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RESEARCH AND EDUCATION

Effects of preparation design on the marginal and internal fit of CAD-CAM overlay restorations: A µCT evaluation

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ABSTRACT

Statement of problem. The effects of different finish line designs on the seating accuracy of partial indirect restorations are unclear.

Purpose. The purpose of this in vitro study was to evaluate the influence of different preparation designs on the marginal and internal discrepancy of lithium disilicate computer-aided design and computer-aided manufacture (CAD-CAM) partial indirect restorations before and after thermomechanical aging by using 3-dimensional (3D) microcomputed tomography (µCT).

Material and methods. Forty human molars were divided according to the preparation design and their location relative to the tooth survey line: SO: rounded shoulder occlusal to the survey line; CO: chamfer occlusal to the survey line; SA: rounded shoulder apical to the survey line; CA: chamfer apical to the survey line (n=10). Ceramic onlays were luted using a universal resin cement (RelyX Universal + Scotchbond Universal Plus). The specimens underwent thermomechanical loading in a mastication simulator (1 200 000 mechanical and 5000 thermal cycles). The marginal and internal discrepancy was evaluated with µCT before and after aging. The volume of cement and internal voids was evaluated with 3-dimensional imaging. The marginal discrepancy (MD), absolute marginal discrepancy (AMD), axial gap (AG), and occlusal gap (OG) were quantified using 2-dimensional analyses. Data were statistically analyzed using a 2-way ANOVA and the Tukey post hoc test (α=.05).

Results. Preparation designs apical to the survey line resulted in a larger volume of cement compared with those occlusal to the survey line (P<.05). No differences were observed in the internal voids among the groups immediately or after aging (P>.05). Both preparation designs and aging had a significant influence on the MD, AMD, AG, and OG (P<.05). Specifically, CB exhibited significantly greater values for AMD, MD, AG, and OG compared with all other preparations (P<.05). CA and SA performed significantly worse than CO and SO in terms of AMD and MD (P<.005).

Conclusions. Preparations located occlusal to the survey line, particularly CO, demonstrated superior results with respect to both marginal and internal adaptations. CA exhibited the least favorable adaptation among the preparations investigated. Aging had a detrimental impact on the marginal adaptation of the restorations, regardless of the specific preparation design used. (J Prosthet Dent 2025;133:1055.e1-e10)

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Clinical Implications

Locating the restoration margin occlusal to the survey line is recommended to enhance the marginal and internal precision of computer-aided design and computer-aided manufactured lithium disilicate partial indirect restorations. However, circumstances may necessitate preparation below the survey line, in which case preparing a shoulder finish line is recommended to minimize variability and optimize restoration precision.

Recent advances in adhesive dentistry have enabled a minimally invasive approach that preserves healthy tooth tissue and favors indirect partial restorations over traditional complete crowns.[1] Concurrently, the use of new materials and computer-aided design and computer-aided manufacture (CAD-CAM) technology has become popular in dentistry.[1,2] In CAD-CAM restorations, poor adaptation may arise because of constraints in the software program design, hardware limitations in 3-dimensional (3D) image capturing, and the milling process.[3,4] The definition of the minimum acceptable precision at the restoration margin has been widely debated in the literature.[5–13] Nevertheless, it has been well established that poor marginal or internal adaptation poses a threat to their longevity by leading to complications such as cement dissolution, microleakage, increased plaque retention, and the risk of caries and periodontal disease.[14–20] Poor marginal and internal adaptations can adversely affect the fracture strength of restorations because of higher stress concentrations at the margins and/or intaglio surfaces.[21–23]

Holmes et al[24] proposed a classification for marginal and internal adaptation in 1989, defining marginal discrepancy (MD) as the perpendicular measurement from the intaglio surface of the restoration to the axial wall of the preparation at the margin and defining the absolute marginal discrepancy (AMD) as the angular combination of the marginal gap and the extension error. The axial (AG) and occlusal gaps (OG) were defined as the perpendicular measurement from the internal surface of the restoration in its axial or occlusal portion (Fig. 1). Various factors, including the cement viscosity,[25,26] cementation technique,[26] aging,[27–30] milling system,[31–33] and finish line design, have been reported to influence the precision of indirect restorations.[34] The current body of literature fails to provide definitive insights into the influence of the different finish line designs on the seating accuracy of indirect partial-coverage restorations. For these reasons, this study aimed to assess the marginal fit, internal fit, and cement volume of lithium disilicate (LiSi) CAD-CAM partial-coverage restorations

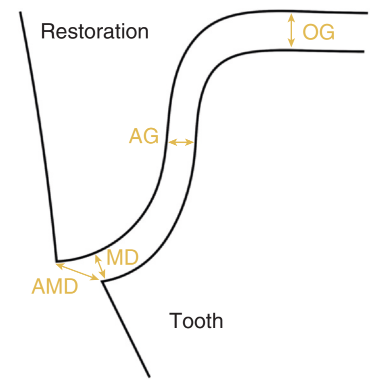

Figure 1. Graphical representation of parameters evaluated in study. AG, axial gap; AMD, average marginal discrepancy; MD, marginal discrepancy; OG, occlusal gap.

based on the preparation designs and on the distances of the preparation margin from the cementum-enamel junction (CEJ) (4 or 1.5 mm). The assessments were conducted immediately after cementation and after thermomechanical aging by using microcomputed tomography (μCT)-based analysis. The null hypotheses were that the preparation design would not impact the marginal and internal fit or the cement volume of CAD-CAM lithium disilicate onlays and that thermomechanical aging would have no influence on the marginal and intaglio fit or the cement volume of CAD-CAM lithium disilicate onlays.

MATERIAL AND METHODS

The abbreviations used in the paper are listed in Table 1. A software package (G*Power Ver. 3.1.5; Heinrich-Heine-University Düsseldorf) was used to determine the sample size based on the effect difference observed in a previous pilot study (f =0.711). With a confidence level of 95% ($1-\alpha$) and power of 90% ($1-\beta$), the required sample size for each group was determined to be 9. Forty noncarious, sound human molars obtained from individuals following informed consent under a protocol

Table 1. Abbreviations used and their definition

Abbreviation	Definition
AG	Axial gap
AMD	Absolute marginal discrepancy
CA	Circumferential chamfer apical to the survey line
CO	Circumferential hollow chamfer occlusal to the survey line
CV	Volume of the cement
MD	Marginal discrepancy
OG	Occlusal gap
PD	Preparation design
SA	Circumferential rounded shoulder preparation apical to the survey line
SO	Circumferential rounded shoulder preparation occlusal to the survey line
SL	Survey line
VV	Volume of the voids

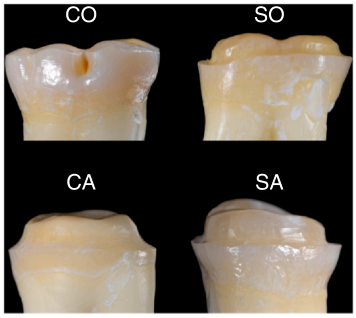

Figure 2. Buccal view of tooth preparations for partial ceramic crown. CA, chamfer preparation apical to survey line; CO, chamfer preparation occlusal to survey line; SA, shoulder preparation apical to survey line; SO, shoulder preparation occlusal to survey line.

approved by the Ethical Committee of the University of Bologna (protocol No: 71/2019/OSS/AUSLBO) were preserved in a 0.5% chloramine T solution at 4 °C for up to 1 month after extraction. Digital scans were acquired from each tooth before preparation (Primescan; Dentsply Sirona) and used for the design of the ceramic restoration. The teeth were assigned to 4 groups according to the different preparation designs (n=10) (Fig. 2): CO: circumferential hollow chamfer occlusal to the tooth survey line (SL) (4 mm from the CEJ); SO: circumferential rounded shoulder preparation occlusal to the SL (4 mm from CEJ); CA: circumferential chamfer apical to the SL (1.5 mm from CEJ); and SA: circumferential rounded shoulder preparation apical to the SL (1.5 mm from CEJ). To control the apical-occlusal margin position before preparation, the planned margin line was marked with a pencil at a height of 4 mm or 1.5 mm from the CEJ as measured with a periodontal probe (CP-15; Hu-Friedy). Standardized preparations with different finish lines were performed on each tooth by following lithium disilicate guidelines (1.5 mm occlusal reduction, 1 mm reduction at the preparation axial walls, rounded edges, and 6-degree taper) (Fig. 3).[35] The teeth were prepared by a single experienced clinician (E.M.) using ×4.5 magnification to verify the preparation thickness using a silicone index (Elite HD+; Zhermack), a periodontal probe (CP-15), and a diamond rotary instrument (Neodiamond; Microcopy Dental) mounted on a red ring contra-angle handpiece (the rotary instruments used are reported in Table 2).[36–38] Following preparation, the teeth were digitized using the same intraoral scanner (Primescan). Subsequently, 40 CAD-CAM lithium disilicate onlay restorations (IPS e.max CAD; Ivoclar AG) were designed and milled (InLab MC XL; Dentsply Sirona). The luting space and adhesive gap were both set at 40 µm. The final sintering of the lithium disilicate restorations was performed after the milling procedure by following the manufacturer's instruction. Glazing (IPS e.max Ceram Glaze Paste; Ivoclar AG) and

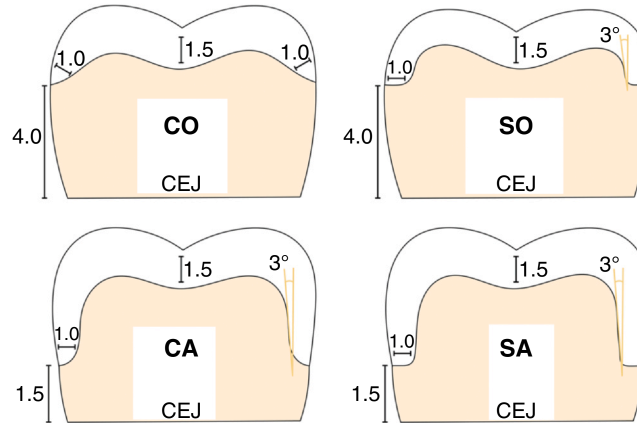

Figure 3. Graphical representation of preparation designs used in study. Measurements of tooth reduction and distance of preparation margin from cemento-enamel junction (CEJ) (mm). CA, chamfer preparation apical to survey line (1.5 mm from CEJ); CO, chamfer preparation occlusal to survey line (4 mm from the CEJ); SA, shoulder preparation apical to survey line (1.5 mm from CEJ); SO, shoulder preparation occlusal to survey line (4 mm from CEJ).

a standard cooling procedure were then applied. The intaglio surfaces of the restorations were etched with 4.9% hydrofluoric acid (IPS Ceramic Etching gel; Ivoclar AG) for 20 seconds, rinsed with water spray, and cleaned in a 70% ethanol ultrasonic bath for 5 minutes. The LiSi onlays were luted with dual-polymerizing RelyX Universal composite cement (3M ESPE) using Scotchbond Universal Plus Adhesive (3M ESPE). The teeth were etched with 37% phosphoric acid (Ultra Etch; 3M ESPE) for 30 seconds on enamel and 15 seconds on dentin. Scotchbond Universal Plus adhesive was applied to the tooth for 20 seconds and gently dried for 5 seconds. The resin cement was loaded into the onlays, which were seated on the prepared teeth and held in position by a device. A 40-N load was applied using a parallelometer with a spherical stainless-steel tip on the occlusal surface. Excess cement was removed, and glycerin gel (Liquid Strip; Ivoclar AG) was applied to the margins. All restoration surfaces were then polymerized with a light-emitting diode (LED) unit (Elipar DeepCure-S; 3M ESPE) at 480 nm and 1110 mW/cm² for 20 seconds per surface. Excess cement was removed with a scalpel and flexible disks (SoftLex Pop-On; 3M Medica) under magnification. After 24-hour storage in distilled water at 37 °C, the specimens were subjected to cyclic intermittent loading in distilled water for 1 200 000 cycles using a mastication simulator (CS-4; SD Mechatronik).[39] With the specimens positioned into chambers containing distilled water, a 98-N force was applied using a ø6-mm steatite ball as the antagonist.[39] The load was applied parallel to the long axis of the teeth (0 degrees) at a frequency of 1.6 Hz, speed=16 mm/second, sliding=2 mm over the buccal triangular crest. The

Table 2. Parameters and armamentarium used for different preparation designs occlusal to or apical to the survey line (SL)

Preparation Designs	Parameters	Rotary Instruments Employed ISO	References
Chamfer occlusal to SL	Margin placed 4 mm occlusal from CEJ Occlusal reduction: 1.5 mm 30-degree finish line	806 314 142 534 014 806 314 277 534 018 806 314 277 514 018 806 314 257 534 016 806 314 257 514 016	36
Shoulder occlusal to SL	Margin placed 4 mm occlusal from CEJ Occlusal reduction: 1.5 mm 1 mm finish line reduction 90-degree finish line	806 314 142 534 014 806 314 173 534 018 806 314 173 514 018 806 314 257 534 016 806 314 257 514 016	37
Chamfer apical to SL	Margin place 1.5 mm occlusal from CEJ Occlusal reduction: 1.5 mm 1 mm finish line reduction 60-degree finish line	806 314 142 534 014 806 314 198 534 021 806 314 198 514 021 806 314 257 534 016 806 314 257 514 016	38
Shoulder apical to SL	Margin placed 1.5 mm occlusal from CEJ Occlusal reduction: 1.5 mm 1 mm finish line reduction 90-degree finish line	806 314 142 534 014 806 314 173 534 018 806 314 173 514 018 806 314 257 534 016 806 314 257 514 016	38

CEJ, cemento-enamel junction; SL, survey line.

specimens were also subjected to 5000 thermal cycles between 5 °C and 55 °C for 60 seconds, each with a dwell time of 12 seconds[40,41] After 24 hours of storage in distilled water at 37 °C from the luting process (T0) and after thermomechanical aging (T1), the specimens were scanned using a microcomputed tomography (μCT) scan. The parameters were set for high resolution: voltage=100 kV, current=100 μA, (Al+Cu) filter, 10 μm pixel size, averaging=5, rotation step=0.1 degree. NRecon and Data Viewer software (Bruker Optik) were used to obtain 3D images from the Digital Imaging and Communications in Medicine (DICOM) files. An image-processing software program (Materialise Mimics; Materialise NV) was used for the volumetric analysis. For each tooth, the restoration was digitally separated from the dental tissues using the different Hounsfield values. The cement and the gaps were also isolated, and 4 standard tessellation language (STL) files were then exported: tooth, restoration, cement, and internal gaps both for T0 and T1 (Fig. 4A, B). Using a 3D analysis software program (Geomagic Control X; 3D Systems), the STL models were analyzed, and the volume of the cement (CV) and of the voids (VV) was acquired and calculated in μm^3. By using the Mimics software program, for every specimen in T0 and T1, 5 equidistant vertical cuts were made both in the buccolingual direction and in the mesiobuccal direction, giving 1000 slices between these cuts (corresponding approximately to 1 mm in distance). For each of these vertical cuts obtained, 12 points of measurement were selected: 2 measurements for MD and for AMD and 4 for OG and for AG (Figs. 5, 6). The measurements of the restorations were digitally acquired in μm.

A statistical software program (SigmaPlot v14.0; Systat Software Inc) was used for the statistical analysis. The normality of the distribution of the data was assessed with the Kolmogorov–Smirnov test, and the equality of variances using the Levene test (α=.05 for all tests). Since CV, VV, AMD, OG, and AG were normally and equally distributed, the 2-way analysis of variance (ANOVA) and

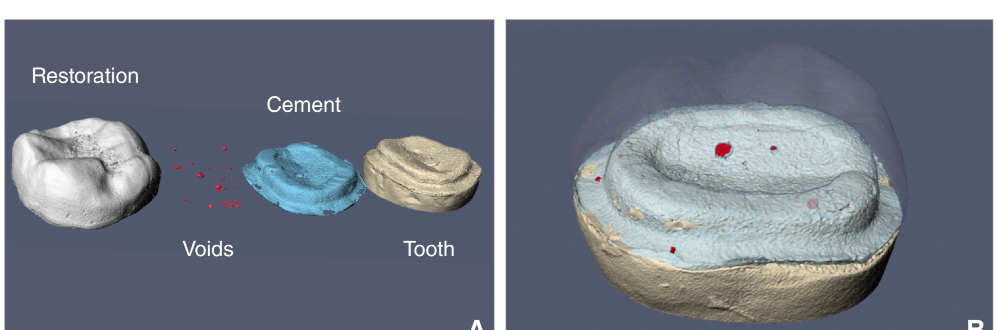

Figure 4. Three-dimensional rendering of components isolated through microcomputed tomography (μCT) scanning. A, Prepared tooth (*yellow*), cement layer (*light blue*), lithium disilicate restoration (*white*), and voids in luting space (*red*). Each element distinguished using specific Hounsfield values and reconstructed into standard tessellation language (STL) files. B, STL files presented in Figure 3A preserved in their spatial coordinates as extrapolated from μCT scanning process.

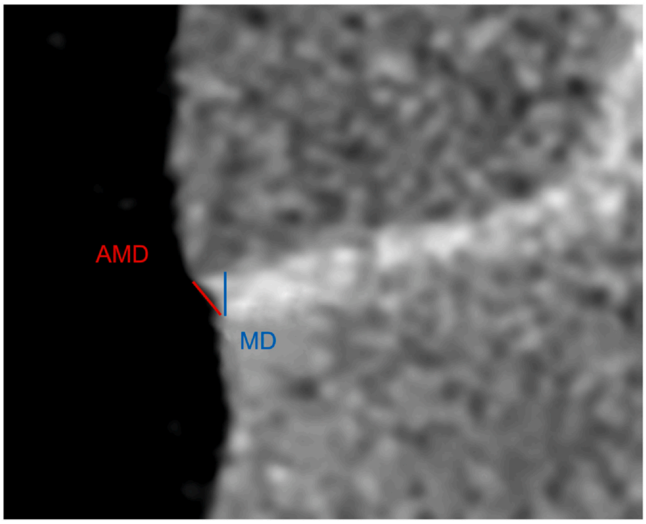

Figure 5. Microcomputed tomography scan image (magnified at margin area): measurement of marginal discrepancy (MD) (perpendicular distance between internal margin of indirect partial restoration and preparation margin on tooth, and absolute marginal discrepancy (AMD)(distance between restoration and tooth preparation margins).

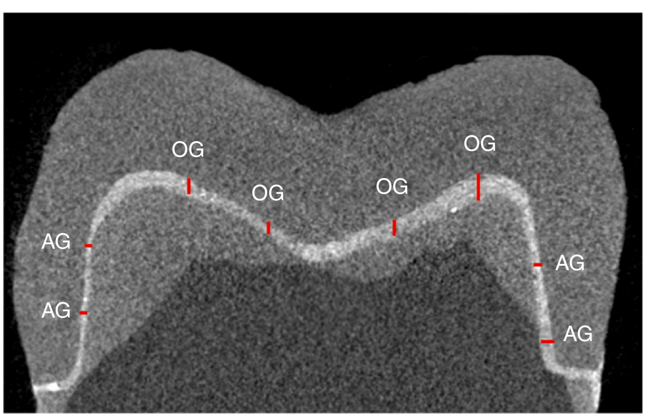

Figure 6. Microcomputed tomography scan image (vertical cut): measurement of axial gap (AG) and occlusal gap (OG) (measured distances perpendicular to ceramic restoration and tooth internal surfaces at selected points).

Tukey post hoc tests were used for multiple pairwise comparisons. MD was not normally distributed, so the Kruskal–Wallis test was used.

RESULTS

Table 3 shows the 3D measurements of CV and VV recorded at T0 and T1. Descriptive statistics for misfit measurements (AMD, MG, AG, and OG) at T0 and T1 are presented in Table 4. The various preparation designs had a statistically significant impact on CV (df=3, MS=625.841, F=10.893, *P*<.001), with preparations performed apical to SL (CA and SA) resulting in increased cement at the tooth-restoration interface. Aging did not influence the CV among the restorations (df=1, MS=46.821, F=0.815, *P*<.371), and the interaction between preparation design and aging was not statistically significant (*P*=.994). Regarding VV measurements, no statistically significant differences were observed among the PDs (df=3, MS=1.630, F=2.124, *P*=.107). Aging (df=1, MS=0.189, F=0247, *P*=.621) or the interaction with PDs (*P*=.921). MD was influenced by PD (*P*<.001), aging (*P*=.025), and the interaction between these factors (*P*<.001). CA had significantly higher MD values than other preparation designs (*P*<.001). Preparations apical to the SL (CA and SA) performed significantly worse than those occlusal to the SL (CO and SA) (*P*<.005). No differences were found between CO and SO (*P*=.903). AMD was influenced by PD (df=3, MS=4.870, F=16.675, *P*<.001) and aging (df=1, MS=2.682, F=9.184, *P*=.002), but their interaction was not significant (*P*=.089). CA exhibited significantly higher AMD values compared with all other preparation designs. SA showed a significant increase in AMD values compared with shoulder preparations performed occlusal to the SL. Among preparations occlusal to the SL, CO statistically outperformed SO. AG was influenced by preparation design (df=3, MS=0.120, F=96.566, *P*<.001), aging (df=1, MS=0.155, F=125.230, *P*<.001), and the interaction between these factors (*P*<.001). CO and SA resulted in statistically lower AG than CA and SO (*P*<.001). OG was influenced by PD (df=3, MS=3.238, F=763.438, *P*<.001) and aging (df=1, MS=0.356, F=83.953, *P*<.001), but their interaction was not significant (*P*=.135). CA was the PD that statistically performed worst (*P*<.001). Preparations occlusal to the SL resulted in statistically lower OG than CA and SA (*P*<.001). No differences were found between CO and SO. The changes in the gaps at each reference point are illustrated in Figure 7.

DISCUSSION

The findings of this study suggest that the preparation can significantly influence the marginal and internal fit as well as the cement volume after the cementation of lithium disilicate partial coverage crowns; hence, the null hypothesis that the preparation design would not impact the marginal and internal fit or the cement volume of CAD-CAM lithium disilicate onlays was rejected. Simulated aging influenced all 2-dimensional (2D) parameters, leading to the rejection of the null hypothesis that thermomechanical aging would have no influence on fit or cement volume. The choice of preparation design plays a crucial role in the marginal adaptation of indirect restorations.[1] These findings were consistent with those

Table 3. Mean volume in mm^3 and standard deviation for parameters cement volume and void volumes

Finish Line	CO		SO		CA		SA	
Time	**T0**	**T1**	**T0**	**T1**	**T0**	**T1**	**T0**	**T1**
Cement Volume	16.9 ±3.6^{Ba}	14.9 ±4.3^{Ba}	22.4 ±5.4^{Ba}	21.5 ±7.4^{Ba}	29.9 ±8.4^{Aa}	27.6 ±5^{Aa}	30.2 ±9.2^{Aa}	28.5 ±10.4^{Aa}
Voids Volume	0.27 ±0.1^{Aa}	0.31 ±0.1^{Aa}	0.14 ±0.07^{Aa}	0.21 ±0.09^{Aa}	0.38 ±0.22^{Aa}	0.4 ±0.22^{Aa}	0.44 ±0.29^{Aa}	0.49 ±0.27^{Aa}

Different uppercase letters indicate significant differences among preparation designs (*P*<.05).

Different lowercase letters indicate significant differences among different testing times (*P*<.05).

CA, chamfer preparation apical to survey line; CO, chamfer preparation occlusal to survey line; SA, shoulder preparation apical to survey line; SO, shoulder preparation occlusal to survey line.

Table 4. Descriptive analysis (μm) for variables marginal discrepancy (MD), absolute marginal discrepancy (AMD), axial gap (AG) and occlusal gap (OG) before and after thermomechanical aging

Finish Line	CO		SO		CA		SA	
Time	**T0**	**T1**	**T0**	**T1**	**T0**	**T1**	**T0**	**T1**
MD, Mean ±SD	72 ±14.6^{Ba}	72 ±15.9^{B,Ca}	72 ±16.7^{Ba}	68 ±12.8^{Ca}	103 ±31.8^{Aa}	124 ±46.7^{Aa}	78 ±21.6^{Ba}	81 ±23.7^{Ba}
AMD, Mean ±SD	190 ±9.4^{A,Ba}	171 ±9.7^{A,Ba}	167 ±8.2^{Ba}	136 ±6.5^{Bb}	223 ±13.5^{Aa}	218 ±13.6^{Aa}	191 ±11.8^{A,Ba}	188 ±11.2^{Aa}
AG, Mean ±SD	91 ±28.2^{Ca}	106 ±34.5^{Cb}	121 ±34.1^{Aa}	140 ±41^{Bb}	112 ±41.4^{Ba}	152 ±42.9^{Ab}	108 ±28.6^{Ba}	109 ±29.6^{Ca}
OG, Mean ±SD	119 ±33.2^{Cb}	147 ±39.2^{Ca}	126 ±29.8^{Cb}	142 ±30.8^{Ca}	283 ±64.5^{Ab}	310 ±40.0^{Aa}	215 ±34.7^{Bb}	251 ±45.0^{Ba}

Different uppercase letters indicate significant differences among preparation designs (*P*<.05).

Different lowercase letters indicate significant differences among different testing times (T0 – T1) for each parameter (*P*<.05).

CA, chamfer preparation apical to survey line; CO, chamfer preparation occlusal to survey line; SA, shoulder preparation apical to survey line; SO, shoulder preparation occlusal to survey line.

of previous studies,[14–16] emphasizing the significant impact of PD on the marginal adaptability of partial restorations. Among the preparation designs examined, those occlusal to the SL demonstrated superior performance in terms of marginal accuracy and intaglio fit and also a reduced volume of cement between the restoration and the tooth. The longer axial walls in groups with preparations apical to the SL (CA and SA) may have increased friction between the intaglio surfaces, hindering the overflow of resin cement during cementation and resulting in a less precise seating of the restorations.[42] Moreover, the preparations below the SL encompass a more complex geometry and present internal angles, adding the possibility of error to the final precision of the restorations during the scanning or milling processes.[15,17] Comparing preparations apical to the survey line, the SA outperformed CA, with mean marginal discrepancy values that ranged from 78 μm for SA to 103 μm for CA. Similar studies on partial restorations reported comparable results (54.4 μm)[43] (67.5 μm)[44] (94 μm).[45] Clinical and in vitro investigations of finish line preparation designs for CAD-CAM crowns also consistently favored shoulder preparations over chamfer finish lines.[13,21,39]

Various authors have recommended a maximum value between 50 and 120 μm for crown marginal discrepancies.[46] However, a higher AMD, ranging from 120 to 250 μm, has been reported in the literature.[22] In our study, AMD values ranged from 151 to 220 μm, with CA producing less precise restorations. The superior performance of shoulder finish lines in CAD-CAM restorations can be attributed to the challenges posed by the tilted surfaces of a chamfer finish line during the production of the restorations.[32] The use of lithium disilicate in this study adds crystallization as a factor affecting marginal precision.[23] Firing ceramic restorations above the material's glass transition temperature, followed by rapid cooling, induces stresses that can distort the marginal area. The thicker margins in shoulder preparations may resist this distortion better, contributing to marginal discrepancies.[1] Studies using μCT have established that a marginal discrepancy below 120 μm is clinically acceptable in terms of longevity.[5,6] In this context, all finish lines examined in the present study resulted in marginal discrepancies within the clinically acceptable range.

Regarding the intaglio fit of the restoration, threshold values for intaglio fit dimensions have not been determined.[7] The in vitro fit of laboratory-produced sintered porcelain partial coverage restorations has been reported as having dimensions ranging from 91 to 308 μm.[8] For the internal gap parameter, OG mean values ranged from 133 μm to 297 μm, and AG ranged from 98 μm to 132 μm. The choice of finish line design significantly influenced the internal fit of the restoration. OG measurements indicated that preparations apical to the SL resulted in more internal distance than those occlusal to the SL. Assuming that clinically acceptable gaps are 200 to 300 μm,[9,33] all preparation designs proved appropriate for partial restorations. In vitro studies, however, reported that an internal gap of 50 to 100 μm could result in the most favorable resin cement performance.[10–12] Thus, preparation occlusal to the SL allowed for reduced occlusal gaps in the range of 100 μm.

Thermomechanical aging influenced all 2D parameters. Specifically, considering MD, simulated aging had an effect only on the CA group, while other

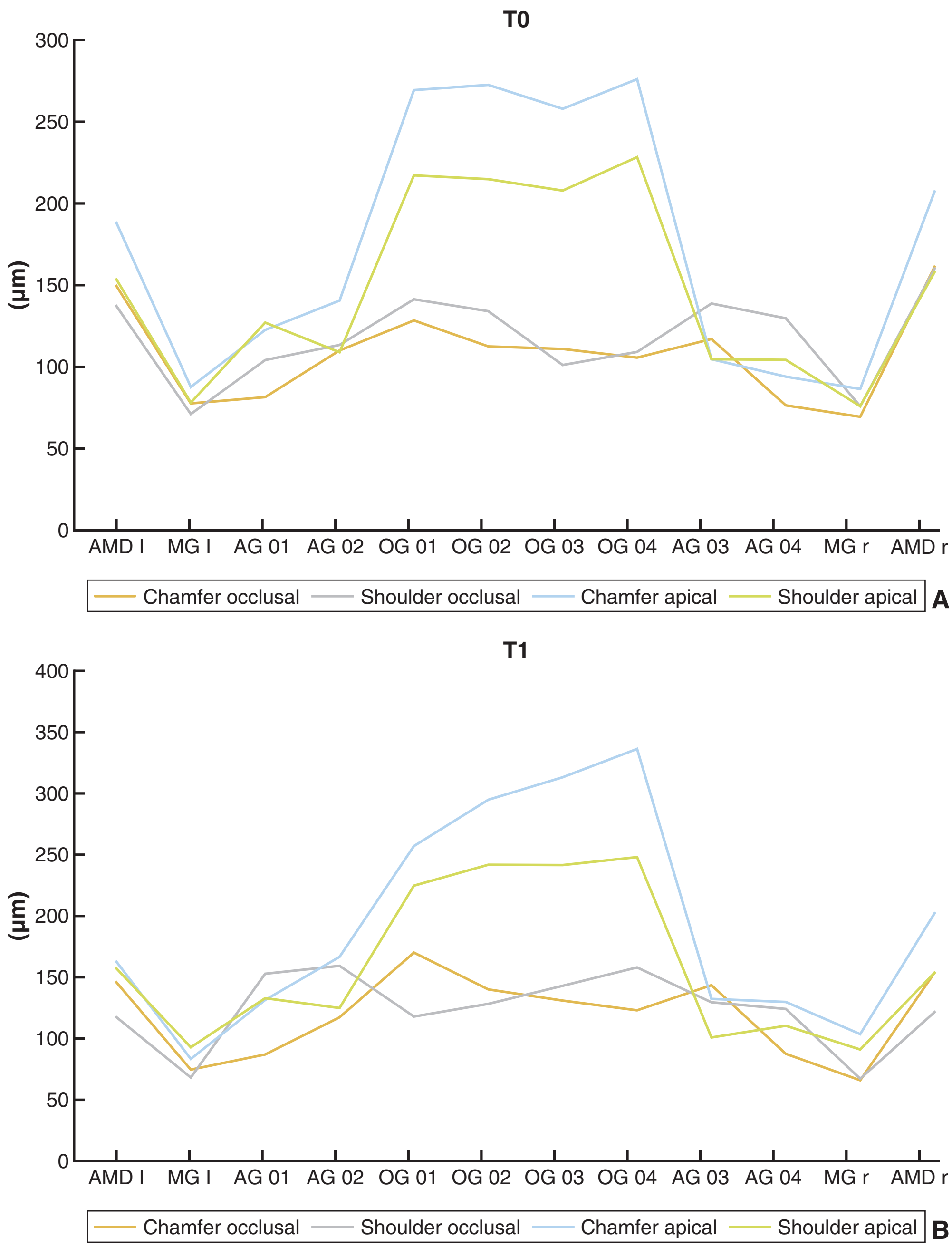

Figure 7. A. Measured parameters of marginal and internal gaps at reference points for groups. A, T0. B, T1. AG, axial gap; AMD l, average marginal discrepancy at left margin; AMD r, average marginal discrepancy at right margin. MG l, marginal discrepancy at left margin; MG r, marginal discrepancy at right margin; OG, occlusal gap. Chamfer occlusal, chamfer preparation occlusal to survey line (4 mm from CEJ); Shoulder occlusal, shoulder preparation occlusal to survey line (4 mm from CEJ); Chamfer apical, chamfer preparation apical to survey line (1.5 mm from CEJ); Shoulder apical, shoulder preparation apical to survey line (1.5 mm from CEJ).

preparation designs remained unaffected. Previous in vitro[27,28,47] and in vivo studies[29,30] reported a decrease in the marginal accuracy of ceramic partial coverage restorations associated with off-axis mouth-motion fatigue and thermal changes. However, inconsistencies exist, with some studies reporting no effect of aging on marginal discrepancies.[45,48] The variation in preparation geometry may explain the change in marginal accuracy over time.[27] CA emerged as the preparation design associated with a less precise restoration among the experimental groups, both in terms of internal and marginal fit. This may be attributed to the higher exposure of the luting materials in the CA group, with the consequent increased water sorption phenomena of composite resin cement, degradation of luting cement as a result of the moist environment, and margin wear.[18,49] A reduction in AMD values across all experimental groups subsequent to the mastication simulator was observed. Krejci et al[8] postulated that the elevated elastic modulus of ceramic transferred occlusal loading stresses to the margins. Hence, the brittle nature of the ceramic partial restoration may render the onlays susceptible to phenomena such as marginal ditching and chipping, potentially explaining the observed AMD alterations. A consistent trend across all experimental groups shows a significant increase in OG and AG measurements after aging. Although no adhesive failures were observed, thermomechanical fatigue likely affects the integrity of adhesively bonded restorations. Resin cement polymerization causes shrinkage stresses at the tooth-restoration interface. Their residual presence on the intaglio surface of the restoration might serve as an epicenter for clinical failures[25] originating from flaws and high-stress zones on the cementation surface of ceramic restorations.[50] Thus, areas already prone to stress concentration may become more susceptible to partial detachment and microleakage, explaining the increase in OG and AG. While no significant change in CV was observed after thermomechanical fatigue loading, a consistent decrease in volume was noted after aging across all groups. This reduction may be due to cement dissolution or chipping at the restoration margin, likely caused by hydrolytic degradation and mechanical stresses.[19,20] The internal gaps were not influenced by the preparation designs or aging. The absence of modifications in gap formations indicated that these were more likely related to the properties of the luting material and its associated bonding agent, particularly their polymerization shrinkage, rather than being influenced by mechanical or thermal stresses.[51] The use of µCT in this study offers a distinct advantage over other evaluation methods. The nondestructive, 3D images enable precise quantitative analysis and exploration of the internal space, providing insights that would otherwise be inaccessible.[51] Simultaneous 2D and 3D measurements, along with the option for additional and repeated testing, contribute to the robustness of the findings. The use of human teeth enhanced the clinical relevance of the study, ensuring alignment with adhesive cementation, bonding protocols, and preparation designs for ceramic partial coverage crowns.[28]

Limitations of this study included that sound teeth without cavities, fractures, prior endodontic treatments, or preexisting restorations were used. These clinical variables, which are commonly encountered in real-world scenarios, could influence the preparation designs and the adhesive cementation substrate. Furthermore, in clinical practice, a varying finishing line tailored to different regions of the tooth is commonly used. In this study, a uniform circumferential preparation was performed on all sound tooth specimens to standardize the protocol. This design choice was made in order to focus on evaluating whether specific preparation designs have a measurable impact on the seating of restorations.

Among the examined PDs, those positioned occlusal to the SL exhibited superior internal and marginal fit. The preservation of remaining tooth structure offered by such preparations occlusal to the DE[35,52] may also distribute stresses favorably, potentially reducing the risk of fracture.[34] However, preparations apical to the SL, particularly with chamfer finish lines, although in the range of clinically acceptability, demonstrated less precision. However, when selecting an appropriate finish line, considerations extend beyond marginal precision, and factors such as the removal of sound tooth structure, ease of realization, and esthetical integration become pivotal for the clinical success of indirect partial restorations. Further studies using different restoration materials and manufacturing processes are needed to better understand the impact of preparation designs on the marginal and internal fit of fixed partial restorations.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The mean marginal discrepancy values of all CAD-CAM lithium disilicate onlay restorations with the different finish line designs, both before and after thermomechanical fatigue, fell within the clinically acceptable range.
2. Preparations located occlusal to the survey line, especially with the chamfer finish line, demonstrated superior marginal and internal adaptations.
3. In contrast, a chamfer placed apical to the survey line exhibited the least favorable adaptation among the investigated preparations.
4. Aging adversely affected the marginal adaptation of the restorations, irrespective of the specific preparation design used.

REFERENCES

1. Grey NJA, Piddock V, Wilson MA. In vitro comparison of conventional crowns and a new all-ceramic system. *J Dent*. 1993;21:3231–3239.
2. Manhart J, Schmidt M, Chen HY, Kunzelmann KH, Hickel R. Marginal quality of tooth-colored restorations in class II cavities after artificial aging. *Oper Dent*. 2001;26:357–366.
3. Conrad HJ, Seong WJ, Pesun IJ. Current ceramic materials and systems with clinical recommendations: A systematic review. *J Prosthet Dent*. 2007;98:389–404.
4. Hamza TA, Sherif RM. In vitro evaluation of marginal discrepancy of monolithic zirconia restorations fabricated with different CAD-CAM systems. *J Prosthet Dent*. 2017;117:762–766.

5. Boeddinghaus M, Breloer ES, Rehman P, Wöstmann B. Accuracy of single-tooth restorations based on intraoral digital and conventional impressions in patients. *Clin Oral Investig*. 2015;19:2027–2034.
6. Borba M, Miranda WG, Cesar PF, Griggs JA, Bona ÁDella. Evaluation of the adaptation of zirconia-based fixed partial dentures using micro-CT technology. *Braz Oral Res*. 2013;27:396–402.
7. Audenino G, Bresciano ME, Bassi F, Carossa S. In vitro evaluation of fit of adhesively luted ceramic inlays. *Int J Prosthodont*. 1999;12:342–347.
8. Krejci I, Lutz F, Reimer M. Marginal adaptation and fit of adhesive ceramic inlays. *J Dent*. 1993;21:39–46.
9. Souza ROA, Özcan M, Pavanelli CA, et al. Marginal and internal discrepancies related to margin design of ceramic crowns fabricated by a CAD/CAM system. *J Prosthodont*. 2012;21:94–100.
10. Alfaro DP, Ruse ND, Carvalho RM, Wyatt CC. Assessment of the internal fit of lithium disilicate crowns using Micro-CT. *J Prosthodont*. 2015;24:381–386.
11. Lins L, Bemfica V, Queiroz C, Canabarro A. In vitro evaluation of the internal and marginal misfit of CAD/CAM zirconia copings. *J Prosthet Dent*. 2015;113:205–211.
12. Mously HA, Finkelman M, Zandparsa R, Hirayama H. Marginal and internal adaptation of ceramic crown restorations fabricated with CAD/CAM technology and the heat-press technique. *J Prosthet Dent*. 2014;112:249–256.
13. Demir N, Ozturk AN, Malkoc MA. Evaluation of the marginal fit of full ceramic crowns by the microcomputed tomography (micro-CT) technique. *Eur J Dent*. 2014;8:437–444.
14. Athab Hasan S, Mohammed-Hussain Abdul-Ameer Z. Effect of three different preparation designs on the marginal adaptation of indirect overlay restoration fabricated from lithium disilicate ceramic material: An in-vitro comparative study. *Saudi Dent J*. 2023;35:372–377.
15. Kim JH, Cho BH, Lee JH, et al. Influence of preparation design on fit and ceramic thickness of CEREC 3 partial ceramic crowns after cementation. *Acta Odontol Scand*. 2014;73:107–113.
16. Yang Y, Yang Z, Zhou J, Chen L, Tan J. Effect of tooth preparation design on marginal adaptation of composite resin CAD-CAM onlays. *J Prosthet Dent*. 2020;124:88–93.
17. Goujat A, Abouelleil H, Colon P, et al. Marginal and internal fit of CAD-CAM inlay/onlay restorations: A systematic review of in vitro studies. *J Prosthet Dent*. 2019;121:590–597.
18. Browning WD, Safirstein J. Effect of gap size and cement type on gingival microleakage in Class V resin composite inlays. *Quintessence Int*. 1997;28:541–544.
19. Ortengren U, Elgh U, Spasenoska V, Milleding P, Haasum J, Karlsson S. Water sorption and flexural properties of a composite resin cement. *Int J Prosthodont*. 2000;13:1417.
20. Gemalmaz D, Pameijer CH, Latta M, Kuybulu F, Alcan T. In vivo disintegration of four different luting agents. *Int J Dent* 2012.
21. Yu H, Chen Y hui, Cheng H, Sawase T. Finish-line designs for ceramic crowns: A systematic review and meta-analysis. *J Prosthet Dent*. 2019;122:22–30.
22. Pelekanos S, Koumanou M, Koutayas SO, Zinelis S, Eliades G. Micro-CT evaluation of the marginal fit of different In-Ceram alumina copings. *Eur J Esthet Dent*. 2009;4:278–292.
23. Dittmer MP, Borchers L, Stiesch M, Kohorst P. Stresses and distortions within zirconia-fixed dental prostheses due to the veneering process. *Acta Biomater*. 2009;5:3231–3239.
24. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. *J Prosthet Dent*. 1989;62:405–408.
25. May LG, Kelly JR, Bottino MA, Hill T. Effects of cement thickness and bonding on the failure loads of CAD/CAM ceramic crowns: Multi-physics FEA modeling and monotonic testing. *Dent Mater*. 2012;28:99–109.
26. Mounajjed R, Salinas TJ, Ingr T, Azar B. Effect of different resin luting cements on the marginal fit of lithium disilicate pressed crowns. *J Prosthet Dent*. 2018;119:975–980.
27. Stappert CFJ, Denner N, Gerds T, Strub JR. Marginal adaptation of different types of all-ceramic partial coverage restorations after exposure to an artificial mouth. *Br Dent J*. 2005;199:779–783.
28. Stappert CFJ, Abe P, Kurths V, Gerds T, Strub JR. Masticatory fatigue, fracture resistance, and marginal discrepancy of ceramic partial crowns with and without coverage of compromised cusps. *J Adhes Dent*. 2008;10:41–48.
29. Krämer N, Frankenberger R, Pelka M, Petschelt A. IPS Empress inlays and onlays after four years - A clinical study. *J Dent*. 1999;27:325–331.
30. Felden A, Schmalz G, Federlin M, Hiller KA. Retrospective clinical investigation and survival analysis on ceramic inlays and partial ceramic crowns: Results up to 7 years. *Clin Oral Investig*. 1998;2:161–167.
31. Luthardt RG, Bornemann G, Lemelson S, Walter MH, Hüls A. An innovative method for evaluation of the 3-D internal fit of CAD/CAM crowns fabricated after direct optical versus indirect laser scan digitizing. *Int J Prosthodont*. 2004;17:680–685.
32. Kokubo Y, Nagayama Y, Tsumita M, Ohkubo C, Fukushima S, Von Steyern Vult. Clinical marginal and internal gaps of In-Ceram crowns fabricated using the GN-I system. *J Oral Rehabil*. 2005;32:753–758.
33. Ribeiro ILA, Campos F, Sousa RS, et al. Marginal and internal discrepancies of zirconia copings: Effects of milling system and finish line design. *Indian J Dent Res*. 2015;26:15–20.
34. Mondelli J, Steagall L, Ishikiriama A, de Lima Navarro MF, Soares FB. Fracture strength of human teeth with cavity preparations. *J Prosthet Dent*. 1980;43:419–422.
35. Edelhoff D, Sorensen JA. Tooth structure removal associated with various preparation designs for posterior teeth. *Int J Periodontics Restorative Dent*. 2002;22:241–249.
36. Veneziani M. Solutions. Tecniche restaurative adesive e procedure chirurgiche integrate. 1st ed. Edra; 2021:211–289.
37. Politano G, Van Meerbeek B, Peumans M. Nonretentive bonded ceramic partial crowns: Concept and simplified protocol for long-lasting dental restorations. *J Adhes Dent*. 2018;20:495–510.
38. Massironi D, Romeo P, Giuseppe R. Precision in dental esthetics. Clinical and laboratory procedures. 1st ed. 2007:56–121.
39. Kern M, Strub JR, Lü XY. Wear of composite resin veneering materials in a dual-axis chewing simulator. *J Oral Rehabil*. 1999;26:372–378.
40. De Kuijper MCFM, Gresnigt MMM, Van Den Houten M, Haumahu D, Schepke U, Cune MS. Fracture strength of various types of large direct composite and indirect glass ceramic restorations. *Oper Dent*. 2019;44:433–442.
41. Scotti N, Forniglia A, Michelotto Tempesta R, et al. Corrigendum to “Effects of fiber-glass-reinforced composite restorations on fracture resistance and failure mode of endodontically treated molars”. *J. Dent*. 2016;53:82–87.
42. Gavelis JR, Morency JD, Riley ED, Sozio RB. The effect of various finish line preparations on the marginal seal and occlusal seat of full crown preparations. *J Prosthet Dent*. 1981;45:138–145.
43. Seo D, Yi Y, Roh B. The effect of preparation designs on the marginal and internal gaps in Cerec3 partial ceramic crowns. *J Dent*. 2009;37:374–382.
44. Uzgur R, Ercan E, Uzgur Z, Çolak H, Yalçın M, Özcan M. Cement thickness of inlay restorations made of lithium disilicate, polymer-infiltrated ceramic and nano-ceramic CAD/CAM materials evaluated using 3D X-ray micro-computed tomography. *J Prosthodont*. 2018;27:456–460.
45. Stappert CFJ, Chitmongkolsuk S, Silva NRFA, Att W, Strub JR. Effect of mouth-motion fatigue and thermal cycling on the marginal accuracy of partial coverage restorations made of various dental materials. *Dent Mater*. 2008;24:1248–1257.
46. Suárez MJ, González de Villaumbrosia P, Pradíes G, Lozano JFL. Comparison of the marginal fit of Procera AllCeram crowns with two finish lines. *Int J Prosthodont*. 2003;16:229–232.
47. Schmalz G, Federlin M, Reich E. Effect of dimension of luting space and luting composite on marginal adaptation of a class II ceramic inlay. *J Prosthet Dent*. 1995;73:392–399.
48. Guess PC, Vagkopoulou T, Zhang Y, Wolkewitz M, Strub JR. Marginal and internal fit of heat pressed versus CAD/CAM fabricated all-ceramic onlays after exposure to thermo-mechanical fatigue. *J Dent*. 2014;42:199–209.
49. Ortengren U, Elgh U, Spasenoska V, Milleding P, Haasum J, Karlsson S. Water sorption and flexural properties of a composite resin cement. *Int J Prosthodont*. 2000;13:1417.
50. Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. *J Prosthet Dent*. 1999;81:652–661.
51. Boroujeni PM, Mousavinasab SM, Hasanli E. Effect of configuration factor on gap formation in hybrid composite resin, low-shrinkage composite resin and resin-modified glass ionomer. *J Investig Clin Dent*. 2015;6:156–160.
52. Mancuso E, Mazzitelli C, Maravic T, Pitta J, Mengozzi A, Comba A, et al. The influence of finishing lines and margin location on enamel and dentin removal for indirect partial restorations: A micro-CT quantitative evaluation. *J Dent*. 2022;127:104–334.

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