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Digital workflow impact on CAD/CAM crown accuracy: a five-protocol comparison

Impacto do fluxo de trabalho digital na precisão de coroas CAD/CAM: uma comparação de cinco protocolos

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ABSTRACT

Objective: The objective of this in-vitro study was to assess and compare the marginal adaptation and internal fit of zirconia-reinforced lithium silicate (ZLS) ceramic crowns produced utilising five distinct digital protocols that include multiple scanners, software, and milling machines. **Material and Methods:** Fifty ceramic crowns were produced from Celtra Duo blocks utilising five digital protocols: (A) CEREC Omnicam + CEREC Premium SW + MCXL; (B) CEREC Omnicam + CEREC Connect SW + MCXL; (C) CEREC Omnicam + CEREC Connect SW + MCX5; (D) InEos X5 + InLab SW + MCXL; (E) InEos X5 + InLab SW + MCX5. The replica technique was used to measure the internal fit at seven set points. While digital microscopy at 50× magnification was used to measure the marginal adaptation across four surfaces. Two-way ANOVA and Tukey's post hoc test (α=0.05) were used to analyze the data. **Results:** Significant differences were identified among digital procedures for both internal fit and marginal adaptation ($p<0.001$). Group E had the superior results, with an internal fit of 180.41±27.22 μm and a marginal adaptation of 55.80±16.49 μm. Group B had the worst internal fit (294.07±18.29 μm), whereas Group A had the worst marginal adaptation (133.93±41.51 μm). The central fossa always had the highest internal gap values for all groups. **Conclusion**: Digital protocol has a great impact on how well ZLS ceramic restorations fit in both marginal adaptation and internal fit. Laboratory-based workflows utilising 5-axis milling (Group E) demonstrated greater fit relative to chairside systems, however data transfer using connect software adversely affected restoration accuracy.

KEYWORDS

CAD/CAM; Digital technology; Internal fit; Marginal adaptation; Zirconia-reinforced lithium silicate.

RESUMO

Objetivo: O objetivo deste estudo *in vitro* foi avaliar e comparar a adaptação marginal e o ajuste interno de coroas de cerâmica de silicato de lítio reforçado por zircônia (ZLS) produzidas utilizando cinco protocolos digitais distintos, que incluem múltiplos scanners, softwares e fresadoras. **Material e Métodos:** Cinquenta coroas cerâmicas foram produzidas a partir de blocos Celtra Duo utilizando cinco protocolos digitais: (A) CEREC Omnicam + CEREC Premium SW + MCXL; (B) CEREC Omnicam + CEREC Connect SW + MCXL; (C) CEREC Omnicam + CEREC Connect SW + MCX5; (D) InEos X5 + InLab SW + MCXL; (E) InEos X5 + InLab SW + MCX5. Uma técnica de réplica foi utilizada para avaliar o ajuste interno em sete pontos pré-definidos, foi utilizada a microscopia digital com aumento de 50 vezes para medir a adaptação marginal em quatro superfícies. Os testes ANOVA dois fatores e post hoc de Tukey (α= 0,05) foram aplicados para analisar estatisticamente os dados obtidos. **Resultados:** Diferenças significativas foram identificadas entre os procedimentos digitais tanto para o ajuste interno quanto para a adaptação marginal ($p<0{,}001$). O Grupo E apresentou resultados superiores, com um ajuste interno de 180,41±27,22μm e uma adaptação marginal de 55,80±16,49μm. O Grupo B apresentou o pior ajuste interno (294,07±18,29μm), enquanto o Grupo A apresentou a pior adaptação marginal (133,93±41,51μm). A região de fossa central apresentou os maiores valores de diferença interna em todos os grupos. **Conclusão:** O protocolo digital tem um grande impacto na qualidade do ajuste de restaurações cerâmicas de ZLS, tanto na adaptação marginal quanto no ajuste interno. Fluxos de trabalho laboratoriais que utilizam fresagem de 5 eixos (Grupo E) demonstraram ajuste superior em relação aos sistemas *chairside* (de consultório); no entanto, a transferência de dados via software Connect afetou negativamente a precisão das restaurações.

PALAVRAS-CHAVE:

CAD/CAM; Tecnologia digital; Ajuste interno; Adaptação marginal; Silicato de lítio reforçado com zircônia.

INTRODUCTION

With the introduction of computer aided design and computer aided manufacturing (CAD/CAM) systems, dental restorations have entered a new era [1]. The digital workflow has many benefits over traditional methods, such as shorter treatment times, better restoration quality, and more comfort for patients [2]. However, the rise of many distinct CAD/CAM systems has made the world of digital protocols quite complicated, and each one could influence restoration outcomes [3].

The marginal adaptation and internal fit of ceramic restorations are crucial determinants of their enduring clinical efficacy [4, 5]. A poor marginal adaptation can cause plaque to build up, secondary cavities, and periodontal problems. A poor internal fit might cause the restoration to debond or fracture [6]. The clinically acceptable marginal gap is still up for controversy. Different studies have suggested ranges between 50 and 200 μm, although McLean and von Fraunhofer's widely recognised limit of 120 μm is the most common [7].

New ceramic materials have been developed thanks to recent improvements in CAD/CAM technology. These include zirconia-reinforced lithium silicate (ZLS) ceramics, which combine the mechanical capabilities of zirconia with the aesthetic properties of glass ceramics [8]. These materials are stronger (370–420 MPa) than regular leucite-reinforced ceramics, but they nevertheless have great optical characteristics [9].

The digital workflow usually has three primary parts: data acquisition (scanning), restoration design (CAD software), and production (milling). There can be big differences between systems in each part, which could impair the quality of the ultimate restoration [10]. Intraoral scanners gather data directly, which means there are no impressions errors. Laboratory scanners, on the other hand, are very accurate but need traditional impressions [11]. Moreover, different design software programs may have different algorithms and tools, and milling machines may have varied axis configurations and precise capabilities [12,13].

Even though the increase utilization of CAD/CAM technology, a few studies have compared different digital protocols in a systematic way using the same material and measurement methods. It is important for evidence-based clinical decision-making to know how different digital workflow combinations affect the fit of restorations [14].

The five protocols were selected to represent the principal digital workflows available within the Dentsply Sirona ecosystem, ranging from a fully chairside workflow (Group A) to a fully laboratory-based workflow (Group E). Key differences include: (1) Data acquisition — the CEREC Omnicam is a chairside intraoral scanner based on continuous video capture, while the InEos X5 is a laboratory extraoral scanner featuring a 5-axis robotic arm with autofocus capability; (2) Design software — CEREC Premium SW enables direct chairside design, CEREC Connect SW requires data transfer through a cloud portal introducing a file conversion step, and InLab SW operates in a closed integrated loop with the scanner and milling unit; (3) Manufacturing — the MCXL is a 4-axis milling machine using two burs with milling times of approximately 8 minutes, while the MCX5 is a 5-axis milling machine using three diamond burs with tangential tool paths and milling times of approximately 40 minutes [15].

The aim of this in-vitro study was to assess and compare the marginal adaptation and internal fit of ZLS ceramic crowns produced utilising five distinct digital protocols, integrating diverse combinations of scanners, design software, and milling machines.

The null hypothesis tested was that there would be no significant difference in marginal adaptation and internal fit of ZLS ceramic crowns fabricated using the five digital protocols

MATERIALS AND METHODS

Study design

This in-vitro experimental study evaluated five distinct digital CAD/CAM techniques for the fabrication of ceramic crowns. The study was structured to isolate the effect of several digital workflows while controlling material, preparation design, and measurement methods (Table I).

Sample preparation

A standardised full coverage crown preparation for an upper right first premolar (#14) was chosen from an Ivoclar Vivadent

Table I - A schematic table clearly showing scanners, software, and milling machines used in each group

Group	Abbreviation	Scanner	Design Software	Milling Machine	Milling Axes
A	OPML	CEREC Omnicam (intraoral)	CEREC Premium SW (direct)	CEREC MCXL	4-axis
B	OCML	CEREC Omnicam (intraoral)	CEREC Connect SW → CEREC Premium SW (cloud transfer)	InLab MCXL	4-axis
C	OCM5	CEREC Omnicam (intraoral)	CEREC Connect SW → InLab SW (cloud transfer)	InLab MCX5	5-axis
D	IIML	InEos X5 (extraoral)	InLab SW (direct)	InLab MCXL	4-axis
E	IIM5	InEos X5 (extraoral)	InLab SW (direct)	InLab MCX5	5-axis

model. The preparation featured a deep chamfer finish line with smooth, rounded internal angles. Crown height measured 9.30 mm from cusp tip to finish line, intercuspal distance was 6.60 mm, and mesiodistal width at the mid-proximal region was 5.90 mm. To avoid differences in impression materials and stone casting methods, the study employed only one master model.

Sample grouping

Fifty crowns were produced with five distinct digital procedures (n=10 per group):Group A (OPML): CEREC Omnicam, CEREC Premium SW, and CEREC MCXL, Group B (OCML): CEREC Omnicam, CEREC Connect SW, and InLab MCXL, Group C (OCM5): CEREC Omnicam + CEREC Connect SW + InLab MCX5, Group D (IIML): InEos X5 + InLab SW + InLab MCXL, Group E (IIM5): InEos X5 + InLab SW + InLab MCX5.

All restorations were fabricated from Celtra Duo (Dentsply Sirona, Bensheim, Germany) zirconia-reinforced lithium silicate blocks using standardized parameters (90 μm occlusal and radial spacer). A standardized 90 μm radial and occlusal spacer was selected based on literature recommendations indicating that cement space values between 60–110 μm optimize marginal adaptation and crown seating in CAD/CAM restorations [16,17].

Digital workflow procedures

Scanning protocols

Direct intraoral scanning (CEREC Omnicam) simulation with balanced, steady motion at 5-15 mm distance was used in the groups A, B and C. While groups D and E used laboratory scanning (InEos X5) using automated 5-axis robotic arm with autofocus capability.

Design process

All restorations were designed using biogeneric individual templates with standardized parameters. Model axes were set, margins identified using automatic and manual tools, and insertion axes confirmed. Crown morphology was adjusted to ensure adequate thickness while maintaining consistent design principles across all groups.

Manufacturing

A 4-axis milling (MCXL) using cylinder pointed 12s and step 12s burs was used in groups A, B and D. Whereas a 5-axis milling (MCX5) using diamond burs (1.2, 1.4, 2.2 mm) were used in groups C and E (Figure 1). Milling times ranged from 8 minutes (4-axis) to 40 minutes (5-axis). All crowns were cleaned ultrasonically after milling to remove debris.

Measurement procedures

Internal fit assessment

Internal fit was measured using the replica technique [18]. Light-body polyvinylsiloxane (3M Express STD ESPE, MN, USA) was injected into each crown, which was then seated on the master die under 3.8 kg constant load. After material setting, the crown-silicone assembly was removed and reinforced with heavy-body silicone (3M Express STD ESPE, MN, USA) [14].

Cross-sections were made in the mid facio-palatal plane and examined under 50× magnification. Seven measurement points were evaluated (500 μm from buccal margin, tip of buccal cusp, mid buccal surface, 500 μm from palatal margin, tip of palatal cusp, mid palatal surface and the central fossa) [19]. (Figure 2).

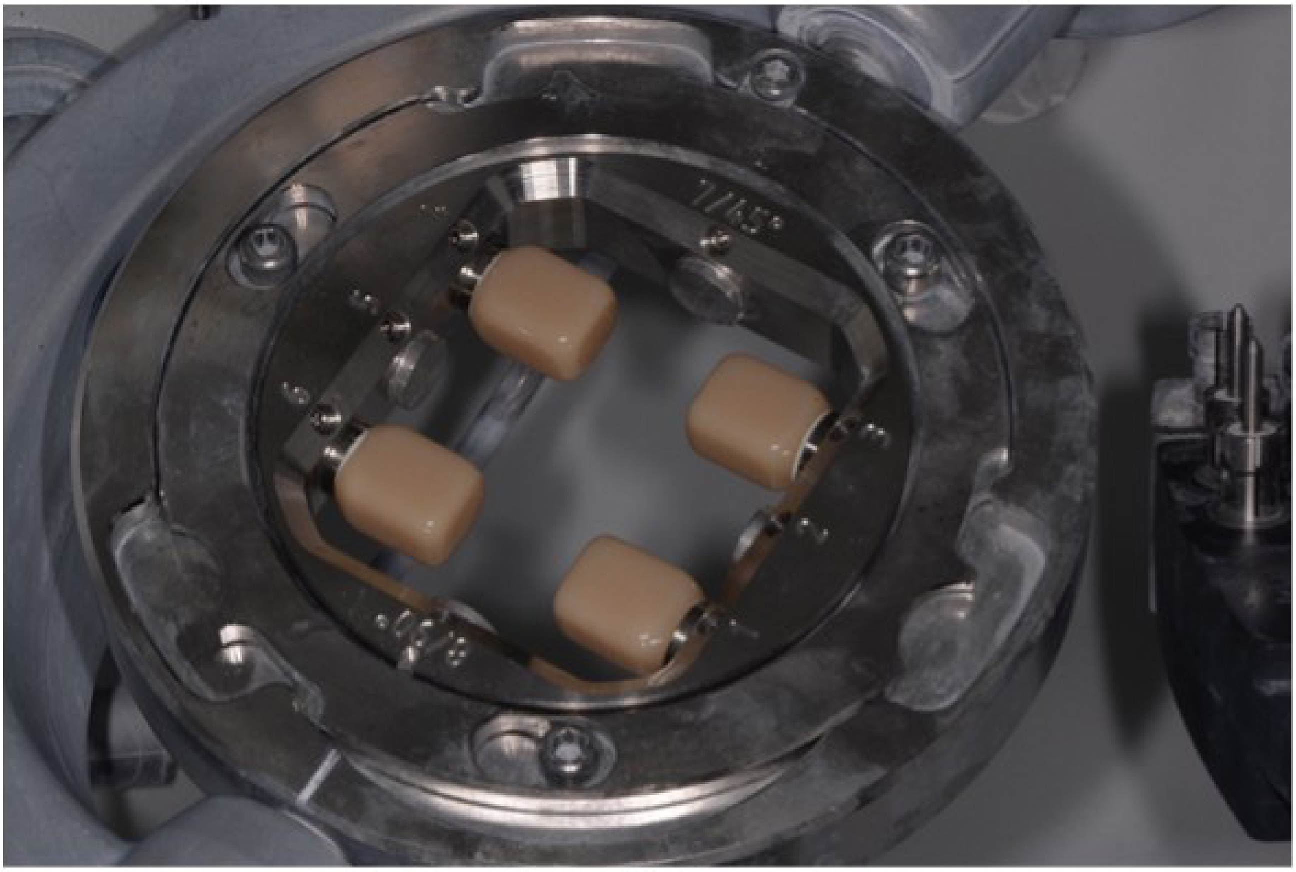

Figure 1 - Celtra Duo blocks placed in the multi-positioning block holder.

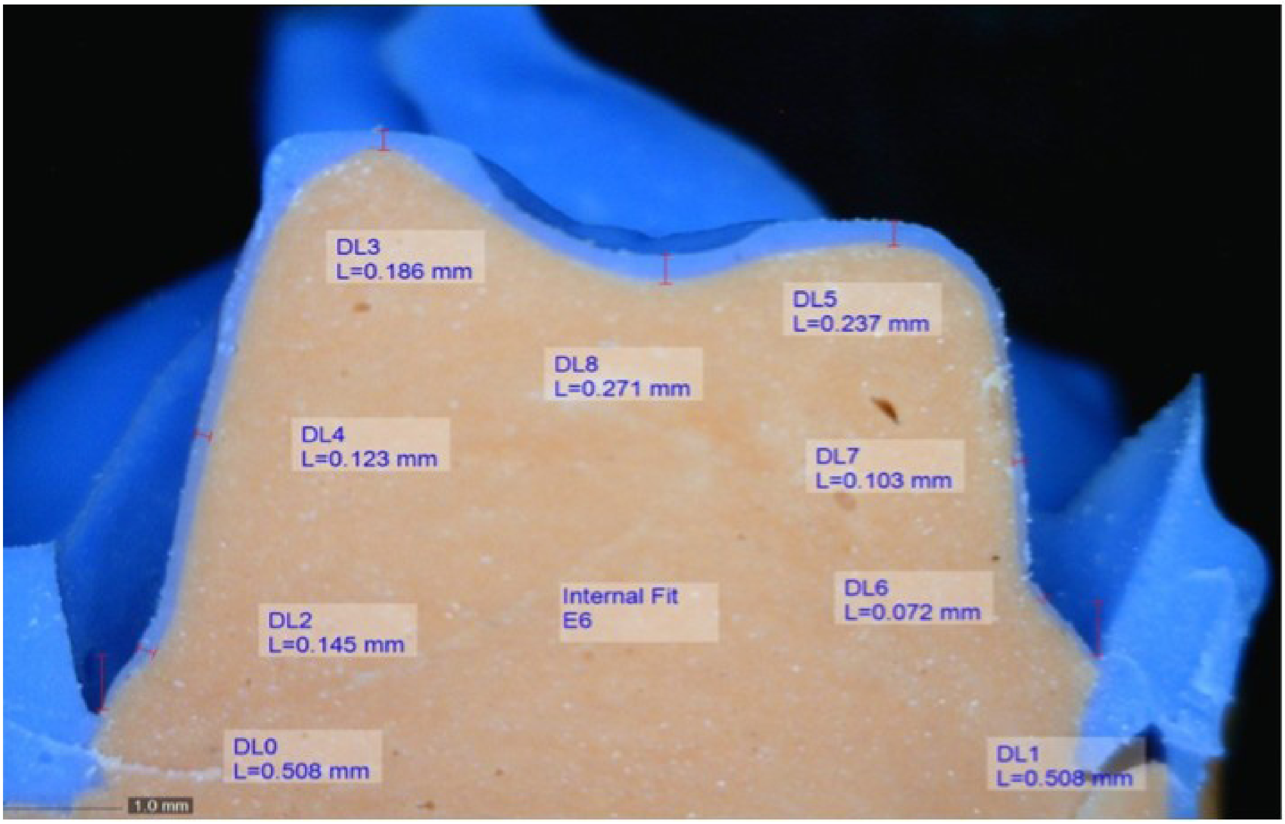

Figure 2 - Sliced replica specimen under magnification x50 (digital Microscope).

Marginal adaptation assessment

Marginal adaptation was measured using digital microscopy at 50× magnification (Figure 3). Four measurement points were evaluated on each surface (buccal, mesial, palatal, distal), with points positioned at line angles and equidistant intermediate positions.

For marginal adaptation assessment, each crown was seated directly on the master die without any interposing material, and marginal gaps were measured at four surfaces under digital microscopy. No cement or cement-simulating material was used for marginal measurements, as this study evaluated pre-cementation fit, consistent with established protocols [20]. For internal fit assessment, light-body polyvinylsiloxane was used to simulate the cement space using the replica technique.

Statistical analysis

Data normality was assessed using Kolmogorov-Smirnov and Shapiro-Wilk tests. Two-way ANOVA was performed to evaluate the effects of digital protocol and measurement point on internal fit and marginal adaptation, followed by Tukey's post hoc test for pairwise comparisons. Statistical significance was set at $p \leq 0.05$. Analysis was performed using IBM SPSS Statistics Version 26.

RESULTS

Internal fit

Significant differences were found among digital protocols ($p<0.001$) and measurement points ($p<0.001$), with significant interaction between these factors ($p<0.001$). Group E demonstrated the best internal fit (180.41±27.22 μm), followed by Group D (217.33±20.46μm), Group A (241.80±20.79μm), Group C (242.11±12.72 μm), and Group B (294.07±18.29 μm). The central fossa consistently showed the highest gap values across

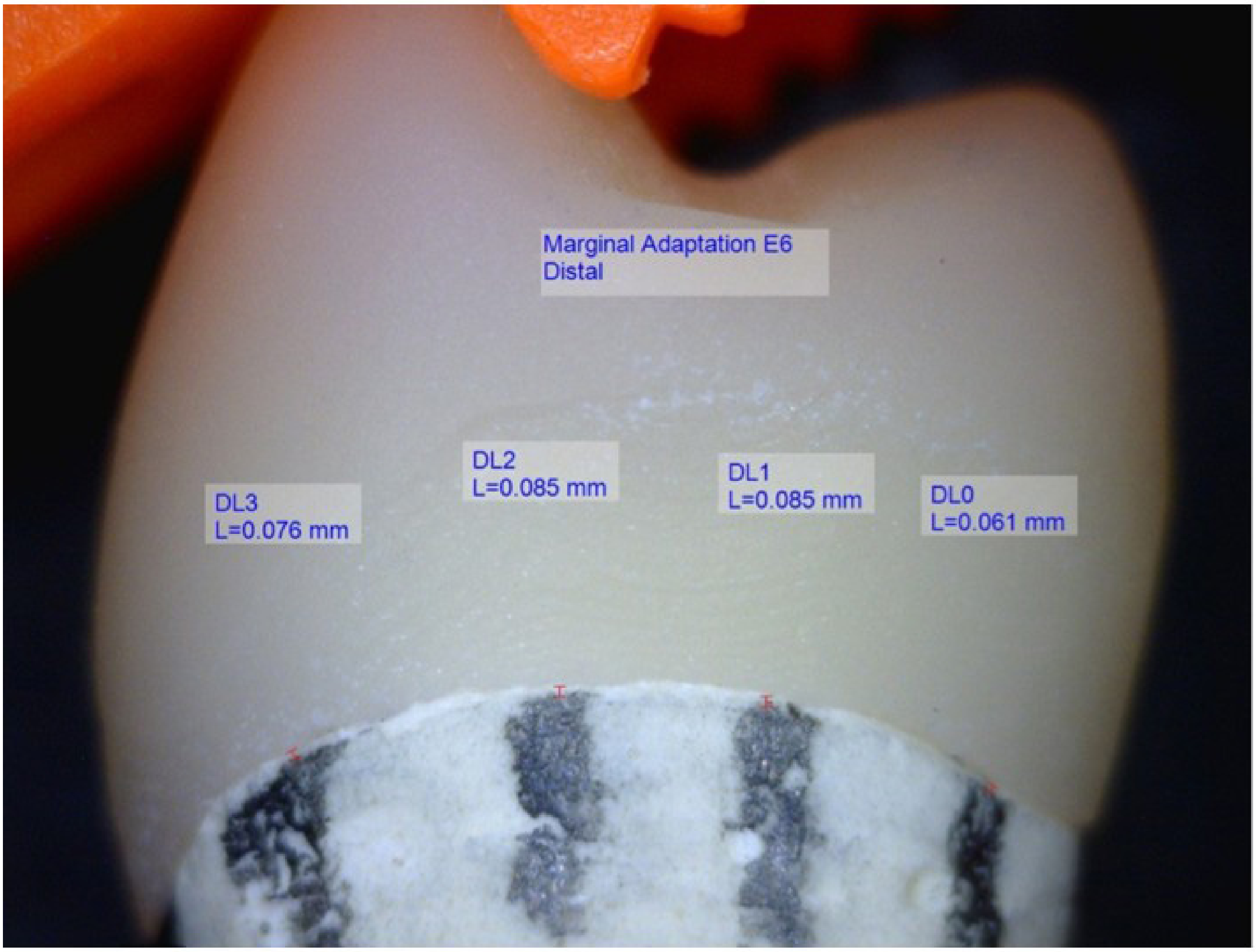

Figure 3 - Marginal adaptation specimen under microscope magnification x50.

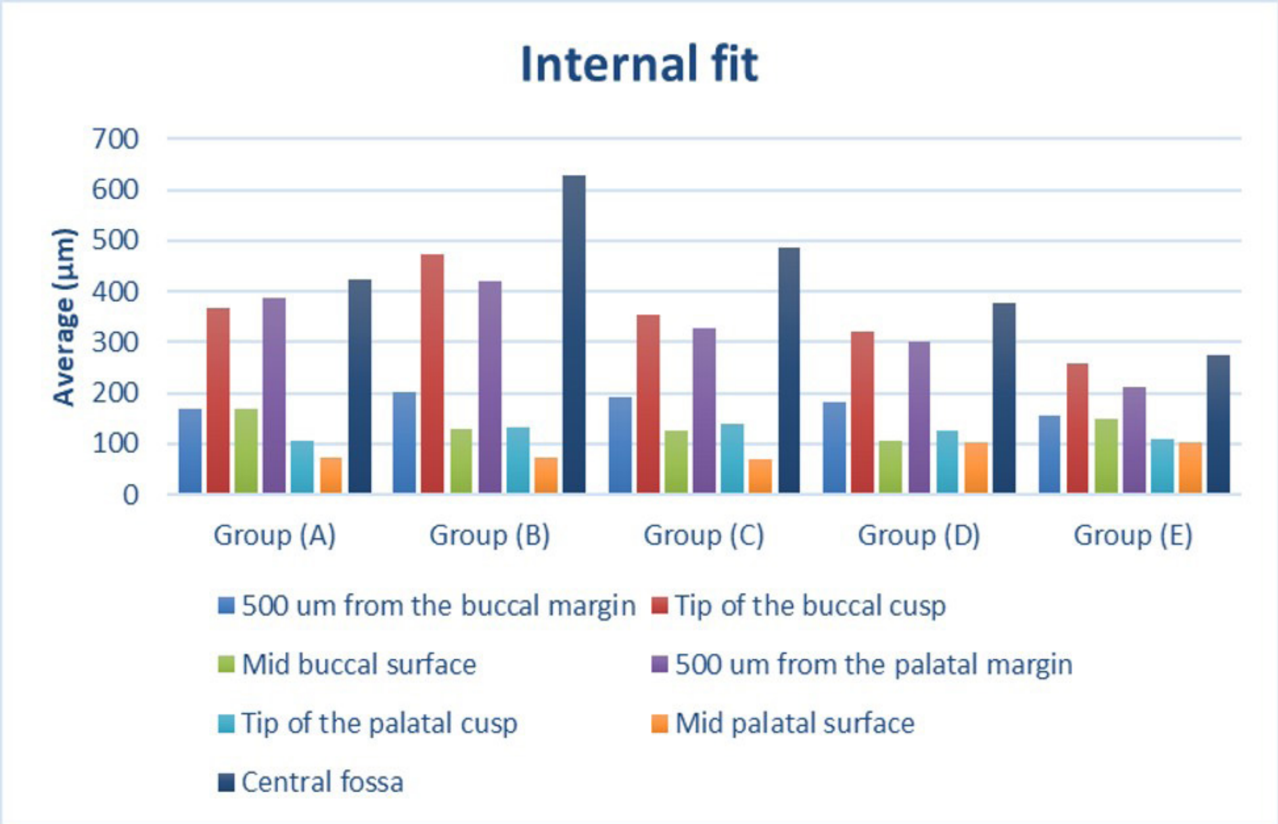

Figure 4 - Bar chart showing average internal fit (μm) of different measurement points within each digital protocol.

all groups: Group B (627.14±31.04 μm), Group C (486.00±55.86 μm), Group A (424.00±36.72 μm), Group D (377.86±36.35 μm), and Group E (274.00±30.20 μm). The lowest values were consistently found at mid-palatal surfaces (Figure 4).

Marginal adaptation

Digital protocol significantly affected marginal adaptation ($p<0.001$), while measurement point location showed no significant effect ($p=0.143$). Group E achieved the best marginal adaptation (55.80±16.49 μm), followed by Group D (86.16±26.76 μm), Group C (93.84±21.24 μm), Group B (118.48±26.43 μm), and Group A (133.93±41.51 μm). However, all groups achieved marginal gaps within clinically acceptable limits, though Group A approached the upper threshold of acceptability shown in (Table II).

DISCUSSION

"This study provides comprehensive evidence that digital protocol selection significantly affects both marginal adaptation and internal fit of ZLS ceramic restorations. To better understand the contribution of each workflow component, targeted pairwise comparisons between groups sharing common variables were performed."

"The effect of the milling machine was isolated by comparing groups that shared the same scanner and design software but differed in milling configuration. Comparing Group D (InEos X5 + InLab SW + MCXL) to Group E (InEos X5 + InLab SW + MCX5), the shift from 4-axis to 5-axis milling reduced mean internal fit from 217.33 ± 20.46 μm to 180.41 ± 27.22 μm and improved marginal adaptation from 86.16 ± 26.76 μm to 55.80 ± 16.49 μm. A similar pattern was observed when comparing Group B (Omnicam + Connect SW + MCXL) to Group C (Omnicam + Connect SW + MCX5), where internal fit improved from 294.07 ± 18.29 μm to 242.11 ± 12.72 μm and marginal adaptation improved from 118.48 ± 26.43 μm to 93.84 ± 21.24 μm. This consistent improvement across both pairs suggests that 5-axis milling produces superior fit regardless of the upstream scanning and design workflow. The MCX5 employs tangential tool paths with three diamond burs (1.2, 1.4, and 2.2 mm), enabling more

Table II - Mean ± standard deviation (SD) of marginal adaptation (μm) for samples of different groups

Digital protocol		Mean±SD	p-value	
Group (A) Group (B)	133.93±41.51A	<0.001*	Group (A)	**0.6413ns**
	118.48±26.43A		Group (B)	
Group (C) Group (D)	93.84±21.24B		Group (C)	
	86.16±26.76B		Group (D)	

*; significant (p ≤ 0.05). ns; non-significant (p>0.05)

precise reproduction of internal geometries compared to the 4-axis MCXL, which is limited to two burs and planar tool movements. This finding is consistent with Saifan et al., who demonstrated significantly better trueness and internal fit with the MCX5 compared to the MCXL for glass ceramic crowns, and with Ruggiero et al., who confirmed the superiority of 5-axis milling in a systematic review [21,22].

"The effect of design software and data transfer was evaluated by comparing Group A (Omnicam + CEREC Premium SW + MCXL) with Group B (Omnicam + CEREC Connect SW + MCXL). Both groups used the same intraoral scanner and 4-axis milling machine, differing only in the software pathway. Group B showed significantly worse internal fit (294.07 ± 18.29 μm) compared to Group A (241.80 ± 20.79 μm), representing a 52 μm increase in internal gap. This deterioration is attributable to the additional data conversion step required when transferring scan data through the CEREC Connect portal. During this process, proprietary scan data must be converted and re-processed by different software, potentially introducing mesh approximation errors and data loss. Interestingly, Group B showed slightly better marginal adaptation (118.48 μm) than Group A (133.93 μm). This may reflect the additional design refinement available in the laboratory software environment that received the transferred data, although this difference was not statistically significant as both groups shared the same Tukey grouping (group A). These findings support minimising data transfer steps in the digital workflow to preserve internal fit accuracy [23,24].

The combined influence of scanner type and design software was assessed by comparing groups that used the same milling machine (MCXL) but different upstream workflows. Group D (InEos X5 + InLab SW + MCXL) demonstrated superior internal fit (217.33 ± 20.46 μm) and marginal adaptation (86.16 ± 26.76 μm) compared to both Group A (Omnicam + Premium SW + MCXL: 241.80 μm internal, 133.93 μm marginal) and Group B (Omnicam + Connect SW + MCXL: 294.07 μm internal, 118.48 μm marginal). Since all three groups used the same 4-axis milling machine, the performance differences are attributable to the scanning and software components. The InEos X5 extraoral scanner, featuring a 5-axis robotic arm with autofocus capability, likely provided more accurate digital impressions than the handheld Omnicam, particularly given that the master die was a standardised model ideal for extraoral scanning. Furthermore, the integrated InLab SW processed data within a closed system without requiring file conversion, preserving data integrity throughout the design phase [11,15].

The negative impact of data transfer through CEREC Connect software (Groups B and C) suggests that data conversion and transfer processes may introduce inaccuracies. This supports findings by Erozan and Ozan, who reported data loss during proprietary format conversions in digital workflows. Direct data acquisition and processing within integrated systems appear to maintain higher accuracy [24].

The consistently high gap values at the central fossa across all groups reflect limitations in milling technology when reproducing complex internal geometries. This phenomenon has been attributed to drill compensation features required when milling internal angles smaller than the minimum tool diameter. The 4-8 times smaller crystal structure of ZLS compared to lithium disilicate may also contribute to improved machinability and surface quality. *Notably, the magnitude of this effect was milling-dependent: the central fossa gap in Group E (274.00 ± 30.20 μm) was approximately 56% smaller than in Group B (627.14 ± 31.04 μm), indicating that the 5-axis milling partially compensates for this geometric limitation through* *its additional degrees of freedom and smaller bur diameters* [25].

The clinical implications of these findings are significant. While all groups achieved internal fit values within reported clinical ranges (73-320 μm), the differences observed are substantial enough to affect restoration longevity [26]. The marginal adaptation results are particularly encouraging, with most groups achieving values well below the 120 μm clinical threshold.

Several study limitations should be acknowledged. First, the in-vitro design limits direct clinical applicability, and the use of a single tooth preparation may not represent the full range of clinical scenarios. Second, the replica technique, while validated [18], has inherent limitations in reproducing complex three-dimensional geometries; sectioning was performed only in the mid facio-palatal plane, and additional mesiodistal sections would have provided more comprehensive internal fit data. Third, the study evaluated complete digital workflows rather than employing a full factorial design (scanner × software × milling machine), which limits the ability to statistically isolate the independent contribution of each component. However, targeted pairwise comparisons were used to partially address this limitation. Finally, all protocols tested were within the Dentsply Sirona ecosystem, which may limit generalizability to other CAD/CAM systems.

CONCLUSIONS

Within the limitations of this in-vitro study, the following conclusions can be drawn:

1- Digital protocol significantly affects both marginal adaptation and internal fit of ZLS ceramic restorations.

2- Laboratory-based workflows with 5-axis milling provide superior restoration fit compared to chairside systems.

3- Data transfer through intermediate software negatively impacts restoration accuracy.

4- All digital protocols produced restorations within clinically acceptable parameters, though with significant differences in quality.

5- The central fossa region consistently shows the poorest internal fit across all systems.

Clinical recommendations

Based on these findings, clinicians should consider:

1- Utilizing laboratory-based CAD/CAM workflows when optimal fit is critical.

2- Preferring 5-axis milling systems when available.

3- Minimizing data transfer steps in the digital workflow.

4- Understanding that chairside systems, while convenient, may compromise restoration fit quality.

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Not applicable

Data availability

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request and will be sent.

Author’s Contributions

AA, TS: Conceptualization. HI, SE, NR: Methodology. HI, SE, NR: Formal Analysis and Investigation. HI, NR: Writing - Original Draft Preparation. AA, TS: Writing - Review & Editing. AA, TS: Supervision.

Conflict of Interest

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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Regulatory Statement

Not applicable

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