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Laboratory Research

Influence of the Crystallization Firing Process on Marginal and Internal Adaptation of Silicate-based Glass-ceramic Inlays Fabricated With a CAD/CAM Chairside System

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Clinical Relevance

Increased cement lines in all-ceramic inlay restorations substantially impact the clinical prognosis due to resin cement wear and discoloration. In the one-step fabrication method, CAD/CAM chairside fabricated crystallized silicate-based glass-ceramic inlay restorations can improve marginal adaptation.

SUMMARY

Objective: Computer-aided design/computer-aided manufacturing (CAD/CAM) systems are widely used in dental treatment. Clinicians can use chairside CAD/CAM technology, which has the advantage of being able to fabricate inlays on the same day. We aimed to evaluate the effects of crystallization firing processes, fabrication methods (one-step and two-step), and materials on marginal and internal adaptations of silicate-based glass-ceramic all-ceramic inlays fabricated with CAD/CAM chairside systems.

Methods: Ten artificial mandibular left first molars were prepared with standardized ceramic class II mesial-occlusal (MO) inlay cavities. Optical impressions were obtained using CEREC Omnicam Ban. IPS e-max CAD

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(IE), (Ivoclar Vivadent, Schaan, Liechtenstein), Initial LiSi Block (LS) (Hongo, Bunkyoku, Tokyo, Japan), VITA Suprinity (SP), (Vita Zahnfabrick, Bad Säckingen, Germany), and Celtra Duo (CD) (Ivoclar Vivadent, Schaan, Liechtenstein) (n=10) were milled using CEREC MC XL (Bensheim, Germany). IE and SP were crystallization-fired using CEREC Speed Fire. The silicone replica technique was used for the measurement of internal (axial and pulpal walls) and marginal (cervical and occlusal edge) adaptations. The adaptations were measured using a thin layer of light-body polyvinyl siloxane impression material placed between the master tooth inlay preparation and restoration. Marginal and internal adaptations of IE, LS, SP, and CD were measured using a stereomicroscope (500×). For IE and SP, marginal and internal adaptations were measured before and after the crystallization firing process. Data analyses were conducted using one-way ANOVA and the Tukey test. For IE and SP, marginal and internal adaptations before and after the crystallization firing process were analyzed using the *t*-test. The significance level was set at α=0.05.

Results: One-way ANOVA revealed statistically significant differences in occlusal and cervical edge marginal adaptations among the material groups (p<0.001). The Tukey HSD test revealed a significant difference in marginal occlusal and cervical edge adaptations between LS and CD groups and IE and SP groups ($p\leq0.05$). For IE and SP inlays, the *t*-test revealed a significant difference between occlusal and cervical edge adaptations before the crystallization firing process and those after the crystallization firing process, with the latter group showing a more significant discrepancy in adaptation than the former group ($p\leq0.05$).

Conclusions: Fabrication methods (one- and two-step) affected the marginal adaptation compatibility but not internal compatibility of MO inlays. The crystallization firing process affected the marginal adaptation of inlays using lithium silicate or lithium disilicate glass-ceramics. However, adaptation to the cavity was considered clinically acceptable for all materials.

INTRODUCTION

CAD/CAM systems are widely used in dental treatment.[1,2] Partial coverage using CAD/CAM inlays has become one of the most frequently used clinical treatments owing to escalated aesthetic demands. Clinicians can use chairside CAD/CAM technology to fabricate inlays, with the advantage of being fabricated on the same day.[3] Chairside CAD/CAM technique is perceived to be timesaving, less contaminating, and more comfortable for patients.[4] For indirect restoration of a tooth, different restorative dental materials can be used; however, for aesthetics, an all-ceramic material is used.[5] Crystallized glass-ceramics based on lithium disilicate or lithium silicate belonging to a high-strength group are used. These silica-based ceramics have largely been used due to their excellent aesthetic properties and high flexural strength compared to other glass-ceramics.[6-8]

Chairside CAD/CAM systems for digital workflow have led to the development of specific dental materials that include a wide range of new nano-structured glass-ceramics.[9] Belli and others conducted a large dataset search for dental ceramic restorations; the IPS e-max CAD of lithium disilicate showed significantly better performance than leucite-based IPS Empress CAD for inlays; this finding highlighted the role of microstructure in the fracture process.[10] Clinicians often seek to minimize marginal gaps to reduce aesthetic deterioration due to cement wear and discoloration by the luting cement. Accuracy of the fit, the extent of marginal adaptation, and cement thickness of the inlay are important factors that determine its long-term clinical success.[11,12] Several factors could directly influence the longevity of indirect ceramic restorations, among which the quality of the marginal seal and thickness of the luting agent seemed to be the most relevant.[13] Adaptation of inlay restorations fabricated using CAD/CAM systems has been commonly evaluated using marginal and/or internal final restorations.[14-16]

Current silica-based ceramics for CAD/CAM systems are divided into two types depending on the manufacturing process: supplied in a final crystallized form ready for machining (one-step) or supplied partly crystallized for subsequent crystallization after machining (two-step).[13] Partially crystallized ceramic is subsequently treated to complete the crystallization and facilitate the CAD/CAM production, achieve final color, and optimize the mechanical properties.[17] Materials that undergo a two-stage crystallization process are designed to acquire higher crystalline content during final heat treatment than those that do not.[18] Unlike the full coverage crown, the morphology of the inlay restoration is complex and can have different effects on marginal and internal adaptations. The crystallization process of IPS e-max for lithium disilicate glass-ceramics reportedly resulted in a 0.2% densification of the material (manufacturer's instructions for use). Gold and others reported that the crystallization firing process required for lithium disilicate crowns resulted in a significant increase in the marginal gap, likely due to marginal shrinkage of the porcelain, which developed during the densification of the material.[19] However, the effect of the crystallization process on the marginal and internal adaptations of inlay restorations has not been reported.

Broad cement lines create gaps between a tooth and restoration due to wear, leading to secondary caries and deterioration of aesthetics due to discoloration.[20-22] In addition, improper internal adaptation can increase cement thickness, alter retention, affect occlusion, and reduce the fracture resistance of the restorations.[10]

We aimed to investigate the influence of the crystallization firing process on the marginal and internal adaptations of silica-based ceramic inlays fabricated with CAD/CAM systems. We evaluated the marginal and internal adaptations of lithium disilicate or lithium silicate glass-ceramic inlays fabricated with CAD/CAM systems, using class II mesial-occlusal (MO) preparation designs. The three null hypotheses to be tested were that there are no differences in the marginal and internal adaptations (1) among the four CAD/CAM materials used to fabricate the silicate-based glass-ceramics inlay, (2) between the crystallization firing processes (one- and two-step crystallization firing processes) of the two fabrication methods, and (3) for the same block before and after the crystallization firing process.

METHODS AND MATERIALS

Inlay Preparations

Ten artificial mandibular left first molar typodont teeth (D16-500E, Nissin Dental Products, Kyoto, Japan) were prepared with standardized ceramic class II MO inlay cavity using diamond points by the same operator. Cavity preparation was performed using a high-speed dental handpiece with water-cooling and 20°-tapered diamond burs, 207CR and SF207CR (Shofu Inc, Kyoto, Japan). The preparation design included a 2 mm deep occlusal box and an isthmus width of 3 mm, the gingival floor of each box had a mesiodistal width of 1 mm and an axial wall height of 1 mm (Figure 1). After tooth preparation, 10 individual optical impressions were taken with the prepared teeth fixed on the model by the same operator using a CEREC Omnicam (software 4.6.1, Dentsply Sirona, Bensheim, Germany) per the manufacturer's instructions. The shape of each model was analyzed using the software to confirm that there were no undercuts in the cavity. The operator-designed "biogenetic individual" design mode was selected for inlay design, and a spacer width of 80 μm was established after cavity preparation for milling parameters; the inlays were subsequently machined in silicate-based glass-ceramics blocks (n=10) and milled using CEREC MC XL (Dentsply Sirona). IPS e-max CAD (IE, a lithium disilicate glass-ceramic, Ivoclar Vivadent, AG, Schaan, Liechtenstein), Initial LiSi Block (LS, a lithium disilicate glass-ceramic, GC, Tokyo, Japan), VITA Suprinity (SP, a lithium silicate glass-ceramic, VITA Zahnfabrik, Bad, Sackingen, Germany), Celtra Duo (CD, a lithium silicate glass-ceramic, Dentsply Sirona) were used as the silica-based ceramics (Table 1). For IE and SP, we used the manufacturer-set program for crystallization firing using CEREC Speed Fire (Dentsply Sirona).

Measurement of Internal and Marginal Adaptations

We used the silicone replica technique,[23,24] through which the internal and marginal adaptations could be accurately measured. This method can be used for measuring marginal (cervical and occlusal edge) and internal (axial and pulpal wall) adaptations using a thin layer of light-body polyvinyl siloxane impression material between the master tooth inlay preparation and restoration. Replicas of the space between the intaglio surface of the inlay and cavity surfaces were prepared by coating the cavity walls with a thin layer of light-body polyvinyl siloxane impression (EXAMIXFINE Injection Type, GC), after which the inlay was placed in the preparation. A 750-g metal weight was placed on the upper surface of a vertically sliding platform, positioned on top of the master tooth fixed on the model, until the impression material had fully polymerized. After excess silicone removal, the inlay was removed, and the thin film of light-body polyvinyl siloxane impression adhering to the master tooth was stabilized by injecting a medium-body

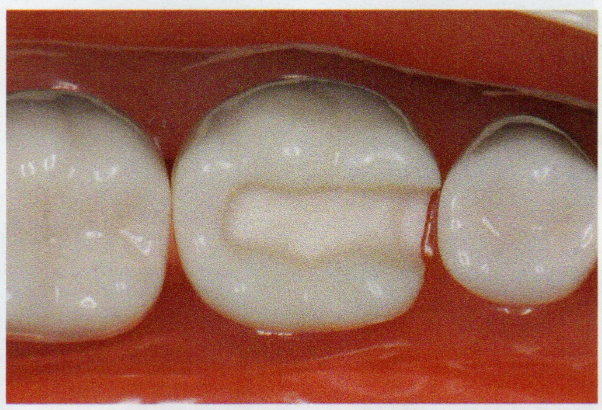

Figure 1. *Prepared class II mesial-occlusal inlay. Mesial-occlusal inlay cavities with 2.0 mm deep occlusal box and an isthmus width of 3.0 mm. The gingival floor of each box had a mesiodistal width of 1 mm and an axial wall height of 1 mm.*

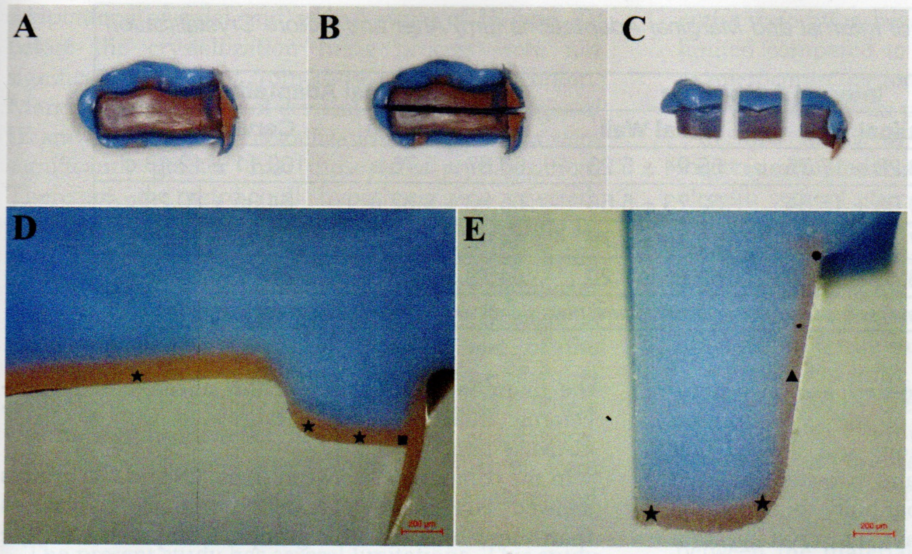

Figure 3. *Internal and marginal adaptation measurements. A: Replica body. B: A guide is used to cut the center of the replica body mesial-distally C: A guide is used to cut the replica body buccal-lingually at two points D: Stereomicrograph of a section of the internal pulpal wall and marginal cervical edge E: Stereomicrograph of a section of the internal axial wall and marginal occlusal edge. The marks correspond as follows: ★ Pulpal wall ▲ Axial wall ● Occlusal edge ■ Cervical edge.*

was set at α=0.05. Data were analyzed using statistical software (JMP 14, SAS Institute, NC, USA).

RESULTS

The results of the assessment of marginal and internal adaptations are shown in Table 2. One-way ANOVA showed no statistically significant difference in relation to pulpal (p=0.1673) and axial (p=0.9468) internal wall adaptations between the material groups. However, one-way ANOVA revealed statistically significant differences in occlusal and cervical edge adaptations among the material groups (p<0.001). The Tukey HSD test revealed a significant difference in marginal occlusal and cervical edge adaptations between LS and CD groups and IE and SP groups ($p \leq 0.05$). IE and SP groups had significantly larger gaps at the occlusal and cervical edges than LS and CD groups.

The results of marginal and internal adaptations for IE and SP inlays before and after the crystallization firing process are shown in Table 3. For IE and SP inlays, the t-test revealed a significant difference between occlusal and cervical edge adaptations before the crystallization firing process and those after the crystallization firing process, with the latter process group showing a significantly higher discrepancy in adaptation than that of the former process group ($p \leq 0.05$). However, there was no significant difference in the internal pulpal wall adaptations between before and after the crystallization firing process in the IE (p=0.2037) and SP (p=0.1349) groups. Similarly, there was no significant difference in the internal axial wall adaptation between before and after the crystallization firing process in the IE (p=0.2074) and SP (p=0.1525) groups.

DISCUSSION

Chairside CAD/CAM inlay restorations using lithium disilicate and lithium silicate glass-ceramics are currently used by many dentists worldwide. Although many studies have reported the compatibility of inlays made of silicate-based glass-ceramics inlays,[25] only a few studies have reported the effects of the firing process. The present study verified the marginal and internal adaptations of silicate-based glass-ceramics inlays fabricated with CAD/CAM systems using

Table 2: *Mean and SD of Internal and Marginal Adaptations (µm) for the Experimental Group*[a]

Experimental Group	Internal Adaptation		Marginal Adaptation	
	Pulpal Wall	Axial Wall	Occlusal Edge	Cervical Edge
LS	124.37 ± 12.51 A	55.78 ± 7.02 A	47.38 ± 6.50 A	64.18 ± 18.27 A
CD	127.09 ± 14.16 A	56.54 ± 9.17 A	46.85 ± 7.34 A	70.48 ± 16.00 A
IE	123.28 ± 17.75 A	56.94 ± 5.23 A	66.87 ± 5.75 B	100.11 ± 12.18 B
SP	117.42 ± 16.98 A	55.18 ± 5.79 A	64.62 ± 6.70 B	104.13 ± 19.88 B

[a] *Different letters indicate significant difference (p≤0.05) between the groups (column).*

Table 3: *Mean and SD of Internal and Marginal Adaptations (µm) After and Before Crystallization Firing Process*[a]

Experimental Group	Internal Adaptation		Marginal Adaptation	
	Pulpal Wall	Axial Wall	Occlusal Edge	Cervical Edge
IE	123.28 ± 17.75	56.94 ± 5.23	66.87 ± 5.75 a	100.11 ± 12.18 c
IE-pre	129.08 ± 15.54	52.73 ± 5.68	55.93 ± 8.52 a	64.95 ± 20.29 c
SP	117.42 ± 16.98	55.18 ± 5.79	64.62 ± 6.70 b	104.13 ± 19.88 d
SP-pre	123.49 ± 19.22	59.95 ± 7.20	54.73 ± 7.25 b	68.72 ± 14.98 d

[a] *Values indicated by the same lowercase letters in each column have significant differences from each other (p≤0.05).*

two preparation processes (one-step and two-step). We focused on the influence of the crystallization firing process on inlay adaptations and showed that fabrication methods (one-step and two-step) affected the marginal adaptation compatibility but not the internal compatibility of MO inlays. The crystallization firing process affected the marginal adaptation of inlays made of lithium silicate or lithium disilicate glass-ceramics. However, adaptation to the cavity was considered clinically acceptable for all materials.

According to a systematic review of marginal and internal adaptation of CAD/CAM inlay/onlay restorations, the values for marginal adaptation ranged primarily from 36 µm to 222.5 µm and those for internal fit from 23 µm to 406.5 µm.[25] Furthermore, a systematic review of the cavity fit of inlay/onlay restorations containing various materials reported marginal adaptation values ranging from 39.1 to 201 µm and internal adaptation values varying from 23 to 230 µm.[26] Excluding SP-pre and EX-pre, which are not crystallization-fired, the internal fit ranged from 55.18 µm to 127.09 µm, and the marginal fit ranged from 46.85 µm to 115.99 µm.

The first null hypothesis that there would be no differences in the marginal and internal adaptations between the four CAD/CAM materials used to fabricate silicate-based glass-ceramics inlays was partially rejected. In the present study, there were no significant differences in the internal adaptation (pulpal and axial walls), between the materials; however, there were significant differences in cervical and occlusal edge marginal adaptations between the materials. LS and CD groups showed significantly greater marginal adaptations compared to the IE and SP groups. This result partially rejected the second null hypothesis that there were no differences in marginal and internal adaptations between the two fabrication methods (with crystallization firing process [two-step] and without crystallization firing process [one-step]). This finding suggests that the fabrication step, ie, the presence or absence of the crystallization firing process, may affect the marginal discrepancy of the silicate-based glass-ceramic inlay restorations fabricated with a CAD/CAM system.

In the comparison between steps, LS and CD groups showed significantly greater marginal adaptations than those of IE and SP groups. Compared with the other groups, LS and CD groups did not require a firing process for crystallization after milling; hence, deformation due to changes in the crystal structure was minimal leading to good marginal adaptation.

Before final crystallization, IE and SP, which are blocks that require a crystallization firing process (two-step method), are in a state of low hardness to improve machinability. On the other hand, blocks that do not require a crystallization firing process (one-step method) have high levels of hardness because they are milled after crystallization. It has been reported that a high-modulus compound such as lithium disilicate may hinder milling, increasing the irregularity of the surface and decreasing the marginal accuracy.[27] On the other hand, another study has reported that less brittle materials have lower edge chipping, better machinability, and better adaptation than those of the more brittle ones.[28]

The difference in crystal structure might have affected the machinability; nevertheless, further investigation is needed in this regard. However, regardless of the manufacturing method with or without the crystallization firing process, the mean marginal adaptation of silicate-based glass-ceramic restoration inlays was within a clinically acceptable range. There is no clinical or evidence-based consensus regarding whether a specific marginal gap is clinically acceptable for a given patient; however, most studies have reported marginal adaptation values within this range (<120 µm).[25]

The third null hypothesis stated that there would be no differences in the marginal and internal adaptations of the same block before and after the crystallization firing process of silicate-based glass-ceramics inlays fabricated with CAD/CAM systems. The internal adaptations of axial and pulpal walls of IE and SP before the crystallization firing process were not significantly different from those after crystallization. Marginal adaptations of cervical and occlusal edges of IE and SP before the crystallization firing process were significantly greater than those after crystallization. Therefore, the third null hypothesis was rejected. Comparing the compatibility before and after firing IE and SP, it was presumed that the crystallization firing process was the most probable cause for the significant differences in marginal adaptations. Shrinkage of silicate-based glass-ceramics could be one of the reasons for increased marginal widths in groups that underwent the crystallization firing process.[11] There was no significant difference in internal adaptations. This result of the present study is different from previous reports,[29] probably because of the lateral and medial cavities in the crown and inlay.[30]

The present study has several limitations. This study used typodonts. It has been suggested that differences in the transparency of enamel, dentin, and typodonts may affect the accuracy of optical impressions.[31,32] However, clinically, there are also studies that show it does not significantly affect the accuracy of optical impressions.[33] Most of the studies investigating the adaptation of inlays using typodonts are reported to be clinically similar in terms of adaptive evaluation.[14,19]

Another limitation was only one type of inlay preparation was assessed. It has been reported that the morphology of the inlay tooth cavity or cavities measurement position affects its compatibility with the restoration, especially if the restoration has a complex shape and deep groove regions.[34-36] Other preparation designs for inlays or partial coverage restorations made of CAD/CAM materials may show different results, and therefore, marginal and internal adaptations of other cavity preparations should also be analyzed. Additionally, CAD/CAM fabrication systems incorporate many digitized processes.[37] In the present study, since the intraoral scanner and milling units used only one system, the influence of the accuracy of the intraoral scanner, milling machine, and CAD software was not considered. The spacer thicknesses of restorations fabricated with a CAD/CAM system were reported to have a direct effect on marginal and internal adaptations of dental restorations.[22] In this study, conformity was evaluated by two-dimensional analysis using the silicone replica technique, a reliable measurement method often used in studies of inlay and crown conformity.[24,38,39] This method can be used for the measurement of marginal and internal gaps.[23] However, the silicone replica technique has the limitation that the results of this study cannot represent the fit of the entire restoration because the measurement points are limited compared to three-dimensional analysis such as microcomputer tomography[40,41], which can measure many measurement points.[25]

In this study, a light-body polyvinyl siloxane impression material was used to reproduce the thickness of resin cement after cementation. Some reports have investigated the effect of differences in resin cement viscosity and composition on the marginal gaps.[42-44] However, this study, which used the silicone replica technique, has limitations, and this issue needs to be evaluated in future studies.

In the present study, cement space was set at 80 μm, as recommended by the CEREC machine manufacturer (MC XL model, Sirona Dental Systems).[27] In the case of crowns, an improved marginal adaptation has been reported to reduce cement space.[45] In the present study, there was a significant difference in marginal adaptation between the materials, the manufacturing processes, and the methods with and without the crystallization firing process. In this study, the cement space was set based on past studies; however, the compatibility in the setting of cement space should be assessed in future studies. The cement space width may be an important factor determining the prognosis of CAD/CAM inlay restorations; however, there is no consensus regarding the optimal size of the space.[27] In the long run, deep grooves on the edges of ceramic inlay repairs can cause ceramic or enamel breakage. Therefore, improving the suitability of inlays leads to a reduction in cement lines and may contribute to the long-term stability of ceramic inlays.

CONCLUSIONS

The type of silica-based ceramic CAD/CAM material affected marginal adaptation compatibility but not internal compatibility of MO inlays. However, adaptation to the cavity was considered clinically acceptable for all materials. The marginal adaptation was excellent with the one-step production process; however, there was no difference in the internal adaptation between the two fabrication methods. The crystallization firing process affected the marginal adaptation of inlays made of lithium silicate or lithium disilicate glass-ceramics.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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