3D and 2D Marginal Fit of Pressed and CAD/CAM Lithium Disilicate Crowns Made from Digital and Conventional Impressions

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Keywords
All-ceramic restoration; CAD/CAM; digital impression; marginal fit; technology; triple-scan protocol.

Abstract

Purpose: This in vitro study evaluated the 3D and 2D marginal fit of pressed and computer-aided-designed/computer-aided-manufactured (CAD/CAM) all-ceramic crowns made from digital and conventional impressions.

Materials and Methods: A dentoform tooth (#30) was prepared for an all-ceramic crown (master die). Thirty type IV definitive casts were made from 30 polyvinyl siloxane (PVS) impressions. Thirty resin models were produced from thirty Lava Chairside Oral Scanner impressions. Thirty crowns were pressed in lithium disilicate (IPS e.max Press; 15/impression technique). Thirty crowns were milled from lithium disilicate blocks (IPS e.max CAD; 15/impression technique) using the E4D scanner and milling engine. The master die and the intaglio of the crowns were digitized using a 3D laser coordinate measurement machine with accuracy of ±0.00898 mm. For each specimen a separate data set was created for the Qualify 2012 software. The digital master die and the digital intaglio of each crown were merged using best-fitting alignment. An area above the margin with 0.75 mm occlusal-gingival width circumferentially was defined. The 3D marginal fit of each specimen was an average of all 3D gap values on that area. For the 2D measurements, the marginal gap was measured at two standardized points (on the margin and at 0.75 mm above the margin), from standardized facial-lingual and mesial-distal digitized sections. One-way ANOVA with post hoc Tukey’s honestly significant difference and two-way ANOVA tests were used, separately, for statistical analysis of the 3D and 2D marginal data (alpha = 0.05).

Results: One-way ANOVA revealed that both 3D and 2D mean marginal gap for group A: PVS impression/IPS e.max Press (0.048 mm ± 0.009 and 0.040 mm ± 0.009) were significantly smaller than those obtained from the other three groups (p < 0.0001), while no significant differences were found among groups B: PVS impression/IPS e.max CAD (0.088 mm ± 0.024 and 0.076 mm ± 0.023), C: digital impression/IPS e.max Press (0.089 mm ± 0.020 and 0.075 mm ± 0.015) and D: digital impression/IPS e.max CAD (0.084 mm ± 0.021 and 0.074 mm ± 0.026). The results of two-way ANOVA revealed a significant interaction between impression techniques and crown fabrication methods for both 3D and 2D measurements.

Conclusions: The combination of PVS impression method and press fabrication technique produced the most accurate 3D and 2D marginal fits.
Accuracy of fit is the characteristic most closely related to the longevity of a restoration.\textsuperscript{1,2} All required steps during the fabrication of a crown necessitate precision and exactness to produce an accurately fitting restoration. Ideally, the cemented crown should precisely meet the finish line of the prepared tooth. In reality, clinical perfection is challenging to achieve and to verify. The importance of a well-fitting full-coverage restoration is most evident when considering an ill-fitting restoration’s implications, such as luting agent dissolution,\textsuperscript{3} microleakage,\textsuperscript{4,5} caries,\textsuperscript{2,4,5} hypersensitivity, and periodontal inflammation.\textsuperscript{6,7}

Although White et al reported that marginal opening alone did not directly correlate with marginal microleakage,\textsuperscript{1} the accuracy of marginal fit is valued as one of the most important criteria for the clinical quality and success of prosthetic restorations. Using a linear regression prediction formula, Christensen found that an acceptable gingival margin range was 34 to 119 µm.\textsuperscript{8} McLean and von Fraunhofer also suggested that restorations with marginal gaps less than 120 µm were more likely to be successful.\textsuperscript{9}

With the increased demand for esthetics, all-ceramic restorations have become very popular over the last decades. Such restorative all-ceramic systems must fulfill biomechanical requirements and should provide longevity similar to metal-ceramic restorations while providing enhanced esthetics.\textsuperscript{10-13} IPS e.max (Ivoclar Vivadent, Schaan, Liechtenstein) is a lithium disilicate all-ceramic restorative material introduced in 2005. According to the manufacturer, it combines high flexural strength along with optimum esthetics. It can be processed using either lost-wax hot pressing techniques (IPS e.max Press) or computer-aided-designed/computer-aided-manufactured (CAD/CAM) milling procedures (IPS e.max CAD).

Pressed ceramics have demonstrated marginal accuracy comparable to that of metal restorations.\textsuperscript{14} Conversely, studies have shown that milled ceramic restorations had inferior marginal fit compared to pressed restorations.\textsuperscript{15,16} The marginal inaccuracy of the early CAD/CAM restorations was attributed to the CAD/CAM system (low-resolution scanning and inadequate computing power) and not to the ceramic material itself.\textsuperscript{17,18}

Recent advances in technology have dramatically altered impression and crown fabrication procedures. Digital impression systems have been introduced in dental clinical practice,\textsuperscript{19-22} and several advancements have occurred in CAD/CAM milling technologies that claim to produce more accurately fitting restorations.\textsuperscript{22} Two such systems are the Lava\textsuperscript{TM} Chairside Oral Scanner (C.O.S.; 3M ESPE, St. Paul, MN) and the E4D Dentist System\textsuperscript{TM} (D4D Technologies LLC, Richardson, TX).

The Lava\textsuperscript{TM} C.O.S. uses active wavefront sampling to capture 3D impressions. Active (optical) wavefront sampling obtains 3D information from the Lava\textsuperscript{TM} C.O.S. proprietary single-lens imaging system by measuring depth based on the defocus of the primary optical system.\textsuperscript{23} The accuracy and precision of this intraoral scanner have been studied.\textsuperscript{24-28} Scotti et al\textsuperscript{24} and Seelbach et al\textsuperscript{26} found that all-ceramic crowns made from Lava\textsuperscript{TM} C.O.S. were as accurate, and Syrek et al\textsuperscript{27} found them even more accurate, than those made from conventional impressions. Guth et al reported that direct digitalization with the Lava\textsuperscript{TM} C.O.S. had the potential to improve the accuracy of fixed dental prostheses as compared to conventional impression making and indirect digitalization.\textsuperscript{28}

The E4D Dentist System\textsuperscript{TM} was introduced in early 2008 and features the working principle of optical coherence tomography and confocal microscopy.\textsuperscript{29} According to the manufacturer, E4D is the only CAD/CAM system that uses a true laser for scanning hard and soft dental tissue, impression material, occlusal registration material, and dental stone. No studies have evaluated the influence of both the impression technique and the prosthesis fabrication technique on the marginal fit of the final all-ceramic restoration. Therefore, the purpose of this study was to evaluate in vitro the marginal fit of all-ceramic crowns made from two impression techniques (digital vs. conventional) and two fabrication methods (CAD vs. press).

**Materials and methods**

The marginal adaptation of IPS e.max crowns made from two impression techniques and two fabrication methods was evaluated. The impression techniques tested were a conventional impression, using poly(vinyl siloxane)(PVS) material in a custom tray and a digital impression, using the Lava\textsuperscript{TM} C.O.S. The crown fabrication methods used in this study were heat-pressed and CAD/CAM. Four study groups (n = 15 per group) were compared: group A: conventional impression/IPS e.max Press (PVS/Press), group B: conventional
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Figure 2 Occlusal view of the prepared dentoform tooth #30.

Impression/IPS e.max CAD (PVS/CAD/CAM), group C: digital impression/IPS e.max Press (Lava/Press), and group D: digital impression/IPS e.max CAD (Lava/CAD/CAM; Fig 1). The dies and the crowns were digitized using a 3D laser scanner, and the adaptation was measured using Geomagic Qualify 2012 software (Geomagic; Research Triangle Park, NC).

Figure 3 Group A-PVS/Press.

Figure 4 Group B-PVS/CAD/CAM.

Master die fabrication

A dentoform (Dentaform Corp., Fresno, CA) replica mandibular first molar tooth (#30) was prepared for an all-ceramic crown by a single operator according to standard tooth preparation procedures (Fig 2).

Figure 3 Group A-PVS/Press.

Figure 4 Group B-PVS/CAD/CAM.

IPS e.max Press crown fabrication

IPS e.max Press (IPS e.max Press LT A1) ingots were used to make the full-coverage crowns using the lost-wax technique on 15 stone casts produced by conventional impression and 15 resin casts produced by digital impressions. One layer of rubber-based removable die spacer (Rem-e-die, Ivoclar Vivadent) was used on all dies, stone, and resin, extending 1 mm occlusal to the cavosurface margin, as recommended by the manufacturer’s (Ivoclar Vivadent) laboratory technician. A PVS (Exafilet Putty; GC America, Alsip, IL; light body Extrude; Kerr Corp.) mold was made, and standardized wax patterns were fabricated with an injection technique. The crown margins were carefully finished and checked under the microscope.

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(10×) using margin wax (Almore International Inc, Portland, OR). The wax patterns were sprued, invested, and pressed according to the manufacturer’s directions. The intaglio of the pressed crowns was observed under the microscope (10×), and any residual positives from the investing procedure were carefully removed with a diamond bur. No further adjustments were made to the intaglio surface (Figs 3 and 5).

**IPS e.max CAD crown fabrication**

The remaining 15 stone casts and 15 resin models were scanned using the E4D scanner, and the crowns were designed with the E4D Design Center as follows: “0.04” spacer thickness and “1.00” crown margin ramp. The crown thickness was greater than 1 mm, and the margin was enhanced to avoid chipping during milling, by enabling the default settings “0.150” and “2.000” under margin boost settings. IPS e.max CAD blocks (IPS e.max CAD LT Block 112 A1) were milled using the E4D milling engine. The horizontally overhanging margins were adjusted under the microscope (10×) with a polishing disk (No. 94002CHP170 Brasseler). No adjustments to the intaglio surface were made, and the crowns were crystallized using a ceramic furnace (Ney Centurion Qex; Denstply Ceramco, Burlington, NJ; Figs 4 and 6).

**Measurement of crown fit**

The measurement method used was the triple scan protocol, as described by Holst et al. Due to its recent introduction and limited literature support, this digital measurement method was validated as part of a pilot study before initiating the definitive study.

The master die and the intaglio of each crown were digitized using the Surveyor ZS-Series scanner, a 3D laser coordinate measurement machine with scan accuracy of ±0.00898 mm (Laser Design Inc, GKS, Minneapolis, MN). A light coat of spray was used to facilitate the scanning (Spotcheck® SKD-S2 Non-Halogenated Solvent Developer; Magnaflux, Glenview, IL). Three scans were made: (1) The prepared dentoform tooth (master die) secured on a standardized metal base with PVS material (Fig 7); 2) the intaglio of each all-ceramic crown (Fig 8); and 3) each crown on the dentoform tooth in a clinically correct final position (Fig 9).

For each specimen, a separate data set in STL format was generated from point clouds with the Geomagic Qualify 2012 software. First, the master die STL file and the crown/master die STL file were registered by manual alignment followed by best-fitting registration. Then the same procedure was followed to register the crown STL file and crown/master die STL file. The crown/master die STL data set was deleted, and the aligned crown to master die STL data set was used for fit assessment.

For the 3D measurements, an area above the cavosurface margin with 0.75 mm occlusal-gingival width circumferentially was defined using Geomagic Studio 2012 software (Fig 10). All values (25,000 to 30,000) obtained by Geomagic software were averaged, and the mean was used for the comparisons (Fig 11). Any negative values (denoting that the crown was smaller than the tooth) were excluded from the calculations, since they did not represent a realistic scenario.

For the 2D measurements, two sections, facial-lingual and mesial-distal, were made through the grooves on the standardized metal base of the tooth (Fig 2). The distance between the die and the intaglio surface of the crown was measured at four standardized points (two on the margin and two at 0.75 mm above the margin) (Figs 12 and 13).

**Statistical analysis**

One-way ANOVA with post hoc Tukey’s honestly significant difference (HSD) test was used to determine whether there were significant differences in mean marginal gap values among the four experimental groups. In addition, a two-way ANOVA was performed to detect a significant interaction between the type of impressions and the type of crowns on the marginal fit.
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Separate analysis was performed for the 2D and 3D measurements. A p value of less than 0.05 was used as a criterion for statistical significance. Statistical analyses were carried out with the statistical package SAS® System version 9.3 (SAS Institute Inc, Cary, NC).

Results

The results of one-way ANOVA and the post hoc Tukey’s HSD test indicated that the mean 3D marginal gap for the conventional impression with pressed crown was significantly smaller than those obtained from the other three experimental groups, while no significant differences were found among PVS/CAD/CAM, Lava/Press, and Lava/CAD/CAM groups (Table 1).

The results of two-way ANOVA revealed a significant interaction between impression techniques and crown types. With the conventional impression, the mean 3D marginal gap for the pressed crowns was significantly smaller than that for the CAD crowns (0.048 mm vs. 0.088 mm); however, no significant simple effect was found for the type of crowns with the digital impression. In addition, with the pressed crowns, the mean 3D marginal gap for the conventional impressions was significantly smaller than that for the digital impressions (0.048 mm vs. 0.089 mm), while no significant simple effect was found for the type of impressions with the CAD crowns. Similar results were drawn from the 2D data (Table 2).

Discussion

The main purpose of the study was to evaluate the marginal fit of all-ceramic crowns made from two impression techniques (digital vs. conventional) and two fabrication methods (CAD/CAM vs. press). No studies in the literature assess the adaptation of all-ceramic crowns made from the combination of those techniques. Therefore, this study provided information as to how either impression technique could be combined with either crown fabrication method to facilitate the needs or the availability of each in clinical practice.
Results from this study indicated that the combination of conventional (PVS) impression method and press fabrication technique produced the most accurate 3D (0.048 mm) and 2D (0.04 mm) marginal adaptation. These results coincided with the findings of previously published studies that compared the fit of pressed crowns to that of cast crowns, which are still considered the gold standard for fit.\textsuperscript{15,16} Previous studies that have evaluated Lava\textsuperscript{TM} C.O.S. accuracy have concluded that it either produced as accurate\textsuperscript{24,26} or more accurate\textsuperscript{27} restorations than PVS impressions. In this study, the Lava\textsuperscript{TM} C.O.S. impressions produced a statistically significantly less accurate marginal adaptation (larger gap) than the conventional impressions. Despite the statistical difference in marginal fit between the pressed crowns made from PVS impressions and the remaining three experimental groups, the clinical significance might not be of great importance. All marginal gaps were less than 90 \( \mu \text{m} \), which is smaller than the reported clinically acceptable limit of 120 \( \mu \text{m} \).\textsuperscript{8,9}

An interesting finding in this study was that the pressed crowns from digital impressions (group C) had statistically significantly larger marginal gap than the pressed crowns made from conventional impressions (group A). The combination of digital impression/pressed crown was not as accurate as the conventional impression/pressed crown combination; however, no difference was found between the CAD/CAM crowns made from the conventional (group B) and digital impressions (group D), indicating that the combined techniques had similar accuracy. Direct comparison between the pressed and the CAD/CAM fabrication techniques should be made with caution, since the production methods were so different; specifically, since for the CAD/CAM crowns the dies were scanned, there was the possibility that any irregularities on the dies were “smoothed out” by the software to facilitate the crown fabrication. The reason the marginal gap of group C (Lava/Press) was statistically greater than that of group A (PVS/Press), might be attributed to the overall internal adaptation of the crown.
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Table 1 Mean 3D marginal gap of 4 experimental groups

<table>
<thead>
<tr>
<th>Experimental groups</th>
<th>N</th>
<th>Mean 3D marginal gap (in mm; SD)</th>
<th>Group comparisons*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVS/Press (Group A)</td>
<td>15</td>
<td>0.040 (0.009)</td>
<td>B</td>
</tr>
<tr>
<td>PVS/CAD/CAM (Group B)</td>
<td>15</td>
<td>0.076 (0.023)</td>
<td>A</td>
</tr>
<tr>
<td>Lava/Press (Group C)</td>
<td>15</td>
<td>0.075 (0.015)</td>
<td>A</td>
</tr>
<tr>
<td>Lava/CAD/CAM (Group D)</td>
<td>15</td>
<td>0.074 (0.026)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Means with the same letter are not significantly different using post hoc Tukey’s HSD test (p > 0.05)

Table 2 Mean 2D marginal gap of 4 experimental groups

<table>
<thead>
<tr>
<th>Experimental groups</th>
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<td>A</td>
</tr>
<tr>
<td>Lava/Press (Group C)</td>
<td>15</td>
<td>0.089 (0.020)</td>
<td>A</td>
</tr>
<tr>
<td>Lava/CAD/CAM (Group D)</td>
<td>15</td>
<td>0.084 (0.021)</td>
<td>A</td>
</tr>
</tbody>
</table>

*Means with the same letter are not significantly different using post hoc Tukey’s HSD test (p > 0.05)

No statistically significant differences were found among PVS/CAD/CAM (group B), Lava/Press (group C), and Lava/CAD/CAM (group D), which showed that CAD/CAM crown margins could be accurately produced when either a stone or an SLA model was scanned using the E4D scanner. This particular scanner claims accuracy of both direct (tooth) and indirect (impression material or cast/model) digitalization. Although it has been shown that indirect digitalization may not be as accurate, the results of this study showed that indirect digitalization may produce all-ceramic crowns with a clinically acceptable (<90 μm) marginal gap.

The fact that the 2D and 3D measurements resulted in the same conclusion validated the reliability of the software and the measurement protocol used. The consistent 10 μm difference between the 2D and 3D data sets was due to the different processing of the software when calculating 3D vs. 2D data, and not due to an error in the measurement protocol. As mentioned before, this new digital measurement technique was validated by comparing it to the replica technique that is well documented in the literature. Seven of ten variables tested had no statistical difference, indicating that the two techniques produced similar results. In addition, two duplicate measurements were taken of the same crowns using the triple-scan protocol and compared with student’s t-test. No statistically significant difference was found between the duplicate measurements, indicating the repeatability of the triple-scan protocol.

The main limitation of the study was the process of digitally aligning the crowns on the master die. After applying the best-fit alignment twice, the crown fit had to be adjusted manually to simulate a clinically relevant crown position. The best-fit alignment finds the path of least resistance between the two objects and then superimposes them. This may result in a portion of the crown intaglio appearing to be “inside” the tooth. Therefore, each time a crown was fitted, if any portion of the crown appeared to fall “inside” the tooth, it was manually repositioned until a clinically relevant alignment was achieved; however, the fact that the fit was improved at the given cross-section did not mean that it was correctly positioned threeimensionally. The measurement protocol was developed with the assistance of Geomagic technical support. Other limitations may include the use of rubber-based die spacer on the SLA models, the grinding of the overhanging margins of the CAD/CAM crowns, and the spray used for digitizing the crowns and the master die. Finally, the crowns were not cemented on the die, as they would be clinically, which may produce different results. The standardization, the nondestructive nature, the rapid processing of data and the storage/availability of the digital measurement technique enables the comparison and analysis of any material desired; however, further advancements are needed to the currently available software to facilitate their use in dental research.

Conclusions

Within the limitations of this study, the following conclusions were drawn:

1. The combination of the conventional impression and the pressed crown combination produced the most accurate marginal fit.
2. There was no statistical difference in marginal fit among conventional impression/CAD/CAM crown, digital impression/press crown, and digital impression/CAD/CAM crown.
3. All combinations produced crowns with clinically acceptable marginal fit.

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