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Influence of Different CAM Strategies on the Fit of Partial Crown Restorations: A Digital Three-dimensional Evaluation

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Clinical Relevance

Ideal fit of CAD/CAM fabricated indirect restorations is important for high clinical long-term success. Insufficient CAM milling strategies may lead to adaption discrepancies of the restoration resulting in poor occlusal fit and microleakage.

ABSTRACT

Objective: CAM fabrication is an important step within the CAD/CAM process. The internal fit of restorations is influenced by the accuracy of the subtractive CAM procedure. Little is known about how CAM strategies might influence the fit of CAD/CAM fabricated restorations. The aim of this study was to three-dimensionally evaluate the fit of CAD/CAM fabricated zirconia-reinforced lithium silicate ceramic partial crowns fabricated with three different CAM strategies. The null hypothesis was that different CAM strategies did not influence the fitting accuracy of CAD/CAM fabricated zirconia-reinforced lithium silicate ceramic partial crowns.

Methods and Materials: Preparation for a partial crown was performed on a maxillary right first molar on a typodont. A chairside CAD/CAM system with the intraoral scanning device CEREC Omnicam (Dentsply Sirona, York, PA, USA) and the 3+1 axis milling unit CEREC MCXL was used. There were three groups with different CAM strategies: step bur 12 (12), step bur 12S (12S), and two step-mode (12TWO). The zirconia-reinforced lithium silicate ceramic Celtra Duo (Dentsply Sirona) was used as the CAD/CAM material. A new

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3D method for evaluating the fit was applied, consisting of the quadrant scan with the intraoral scanning device CEREC Omnicam. The scan of the PVS material adherent to the preparation and the preparation scan were matched, and the difference analysis was performed with special software OraCheck (Cyfex AG, Zurich, Switzerland). Three areas were selected for analysis: margin (MA), axial (AX), and occlusal (OC). Statistical analysis was performed using 80% percentile, one-way ANOVA, and the *post hoc* Scheffé test with α=0.05.

Results: Statistically significant differences were found both within and between the test groups. The aspect axial fit results varied from 90.5 ± 20.1 μm for the two-step milling mode (12TWO_AX) to 122.8 ± 12.2 μm for the milling with step bur 12S (12S_AX). The worst result in all groups was found for the aspect occlusal fit with the highest value for group 12S of 222.8 ± 35.6 μm. Group two-step milling mode (12TWO) performed statistically significantly better from groups 12 and 12S for the occlusal fit (p<0.05). Deviation patterns were visually analyzed with a color-coded scheme for each restoration.

Conclusions: CAM strategy influenced the internal adaptation of zirconia-reinforced lithium silicate partial crowns fabricated with a chairside CAD/CAM system. Sensible selection of specific areas of internal adaptation and fit is an important factor for evaluating the CAM accuracy of CAD/CAM systems.

INTRODUCTION

Computer aided design/computer aided machining (CAD/CAM) technology has become a common fabrication technique for dental restorations.[1] The CAD/CAM workflow is composed of three essential steps.[2] The first step is to record the intraoral geometry of the dentition in a computer program in the form of a digital file. The second step involves a software program for computer modeling of the desired shape of the proposed restoration. The third step involves machining the designed restoration from a millable restorative CAD/CAM material. CAD/CAM technology is available for both laboratory and in-office applications.

The CAM process for current chairside CAD/CAM systems is subtractive milling. The CAM milling unit may utilize either carbide or diamond instruments for shaping the designed restoration from a premanufactured block of restorative CAD/CAM material. The main instruments used for milling acrylic and zirconia material are carbide, whereas diamond instruments are the chief type used for grinding resin-based and glass ceramic materials.

The accuracy of the CAM procedure is an obvious key factor in the final fit and adaptation of the restoration. There are several primary items that can influence the accuracy of the CAM milling process. Both milling instrument geometries, such as diameter, length, and type of instrument, and the CAD/CAM software parameter setting will influence the relief space created during the milling process between the imaged tooth preparation and the internal surface of the restoration.[3-6] The different machinability of CAD/CAM materials may be an additional factor influencing the internal adaption of CAD/CAM fabricated restorations. Brittle ceramic materials may behave differently from resin-based composite materials when milled with a CAD/CAM system.[7,8] In the literature, the overall selection of all individual CAM manufacturing parameters is often summarized with the term "CAM strategy."[2,6]

The most commonly used in-office CAD/CAM milling machines are 4-axis milling units. Today, the most popular chairside CAD/CAM system is the CEREC system. The MCXL milling unit (Dentsply Sirona, York, PA, USA) is a 3+1 axis milling machine that contains two or four motors with the option to use different instruments for milling. For fabricating glass-ceramic restorations, three different CAM strategies are currently available for the CEREC MCXL milling unit. When grinding glass-ceramics, the MCXL milling unit can be equipped with three different-sized diamond instruments (step bur 12S, step bur 12, and cylinder pointed bur 12S).

Although restorative material manufacturers work closely with software engineers to determine optimum milling paths for a specific material, milling paths and milling instruments are often preset in the CAD/CAM software. Especially for chairside CAD/CAM systems parameters, the different CAM milling strategies are often predefined and are not adjustable.

Zirconia-reinforced lithium silicate-ceramic (ZLS) is a new CAD/CAM glass-ceramic material that contains 10% by weight of 500-800 nm zirconia dispersed within a glass matrix.[9] It is available as a completely crystallized block. ZLS ceramics can be used for high-strength partial coverage crowns, and the postmilling processing that might affect restoration fit is not required. ZLS CAD/CAM restorations do not need oven firing as do lithium disilicate ceramic CAD/CAM restorations such as e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein). ZLS ceramics can be hand polished prior to adhesive insertion and are thus suitable for chairside esthetic CAD/CAM restorations.

No controlled studies are available that investigate the possible change in dimensional fit and adaptation for ZLS restorations milled with different CAM strategies. The aim of this study was to three-dimensionally evaluate the marginal fit and internal adaptation of chairside CAD/CAM fabricated ZLS partial crowns using different CAM strategies. The null hypothesis was that different CAM strategies do not influence the marginal fit and internal adaption of chairside CAD/CAM fabricated ZLS partial crowns.

METHODS AND MATERIALS

This study represents an *in vitro* study. Preparation of a master partial crown was performed on a typodont on the maxillary right first molar. Tooth preparation was done according to recommended guidelines for all-ceramic partial crowns.[10] The preparation guidelines were 1.5 mm anatomical reduction of the palatal cusp with a butt-joint facial margin and an occlusal plateau with a mesiodistal standard inlay preparation. All internal angles were rounded and the deviation angle of the axial walls varied between 4° to 6°.

A chairside CAD/CAM system (CEREC, Dentsply Sirona) was used to fabricate the partial crowns. The powder-free intraoral scanning system CEREC Omnicam (Dentsply Sirona) was used to make a quadrant scan of the preparation. The manufacturer's recommendations of the scanning technique were respected.[11] The CAD design was performed with CAD software (CEREC SW v.4.0) using the biogeneric individual design mode. The parameter settings for the restoration were set to the manufacturer's recommendations with a spacer of 80 μm, margin thickness of 0 μm, minimum radial thickness of 400 μm, and minimum occlusal thickness of 1500 μm. Zirconia-reinforced lithium silicate-ceramic (ZLS) Celtra Duo (Dentsply Sirona) was selected as the CAD/CAM material.

A 3+1 axis milling unit CEREC MCXL (Dentsply Sirona) was used for CAM fabrication. There were three different groups corresponding to the three different CAM strategies available for grinding glass-ceramics with the MCX milling unit (group 12, group 12S, and group 12TWO). The MCXL milling unit was equipped with different milling instruments for each group: Groups 12 and 12TWO used two microfine diamonds, step bur 12, and cylinder pointed bur 12S; group 12S, two microfine diamonds, step bur 12S, and cylinder pointed bur 12S. The diameter sizes of the instruments were as follows: step bur 12, tip diameter 0.95 mm; step bur 12S, tip diameter 1.35 mm; and cylinder pointed bur 12S, tip diameter 1.75 mm. All diamond instruments had 65-micron grit grain size. Step bur instruments were used for subtractive milling of the inner surface of the restoration and cylinder pointed instruments for the outer surface. Geometry for the milling instruments used in this study is shown exemplarily in Figure 1.

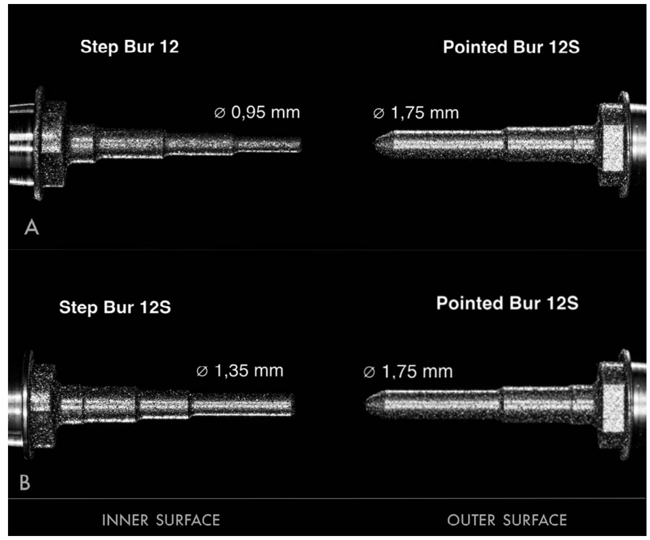

Figure 1. *Diamond instruments used for fabricating zirconia-reinforced partial crown CAD/CAM restorations with the CEREC MCXL milling unit. Different instrument setups (A, B) and milling paths were used for the respective groups; group 12: normal milling with instruments A; group 12S: normal milling with instruments B; and group 12TWO: two-step milling with instruments A.*

Milling modes were different for the respective groups. Group 12: normal milling mode (Figure 1: instruments A); group 12S: normal milling mode (Figure 1: instruments B); group 12TWO: two-step milling mode (Figure 1: instruments A). With the normal milling mode, the partial crown restoration was already ground in its final form. With the two-step milling mode, the restoration was first ground with the 200 μm restoration material left before the rest of the material was removed with the same instruments in a second circulation of the instruments. The milling time was almost double for group 12TWO than for groups 12 and 12S. In total, there were three different CAM strategies using different

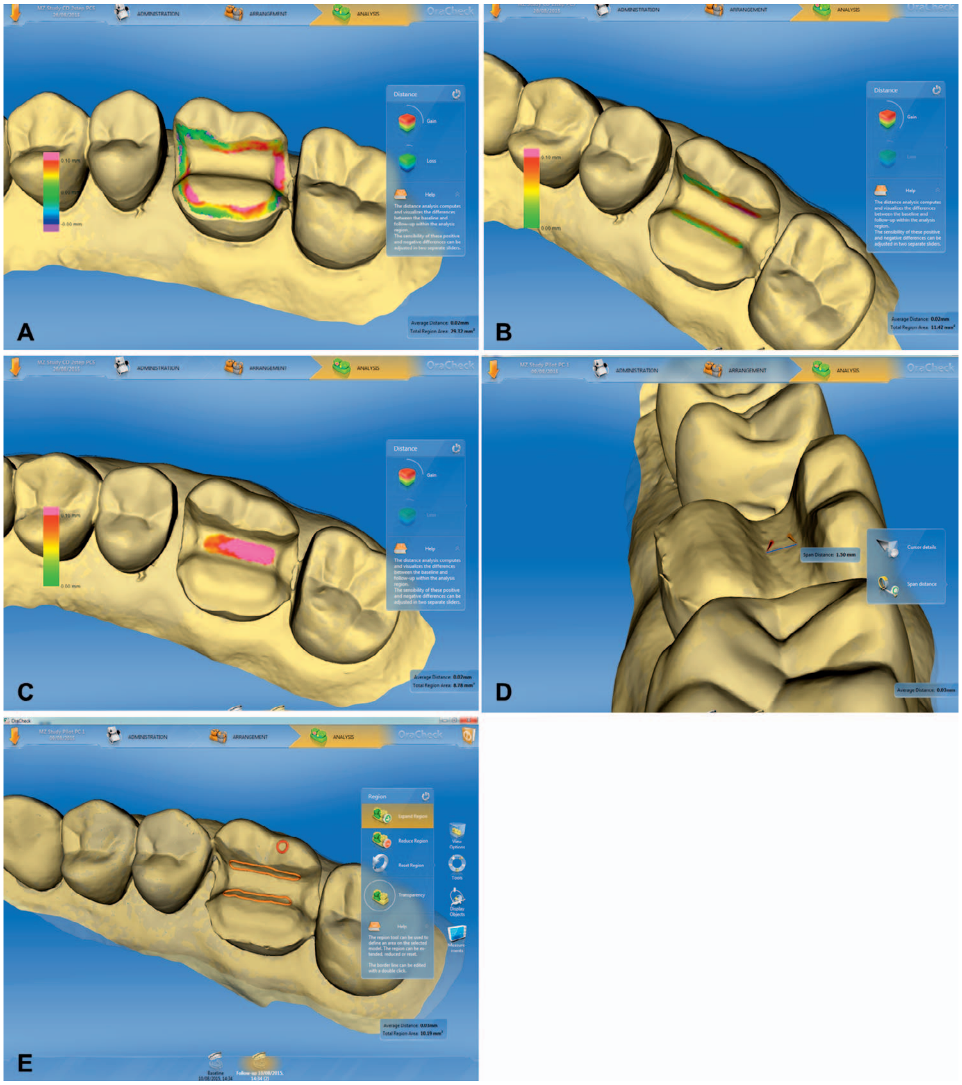

Figure 2. *Three-dimensional evaluation of the margin fit and internal adaptation of two-step milling mode fabricated partial crown. Three areas were selected: (A) margin; (B) axial; and (C) occlusal. Difference analysis with software OraCheck. Deviation pattern color coded with (+100 μm; red). Digital measuring tools such as "span distance" implemented within OraCheck software were used to ensure identical selection of the respective areas (D, E).*

milling instruments and milling paths that were investigated in this study.

For each test group, 10 partial crown restorations were fabricated (n = 10). Milling instruments and water were changed after each 10 restorations. No internal adjustments nor any postprocessing protocols were made on the restorations after grinding.

In this study, a special three-dimensional technique with a proprietary software program (OraCheck, Cyfex AG, Zurich, Switzerland) was done to evaluate the marginal fit and internal adaptation. First, the preparation was scanned using an intraoral scanner (CEREC Omnicam, Dentsply Sirona). Second, a polyvinylsiloxane impression recording the marginal fit and internal adaptation of each restoration was performed. The inner surface of each restoration was wiped with a lubricant (Vaseline) and a thin layer of light body polyvinylsiloxane impression material (Aquasil Ultra LV, Dentsply Sirona) was applied to the inner surface of the partial crown. The restoration was seated on the master preparation with moderate finger pressure for 15 seconds with approximately 25.0 N. Excess PVS material was carefully removed from the margins. After a setting time of 2 minutes, the partial crown was carefully removed from the preparation with the polyvinylsiloxane impression material left on its surface. Then, a second quadrant scan with the intraoral scanning device CEREC Omnicam (Dentsply Sirona) of the preparation was performed with the PVS material covering the preparation. The second scan was thus a replica of the adhesive cement space representing the marginal fit and internal adaptation.

Dimensional differences between the two recorded quadrant scans were analyzed with a proprietary

Table 1: *Results of Margin Fit and Internal Adaptation of ZLS Partial Crowns Fabricated With Three Different CAM Strategies (12, 12TWO, 12S)* [a]

Group	Area	n	Mean	SD	Min	Max	95% Confidence Interval	
							Lower	Upper
(12) step bur 12, normal milling	MA	10	120.4	11.9	103.8	141.6	111.9	128.9
	AX	10	96.9	12.0	80.2	117.6	88.4	105.5
	OC	10	215.8	14.4	201.8	250.0	205.5	226.0
(12TWO) step bur 12, two-step milling	MA	10	110.3	22.2	71.1	148.8	94.4	126.1
	AX	10	90.5	20.1	63.9	130.6	76.1	104.8
	OC	10	155.0	40.1	108.1	244.8	126.4	183.7
(12S) step bur 12S, normal milling	MA	10	144.6	14.4	121.4	164.2	134.3	154.9
	AX	10	122.8	12.2	111.1	142.9	114.1	131.5
	OC	10	222.8	35.6	176.7	297.0	197.3	248.3

[a] *Three areas were selected for 3D analysis: margin (MA), axial (AX), and occlusal (OC). Difference values were calculated as 80% percentile (μm).*

three-dimensional software program (OraCheck, Cyfex AG) for each test's partial crown. The principle of OraCheck software has recently been described in the literature.[12] First, the two scans were imported into the OraCheck software and superimposed using the software's best-fit algorithm. Second, subtractive analysis was performed by an automatic calculation of the distances between previously selected areas of interest. A point-to-surface distance approach was used in the study. An approximately 20,000 points-per-surface matching process was selected. There were three different regions of interest to evaluate the marginal fit and internal adaption. The margin area included the circumferential area of the preparation within 0.5 mm of the preparation margin line. The axial adaptation included a 0.5 mm diameter region for both the entire inner buccal and oral walls of the preparation. The occlusal surface (OC) adaptation included a 1.5 mm diameter occlusal plateau within the mesial and distal inlay slot preparation. The respective areas selected are shown in Figure 2 A-C. Selection of the respective areas, such as "span distance," was ensured with digital measuring instruments, implemented within the OraCheck software. The method of selecting the respective areas for the axial and occlusal aspect of the partial crowns is shown exemplarily in Figure 2 D-E.

The differences between the two superimposed digital files were measured by mathematically calculating the 80% percentile value. Values were exported as a CSV file and imported into statistical analysis software (SPSS v24.0, IBM Statistics, Armonk, NY, USA). The Kolmogorov-Smirnoff test was used for normal distribution of the data. The Levène test was used for homogeneity of variances. Descriptive statistics, including the mean, median, standard deviation, and 95% confidence interval, were calculated for each group. Statistical analysis was performed with one-way ANOVA and *post hoc* Scheffé test (α=0.05).

RESULTS

The results showed a normal distribution with equality of variances. Results for the fitting accuracy of a partial crown restoration with different CAM strategies are shown in Table 1. A box plot with median values is shown in Figure 3.

One-way ANOVA and *post hoc* Scheffé tests revealed statistically significant differences for the values both within and between the test groups ($p<0.05$). Homogenous subsets for one-way ANOVA with *post hoc* Scheffé test for all test groups are shown in Table 2.

For the aspect axial fit, results varied from 90.5 ± 20.1 μm (group 12TWO_AX) to 122.8 ± 12.2 μm (group 12S_AX). For the aspect margin fit, results varied from 110.3 ± 22.2 μm (group 12TWO_MA) to 144.6 ± 14.4 μm (group 12S_AX). The worst fit was found for the aspect occlusal fit in all groups, with the highest value for group 12S with 222.8 ± 35.6 μm (group 12S_OC). For the aspect occlusal fit, two-step milling with step bur 12 (group 12TWO_OC) performed statistically significantly better than did groups 12 (group 12_OC; $p<0.01$) and 12S (group 12S_OC; $p<0.01$). For both aspects axial fit and marginal fit, no statistically significant differences were found within all three test groups ($p>0.05$).

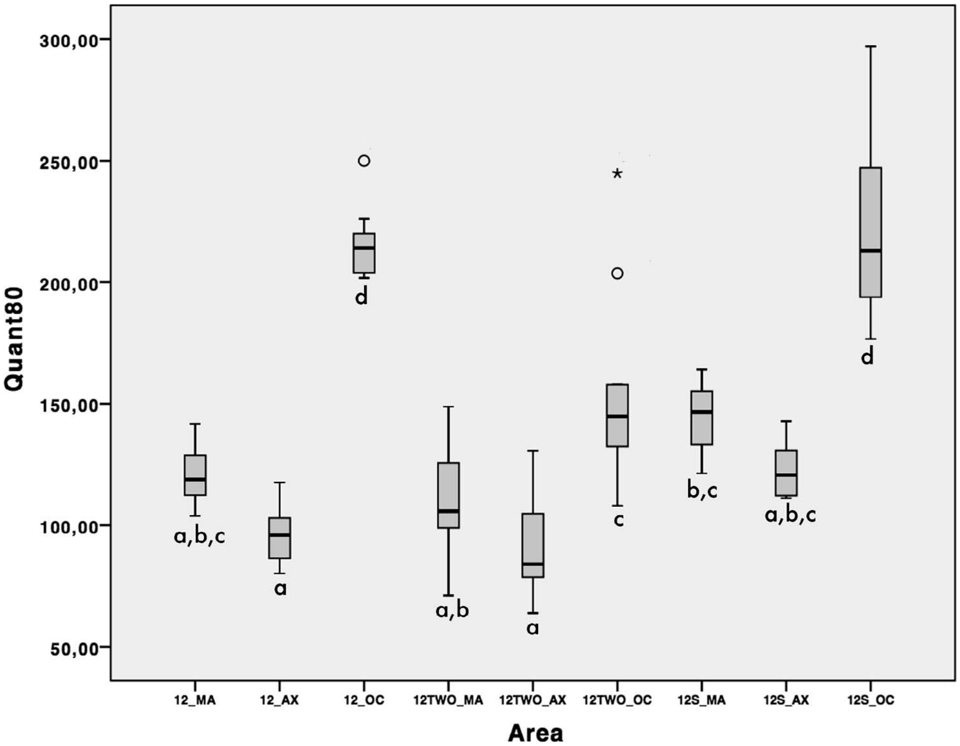

Figure 3. *Box plot for evaluating margin fit and internal adaptation of partial crowns fabricated with three different CAM strategies (step bur 12; 12), (two-step mode; 12TWO), and (step bur 12S; 12S). Three areas were selected for 3D analysis: margin (MA), axial (AX), and occlusal (OC). Mean precision for test groups is represented by the bar, circles represent outliers. Difference values were calculated as 80% percentile (μm). No statistically significant difference for box plots with same superscript letters.*

DISCUSSION

The aim of this study was to three-dimensionally evaluate the fit of CAD/CAM-fabricated ZLS partial crowns fabricated with three different CAM strategies. Based on the results found in this study, the null hypothesis is rejected. Statistically significant differences were found both within and between the test groups ($p<0.05$). For all aspects of internal fit investigated in this study, the two-step milling mode (group 12TWO) performed superiorly to normal milling with step bur 12 (group 12) and normal milling with step bur 12S (group 12S). Statistical significance could be found only for aspect OC between the three groups ($p<0.05$). In terms of area, the milling accuracy of occlusal areas performed worst for all milling strategies. In terms of milling strategies, the milling accuracy with instrument step burs 12S (group 12S) performed worst for all areas. There are several results that need to be discussed.

The CEREC MCXL used in this study is a 3+1 axis milling machine. The CAD/CAM block can be rotated and moved vertically while two instruments work simultaneously within the other three dimensions.

Table 2: *Homogenous Subsets for Test Groups. No Statistically Significant Difference for Values Within One Subset Group.* [a]

Material_Area	n	Subsets for Alpha = 0.05			
		1	2	3	4
12TWO_AX	10	90.5			
12_AX	10	96.9			
12TWO_MA	10	110.3	110.3		
12_MA	10	120.4	120.4	120.4	
12S_AX	10	122.8	122.8	122.8	
12S_MA	10		144.6	144.6	
12TWO_OC	10			155.0	
12_OC	10				215.8
12S_OC	10				222.8
Sig		.268	.195	.185	1.000

[a] *Statistical analysis with one-way ANOVA and* post hoc *Scheffé test. Significance level (α=0.05) (μm).*

The step bur instrument mounted on the left motor of the MCXL milling unit is used for subtractive milling of the inner surface, whereas the cylinder-pointed instrument mounted on the right motor is used for subtractive milling of the outer surface. Because of the limited degree of freedom of the CEREC MCXL milling unit, only specific sides of the instruments are used for the subtractive milling process. Steep areas of the inner surface such as axial walls and outer marginal contours are milled with the outer edge of the step bur instrument. Flat areas of the inner surface are milled with the tip of the instrument. Thus, because of dimensional discrepancies between instrument size and inner geometry of the restoration, milling inaccuracies might occur predominantly for occlusal surfaces of the CAD/CAM restoration. This affirmation is consistent with the results found in this study. All milling strategies showed the worst internal fit for the occlusal area, while the two-step milling mode (group 12TWO) performed statistically significantly better. Marginal areas and axial walls showed fewer milling discrepancies and a better internal fit. These findings are a direct result of the technical specifications of the CEREC MCXL milling unit.

The tip diameter of the step burs used in this study varied from 0.95 mm for the step bur 12 to 1.35 mm for step bur 12S. To ensure milling accuracy of flat surfaces such as the occlusal plateau of partial crowns, the tip diameter of the instrument is extremely important. When oversized instruments such as the step bur 12S are used, so-called over-milling occurs, resulting in a poor internal fit of the restoration. The results found in this study are in high agreement with this statement. The highest discrepancies for the occlusal area were found for group 12S. Group 12TWO_OC performed statistically significantly better than did groups 12_OC and 12S_OC. Results of this study are also in high agreement with published literature about the fit of different types of CEREC restorations where occlusal areas of crowns also showed the poorest fit of internal adaptation.[13,14]

Results of this study demonstrate that, even if identical milling instruments are used, the milling pathway might be highly decisive for the internal fit of restorations. For groups 12TWO and 12, the MCXL milling unit was equipped with the identical milling instrument step bur 12, but the machine used a different milling pathway for the instruments. The milling pathway is generally characterized by the x-, y-, and z-position of the instrument and its feeding rate as well as its revolutions per minute.[2] The higher the feeding rate, the higher the revolutions, the more abrasive the milling instrument, and the more material that is removed during subtractive CAD/CAM milling. Little can be found in the literature about the influence of different milling strategies on the internal fit of restorations. Most studies focus on the influence of the different parameter settings on the internal fit of restorations.[6,15]

CAD/CAM milling strategies must take into account the respective CAD/CAM material. In this study, ZLS Celtra Duo (Dentsply Sirona) was selected as the material. ZLS ceramic is a new CAD/CAM glass-ceramic material containing 10% by weight 500-800 nm zirconia dispersed within a glass matrix.[9] The material indication of ZLS ceramic includes full coverage restorations such as partial crowns. The crystallite size of ZLS is smaller than that of lithium disilicate ceramics such as e.max CAD (Ivoclar Vivadent), thus making ZLS ceramic highly favorable for subtractive CAD/CAM milling procedures.[9] Other studies have reported that various margin stabilities of CAD/CAM materials are a direct result of their material composition.[16] Compared with ZLS ceramics, particle-filled composite materials might possess a superior margin stability and, thus, better machinability, resulting in a superior internal fit of CAD/CAM restorations. It would also be interesting to investigate the influence of CAM strategies on different CAD/CAM materials.

Interestingly, no recommendation is given by the manufacturer of the 3+1 axis CAM machine that has been used in this study for the ideal CAM strategy for ZLS. However, our findings suggest that ideal CAM strategies are possible with respect to the respective CAM machining process and its parameters such as type of CAD/CAM material and restoration design. Ideally, by combining all individual parameters possible for the CAM machining process, the final CAM machining outcome and thus the marginal and internal fit of the restoration could be significantly improved.

Grinding glass ceramic materials is generally accomplished with diamond instruments. Little is reported in the literature about the influence of tool wear on the milling accuracy of CAD/CAM restorations.[17] In this study, diamond instruments were renewed after each 10 restorations to minimize the effect of tool wear. It might be interesting to further investigate the aspect of tool wear as a function of the respective CAM strategy used. The idea of the two-step milling mode is to reduce the pressure of the milling instruments on the restoration by initially leaving about 200 μm rest material on the object to be milled. On the one hand, this approach might result in fewer material break-outs and thus a better internal fit of restorations, but on the other hand, this might also prolong the durability of the milling instruments. Further investigation seems to be necessary to elucidate this aspect in more detail.

The method of evaluating the fit of a restoration needs discussion. In the literature, mostly 2D methods in the form of a replica technique are used.[18] However, 2D methods seem to be less favorable than 3D as only point-to-point measurements can be carried out. The 2D method does not allow an entire circumferential analysis and can thus be seen only as an approximation because preselected points and distances instead of real geometries are used. In this study, approximately 20,000 points were used for the 3D analysis of each specimen. This is in strong contrast to the usual three to five linear measurements usually performed for 2D analysis. 3D methods may thus provide a better interpretation of restoration fit. Only a few 3D methods have been described in the literature, and all those are highly technique sensitive and not easily applicable.[19,20] The 3D method described in this study using intraoral scanning devices represents a far more clinically applicable approach. However, it does not represent a full digital approach and can be designated a 3D hybrid method as it describes the digitalization of an analog silicone layer and its further digital assessment.

The *in vivo* precision of the CEREC Omnicam intraoral scanner used in this study has been described in the recent literature for quadrant and full-arch scans with 37.4 ± 8.1 μm and 48.6 ± 11.6 μm, respectively (mean ± SD).[21,22] In this study, quadrant scans of a typodont were performed with local analysis of a single tooth area. Digital models are always a result of a matching process of single images with specific overlapping areas. Insufficient scientific data are available that analyze intraoral scanners' local accuracy for small regions such as a single tooth. It is important to mention that both complex geometric information, lack of surface texture details, *in vivo* conditions, and incorrect scanning strategy might significantly worsen the local scanning accuracy of intraoral scanners. Our own data (not yet published) reveal that the ideal *in vitro* accuracy of the CEREC Omnicam can be up to 10-15 μm for single teeth.

Many studies investigating the fit of restorations focus only on the overall internal fit.[5] This study represents a unique approach, investigating specific areas of internal fit three-dimensionally dependent on different CAM strategies using intraoral scanning. Many factors influencing the final fit of restorations have been described in the literature.[6,23,24] Several consequences have been reported for poor internal fit of restorations such as secondary caries, periodontal inflammation, retention loss, pulpal inflammation, and reduced fracture toughness.[25-27] This study thus demonstrates the clinical importance of the proper choice of CAM strategy as one important variable for the fitting accuracy of CAD/CAM fabricated restorations within the digital workflow. Because of the rapid development of CAD/CAM technology, improvements in the field of CAM fabrication are highly likely to occur in the future.

CONCLUSION

CAM strategy influenced the internal adaptation of ZLS partial crowns fabricated with a chairside CAD/CAM system. Sensible selection of specific areas of internal adaptation and fit is an important factor in evaluating CAM accuracy of CAD/CAM systems.

Conflict of Interest

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

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