of 5 years was chosen because ceramic crowns are expected to survive for at least 10 to 15 years. Thus, if the crowns fail under high force after a simulated 10 years of service, this is not necessarily a problem. However, if they fail under the maximum bite force after 5 years of simulated service, this is a problem for the longevity. Thus, the experiment was designed so that a failure under expected bite force would indicate a clinical problem with the restoration design.

The fracture resistance of the tested crowns ranged from 927.4 N to 1,486.8 N in load at break and from 980.0 N to 1,540.2 N in peak load. Thus, in this study, lithium disilicate crowns each of the three different thicknesses showed a higher fracture resistance than the reported maximum biting force in the first molar region. It is true that, under different clinical conditions such as bruxism, the crowns are subject to higher forces, and there are reports that bruxism in first molar region can reach up to 111.6% of normal biting force\[^{14}\]. However, these crowns have a comfortable margin of safety over the reported maximum nocturnal bite forces during bruxism. Therefore, the fracture resistance of all tested crowns of IPS e.max CAD considerably exceeded the clinical bite forces at the first molars, regardless of the thickness.

The ability to reduce the occlusal thickness of restorations while preserving sufficient resistance to mastication cycles may have a remarkable impact on clinical applications. As the crowns showed sufficient fracture resistance after a simulated five years, lithium disilicate crowns with 0.8-mm occlusal thickness may be acceptable for clinical use as less invasive design in clinical situations for limited occlusal space, extensive wear, or desire to avoid pulp exposure. On the other hand, 10% of the 1.5 mm crowns and 20% of the 1.0 mm and 0.8 mm crowns failed during the fatigue application. This is a high failure rate for crowns over a five-year period, which suggests that the application of fatigue in this experiment may have been harsher than that normally experienced during mastication. Further investigation of this point is warranted.

Statistically significant differences in the fracture resistance of the crowns were found depending on the occlusal thickness. Therefore, the null hypothesis that there would be no difference in the fracture resistance measured by load at crack initiation, load for complete fracture, and time for crack propagation, of CAD/CAM lithium disilicate molar crowns with different thicknesses, was rejected. A previous study revealed that a lithium disilicate crown cemented on a mandibular first molar Paradigm MZ100 abutment fractured at a load of 1,228 N for 0.7-mm and 1,499 N for 1.5-mm occlusal thickness, but there was no statistically significant difference between those values\[^{15}\]. However, the fracture resistance of the 0.8-mm crowns in this study showed statistically significant lower values in all parameters than those of the 1.5-mm crowns. In addition, SEM observations of fracture surface of 1.5-mm crowns demonstrated much more complex fracture patterns, including marginal fracture, which may be related to higher bending forces than in thinner crowns. This difference may be related to the difference in elastic modules of the material used for abutments. The study mentioned earlier\[^{16}\] used CAD/CAM resin composite (3M Paradigm MZ100), with an elastic modulus of 18 GPa as a dentin replacement and lithium disilicate ceramic blocks with an elastic modulus of 95 GPa as an enamel replacement, while the 3D printing model resin used in this study has an elastic modulus of 10 GPa. Analyses of the fracture resistance of monolithic lithium disilicate CAD/CAM posterior restorations have been conducted using many different abutment materials. Although it is difficult to compare the previous studies to the present study due to the differences in methodology, a study using titanium abutments showed a higher fracture resistance of a lithium disilicate molar crown with 1.5 mm occlusal thickness (2,437.6 N) than the present study\[^{17}\]. Therefore, the difference in elastic modulus between a CAD/CAM resin block and 3D printing model resin may have influenced the results. If natural teeth...
were used as the abutment, the results might be more clinically realistic, but the collecting, storing, handling, and hand prepping of several natural teeth may increase the variability of the results. Further research to find the best material to substitute for natural tooth as the abutment in laboratory research would be valuable.

Overall, based on the results of this study, decreasing the occlusal thickness of lithium disilicate crowns appeared to reduce fracture resistance, but the fracture resistance of the crowns was within the clinically acceptable range even for 0.8-mm thickness. However, the high rate of failure under the fatigue testing (of 20% for the 1.0 mm and 0.8 mm crowns) is concerning, and further investigation of the clinical equivalence of the fatigue application method used is warranted.

CONCLUSION

The fracture resistance of molar crowns fabricated with chair-side CAD/CAM lithium disilicate varied according to the occlusal thickness. The load at crack initiation and time for crack propagation of chair-side CAD/CAM lithium disilicate with the new occlusal thickness recommendation of 1.0-mm thick did not show any statistical difference from the previous recommendation of 1.5-mm thick, although there was a significant difference in the peak load. Although the lower occlusal thickness of 0.8 mm offers comparable values to the new recommendation, all of those values are significantly lower than those of the previous recommendation of 1.5 mm.

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