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Comparison of fit accuracy of CAD/milled waxes

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Abstract

Background and objectives: Marginal and internal fit are critical to crown longevity; inadequate adaptation risks micro-leakage and failure. CAD/CAM-milled wax patterns are widely used, but the effect of material on fit remains unclear. This study aimed to determine whether material-specific factors affect fit accuracy which may guide material selection and improve predictability of crown restorations. ***Methods:*** A mandibular first molar was prepared and a lithium-disilicate crown digitally designed with a 0 µm cement spacer. Dies were digitally sectioned and 3D-printed; Three waxes were used; Dentsply Sirona Gray, Ivoclar ProArt CAD Yellow and Aidite Milling Blue. Wax patterns were milled in two sectioned forms, seated and measured under a stereomicroscope at ten predefined points (two marginal, three internal per section). Data were analysed using three-way ANOVA with Tukey HSD and LS-Means are reported. ***Results:*** LS-Mean gap values were 79.5 ± 42.3 µm for Aidite, 76.1 ± 42.3 µm for Dentsply, and 71.6 ± 42.3 µm for Ivoclar. The main difference between materials was not significant, $F(2, 288) = 0.87$, $p = 0.420$, indicating the three CAD/CAM waxes produced a comparable fit. The largest gaps occurred at the occluso-axial internal position in the mesio-distal orientation. Bucco-lingual measurements had smaller gaps than mesio-distal. ***Conclusion:*** All three waxes produced clinically acceptable fits (<120 µm marginal; <300 µm internal), indicating although material choice exerted little influence, the production factor of milling bur radius had a measurable effect on internal fit and should be carefully considered in clinical application, as it may influence final restoration fit and clinical performance.

Introduction

Computer Assisted Design/Computer Assisted Manufacturing (CAD/CAM) has become well-imbedded in modern dentistry, since its initial introduction in 1985 (Susic *et al.*, 2017). Over the past few decades, digital workflows have largely supplanted many traditional techniques (Davidowitz & Kotick, 2011; Goujat *et al.*, 2019). Today both subtractive (milling) and additive (3D printing) CAD/CAM processes are commonly used to produce crowns, bridges and other prostheses with speed and accuracy (Ahmed, 2018). This widespread adoption, with one report noting up to 32% of dentists in New Zealand now incorporating CAD/CAM into practice (Lee *et al.*, 2018), reflects the efficiencies and improved patient outcomes enabled by digital dentistry. Irrespective of fabrication method, however, the long-term success of a fixed restoration hinges on its marginal and internal fit accuracy (Contrepois *et al.*, 2013; Kim *et al.*, 2018).

Marginal and internal fit are recognised as critical factors for the clinical performance and longevity of indirect restorations. Marginal fit refers to how closely the restoration's edge conforms to the prepared tooth margin. Poor marginal adaptation can permit microleakage, plaque accumulation and bacterial ingress, leading to secondary caries and periodontal inflammation that compromise the restoration's lifespan (Goldman *et al.*, 1992). Even minor discrepancies at the crown margin create a pathway for biofilm formation and weaken the seal between tooth and restoration. Internal fit describes the adaptation of the internal surface of the restoration to the underlying tooth preparation. An excessive or uneven internal gap may undermine retention and resistance form by increasing stress within the cement layer (Martins *et al.*, 2012; Morsy *et al.*, 2024). Such stress can weaken the cement and concentrate occlusal forces, raising the risk of fracture or debonding over time. Thus, optimising both marginal and internal adaptation is essential to prevent microleakage and mechanical failure (Akçin *et al.*, 2018).

Researchers have long sought to define what constitutes a "clinically acceptable" fit. Early studies by Christensen (1966) and McLean and von (1971) suggested that marginal gaps up to around 39 µm (visually detectable threshold) and 120 µm (clinical acceptability over five years) could be tolerated. In recent decades, systematic reviews such as that of Heboyan (2019) have converged on ~100 µm as a reasonable upper threshold for marginal discrepancy. Some authors advocate stricter limits of ~50 µm or less, although achieving such precision in practice is rare (Alshehri *et al.*, 2022). Unlike marginal gaps, a certain internal gap is necessary to accommodate the luting cement, often cited around 25–30 µm ideal cement space (Guess *et al.*, 2014; Fathi *et al.*, 2016; Farjood *et al.*, 2017) depending on the type of cement material and prosthesis (Keunbada Son *et al.*, 2019). There is still no universal standard for acceptable internal fit, but internal gaps on the order of 50–100 µm are generally considered acceptable, while those exceeding 300 µm may jeopardise mechanical integrity (Martins *et al.*, 2012).These guidelines underscore that both types of fit must be controlled within tight tolerances to ensure clinical success.

The fit accuracy of indirect restorations is influenced by multiple factors, including tooth preparation geometry, finish line design, restoration type and material, impression method, and cement space (Olivera & Saito, 2006; Pimenta *et al.*, 2015; Mounajjed *et al.*, 2018; Heboyan, 2019; Merrill *et al.*, 2021). Where wax patterns are utilised, an additional layer of complexity is introduced. Variability arises not only from the wax pattern itself, whether hand-carved, CAD/

milled, or CAD/3D-printed (Kim *et al.*, 2018; Khaledi *et al.*, 2020), but also from the subsequent lost-wax process, which can introduce further distortion (Sias Jr & Sias, 2005). Conventional inlay waxes, typically composed of paraffin, beeswax, and carnauba, are prone to distortion and shrinkage due to high thermal expansion, elastic memory, and sensitivity to handling (Manappallil, 2016; Farjood *et al.*, 2017). This operator-dependent variability can compromise fit. By contrast, CAD/CAM milling waxes are engineered with synthetic polymers and reinforcing agents that enhance rigidity, reduce flow, and improve machinability, producing patterns that are more dimensionally stable and reproducible (Lee *et al.*, 2020; McCabe & Walls, 2013). Comparative studies confirm these advantages, reporting smaller marginal discrepancies and improved consistency compared to conventional wax-ups (Fathi *et al.*, 2016; Homsy *et al.*, 2018).

The use of CAD/CAM technology in wax pattern fabrication introduces its own set of variables, including scanner resolution, scan strategy, and software algorithms, which may all contribute to deviations. Likewise, milling unit configuration (three- versus five-axis), bur diameter, and bur wear influence the surface finish and reproduction of internal geometry (Beuer *et al.*, 2008; Kim *et al.*, 2018). These digital factors interact with material properties, increasing the complexity of predicting and controlling marginal and internal fit in CAD/CAM workflows.

Despite extensive research into the fit accuracy of definitive indirect restorations, including ceramics, metal alloys, and hybrid materials using a variety of assessment methods (K. Son *et al.*, 2019), the contribution of wax patterns within CAD/CAM workflows has received limited attention. Most studies have prioritised the marginal and internal adaptation of definitive restorations, often overlooking the influence of the wax stage that precedes pressable ceramic or cast restorations (Alshehri *et al.*, 2022).

This study addresses that knowledge gap by investigating whether different CAD/CAM milling wax materials influence the marginal and internal fit of full-coverage crown patterns. Three widely used CAD/CAM wax blocks were evaluated: Dentsply Sirona Gray, Ivoclar ProArt CAD Yellow, and Aidite Milling Wax Blue, each representing a popular choice in digital crown pattern fabrication. By comparing the fit of crown patterns milled from these materials, this study aims to determine whether material-specific factors affect fit accuracy. Clarifying such differences may help guide material selection in hybrid CAD/CAM workflows and improve the predictability of crown restorations.

Materials and methods

Tooth preparation

A standardised full crown preparation was performed on tooth #46 (mandibular right first molar) of a typodont model (Nissin Dental Products Inc., Kyoto, Japan). Tooth #46 was selected because its broad occlusal surface and complex anatomy present greater challenges for digital scanning and milling (Son & Lee, 2020), making it a suitable model for evaluating differences in fit accuracy across materials and orientations. As shown in Figure 1, the abutment was prepared with uniform axial and occlusal reductions

Figure 1. Standardised full-coverage crown preparation of mandibular first molar (#46) on a Nissin typodont model used as the reference tooth for CAD/CAM wax pattern fabrication and fit evaluation.

consistent with the guidelines for lithium disilicate crowns (IPS e.max Press) (Ivoclar, 2025), incorporating a 1.0 mm rounded shoulder finish line. A rounded shoulder was chosen as the clearly defined margin is more reliably detected by scanning systems and accurately reproduced by milling burs, thereby minimising margin-related variability and improving reproducibility. Evidence indicates that shoulder margins are associated with superior milling fidelity and reduced marginal discrepancy compared with chamfer or feather-edge designs (Altan *et al.*, 2023).

Digital workflow

The prepared tooth was scanned using the Primescan intraoral scanner (Dentsply Sirona, Charlotte, NC, USA) (see Figure 2). A full-coverage crown was then designed in CEREC software (Dentsply Sirona) with the virtual cement space parameter set to 0 µm (see Figure 3). This parameter was chosen to ensure that any discrepancies measured reflected only the accuracy of scanning and milling, rather than being influenced by spacer settings. Previous work has shown that the magnitude of marginal and internal gaps can vary with cement space parameters (Nakamura *et al.*, 2003), and using a zero-spacer design in vitro isolates the role of material and workflow factors (Ibrahim *et al.*, 2024).

To enable controlled measurements, the digital models of the prepared tooth and crown were virtually sectioned along the mesio-distal and bucco-lingual planes using Meshmixer software (Autodesk Inc., San Rafael, CA, USA) (see Figure 4a-4d). Virtual sectioning avoided the risk of distortion that can occur with physical sectioning methods. Two master dies corresponding to these sectioning planes were subsequently fabricated using an Asiga Max UV printer (Asiga, Sydney, Australia) with Asiga Denta Model resin, ensuring consistent abutment forms across all specimens.

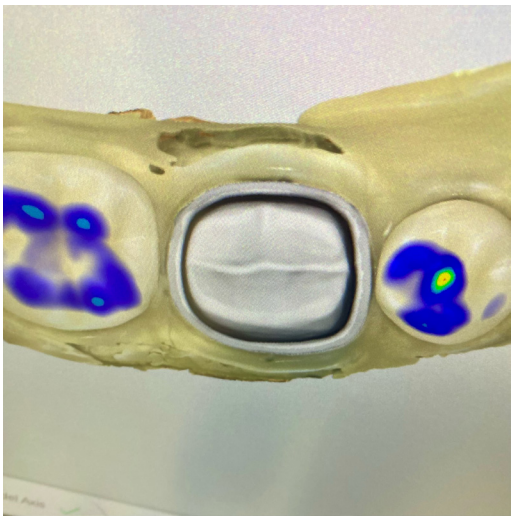

Figure 2. Digital scan of the prepared mandibular first molar (#46) captured using the Dentsply Sirona Primescan. The scan served as the basis for the CAD design and subsequent fabrication of the wax patterns used for fit analysis.

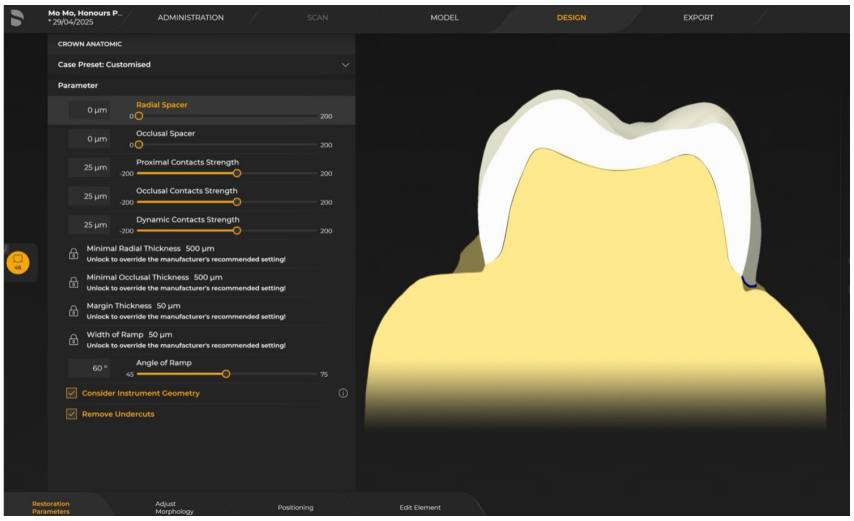

Figure 3. Restoration design in the bucco-lingual plane with parameter settings in CEREC software.

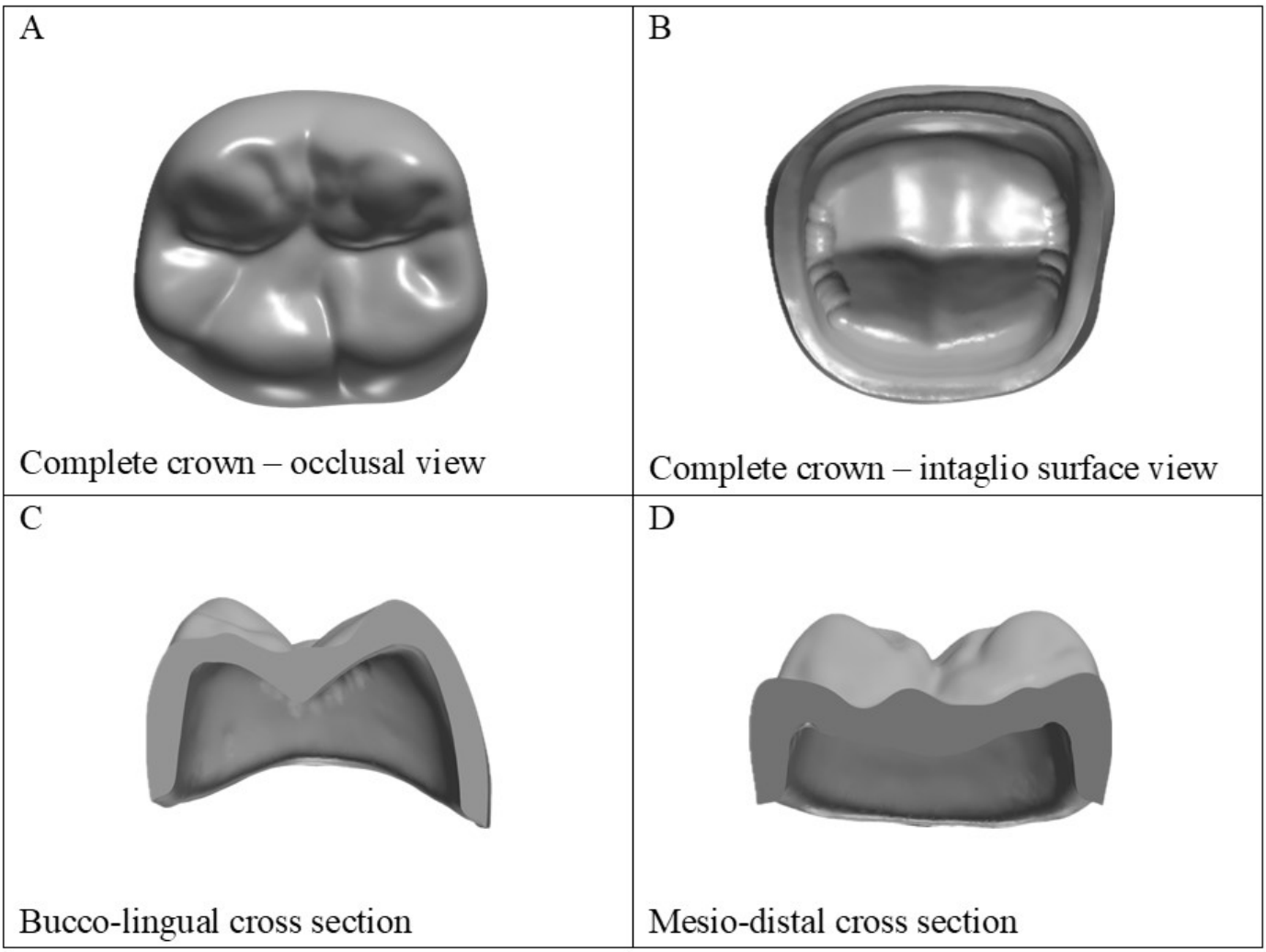

Figure 4. Digital design of the crown restoration for tooth #46 generated from the scanned preparation.
(A) Occlusal view of the complete crown morphology. (B) Internal view of the fully designed crown showing anatomical contour. (C) Cross-sectional view of the crown illustrating the internal surface in the bucco-lingual orientation.
(D) Cross-sectional view of the crown in the mesio-distal orientation.

Materials

Three CAD/CAM wax materials were evaluated in this study: Dentsply Sirona Gray Wax (Dentsply Sirona, Charlotte, NC, USA), Ivoclar ProArt CAD Yellow (Ivoclar AG, Schaan, Liechtenstein), and Aidite Milling Wax Blue (Aidite (Qinhuangdao) Technology Co., Ltd., Qinhuangdao, China).

Hardness and elastic modulus

Nanoindentation (Berkovich indenter tip, Ti-Premier, Bruker, Massachusetts, USA) was used to determine the hardness and elastic modulus of the three waxes. One specimen of each wax was cut from the same milling pucks used to fabricate the crowns for the other tests and mounted on the test platform of the nanoindenter. Indentation measurements were conducted to a maximum load of 10000uN and held for 2 seconds. Elastic modulus and hardness calculations were performed following the approach developed by Oliver and Pharr (Oliver & Pharr, 1992).

Milling procedure

Sixty wax crowns were fabricated in total, with 20 specimens produced for each of the three CAD/CAM wax materials. Within each material group, specimens were equally divided between the bucco-lingual (BL) and mesio-distal (MD) orientations (n = 10 per orientation). The chosen sample size was based on evidence from comparable studies of fit accuracy, where 10 specimens per group were commonly used (Shamseddine *et al.*, 2016) and supported by power analyses indicating that as few as six specimens per group can achieve 80% power at $\alpha = 0.05$ (Akçin *et al.*, 2018). The larger sample size in the present study was therefore selected to ensure robust statistical validity and to account for variability across materials and orientations. All specimens were milled under identical conditions using a 5-axis inLab MC X5 unit (Dentsply Sirona, Bensheim, Germany). The milling process utilised the system's standard three-bur configuration, a 2.5 mm bur (REF 6478031), 1.0 mm bur (REF 6478049), and 0.5 mm bur (REF 6478056), which is routinely used for milling wax, PMMA (polymethyl methacrylate), and PEEK (polyether-ether-ketone). Following retrieval from the milling discs, the wax patterns were placed on the printed resin dies without cementation for subsequent analysis.

Measurement protocol

For gap measurement, each wax pattern was placed onto the corresponding sectioned resin die and held in position with a clamp in both the mesio-distal (MD) and bucco-lingual (BL) orientations. Care was taken to avoid deforming the wax; the clamp applied only minimal passive pressure to keep the crown seated (see Figure 5). Ten standardised measurement points were defined on each sectioned specimen as shown in Figure 5: four marginal points (positions 1, 5, 6, and 10) and six internal points (positions 2, 3, 4, 7, 8, and 9). The marginal gap and internal gap at each point were measured under 200× magnification using a Nikon SMZ800 stereomicroscope (Nikon Corp., Tokyo, Japan) equipped with C-W 10×/22 eyepieces. Digital image analysis software integrated with the microscope was used to record gap values in micrometres (µm), with a corresponding screenshot saved for documentation and subsequent analysis (see Figure 6).

Data organisation and statistical analysis

All measurement data (total of 300 gap measurements: 10 points × 60 specimens) were tabulated in long format with identifying variables for material type, section orientation (MD or BL), gap location (marginal or internal), point number, and the gap value in micrometres. For each material group, descriptive statistics (mean, standard deviation, and range) were calculated for the marginal fit and internal fit. A one-way ANOVA was performed to detect any significant differences in gap values among the three wax materials. Additionally, orientation was analysed as a factor within a three-way ANOVA model (Material × Orientation × Fit Type) to compare MD vs. BL section measurements within each

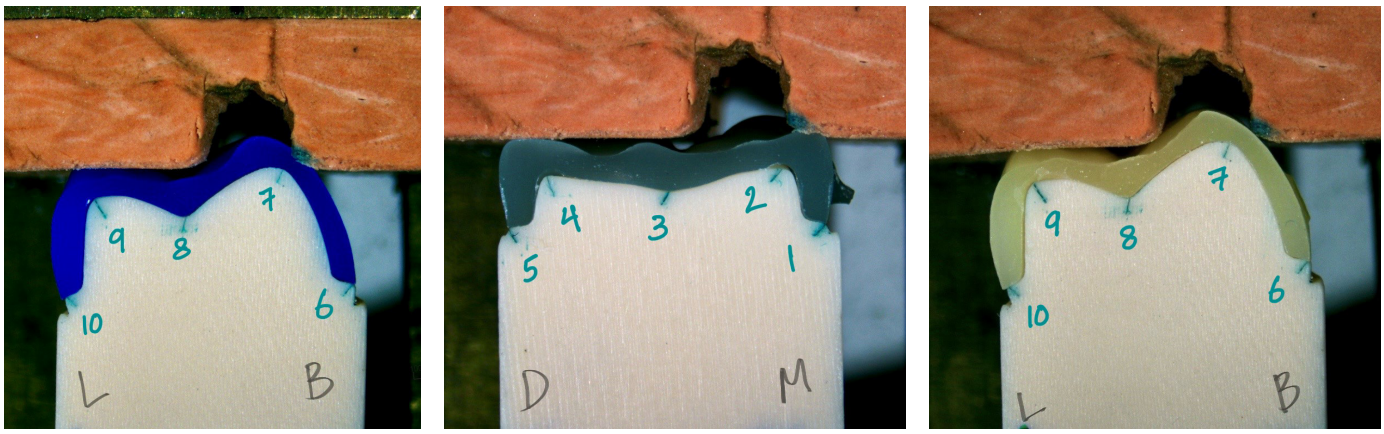

Figure 5. Sectioned wax patterns positioned on the die and mounted for stereomicroscopic measurement. A: Aidite wax (bucco-lingual section). B: Dentsply Sirona wax (mesio-distal section). C: Ivoclar ProArt CAD wax (bucco-lingual section). The sectioned dies are shown in the bucco-lingual (A and C) and mesio-distal (B) orientations. Predetermined measurement locations used to assess marginal and internal fit are indicated directly on the dies. In the bucco-lingual sections (A and C), points 6 and 10 represent marginal gaps, 7 and 9 represent axial internal gaps, and 8 represents the occlusal internal gap. In the mesio-distal section (B), points 1 and 5 represent marginal gaps, 2 and 4 represent axial internal gaps, and 3 represents the occlusal internal gap. Orientation markings on the die indicate buccal (B), lingual (L), mesial (M), and distal (D) surfaces.

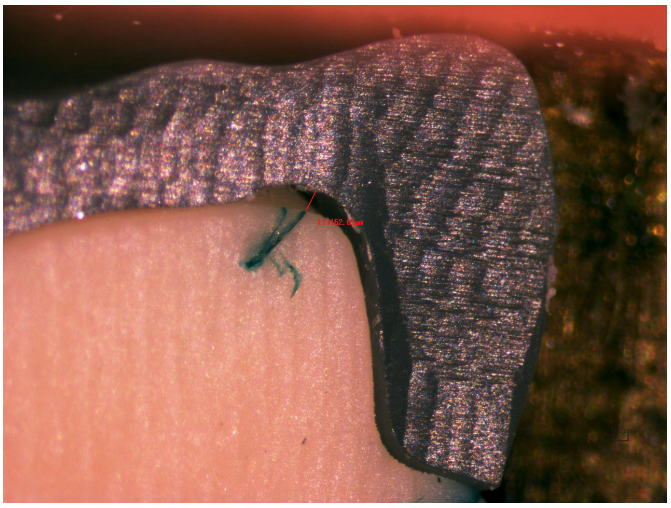

Figure 6. Representative image of measurements taken with the stereomicroscope. This example is of a Dentsply wax showing a 152.05µm gap between wax and printed die.

material group. Tukey's HSD post-hoc test was planned for multiple comparisons if the ANOVA indicated significant differences. All statistical analyses were conducted using Microsoft Excel and JMP Pro 18 (SAS Institute Inc., Cary, NC, USA), with the level of significance set at $\alpha = 0.05$ ($p < 0.05$ for significance).

Results

LS-Mean gap values were 79.5 ± 42.3 µm for Aidite, 76.1 ± 42.3 µm for Dentsply, and 71.6 ± 42.3 µm for Ivoclar. The main effect of material was not significant, $F(2, 288) = 0.87$, $p = 0.420$, indicating that the three CAD/CAM waxes produced a comparable fit (Table 1).

By contrast, section orientation and fit type both showed significant effects. Crowns sectioned in the bucco-lingual (BL) plane had smaller gaps than those in the mesio-distal (MD) plane, $F(1, 288) = 85.91$, $p < .001$ (BL mean = 53.1 ± 42.3 µm; MD mean = 98.4 ± 42.3 µm) (see Figures 7-8). Marginal gaps were also significantly smaller than internal gaps, $F(1, 288) = 55.48$, $p < .001$ (marginal mean = 57.6 ± 29.3 µm; internal mean = 94.0 ± 47.9 µm).

A significant Orientation × Fit Type interaction was observed, $F(1, 288) = 31.32$, $p < .001$. The orientation effect was more pronounced for internal fit: in the MD sections, internal gaps were much larger than marginal gaps, whereas in the BL sections the difference was minimal, these trends are illustrated in Figure 9 (a) and (b).

Notably, the occluso-axial internal point (Point 2) in the MD plane showed the highest discrepancy, with a mean gap of ~134 µm and individual values exceeding 200 µm. This interaction is illustrated in Figure 6. In contrast, BL sections showed relatively uniform gaps across all measurement points.

Table 1. Mean marginal and internal gap values (µm) of CAD/CAM milled wax patterns according to material and section orientation. Values are presented as mean ± SD.

Material	Orientation	Marginal Fit (µm)	Internal Fit (µm)	Overall Mean (µm)
Dentsply	BL	54.08± SD[a]	58.98 ± SD[b]	56.53 ± SD
Dentsply	MD	65.71± SD[a]	125.70± SD[c]	95.71 ± SD
Ivoclar	BL	44.53± SD[a]	44.15 ± SD[b]	44.34 ± SD
Ivoclar	MD	63.85± SD[a]	134.06± SD[c]	98.96 ± SD
Aidite	BL	47.20± SD[a]	69.81 ± SD[b]	58.51 ± SD
Aidite	MD	70.06± SD[a]	131.01± SD[c]	100.54 ± SD

Note: Values are presented as mean ± standard deviation (µm). BL = bucco-lingual orientation; MD = mesio-distal orientation. Different superscript letters indicate statistically significant differences between groups ($p < 0.05$) based on Tukey HSD post-hoc comparisons following three-way ANOVA.

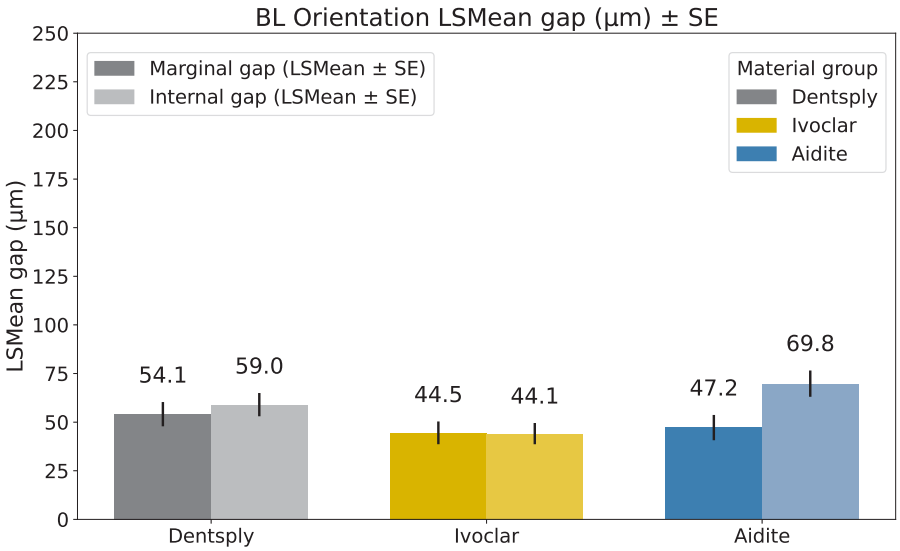

Figure 7. Least-squares mean (LSMean) marginal and internal gap values in the bucco-lingual (BL) orientation for Dentsply, Ivoclar, and Aidite wax patterns. Error bars represent standard error (SE). Three-way ANOVA showed that orientation and fit type significantly affected gap values ($p < 0.001$), with a significant orientation × fit type interaction ($p < 0.001$), while material type was not statistically significant ($p = 0.4196$). Darker shade representing the Marginal gap and lighter shade the internal gap.

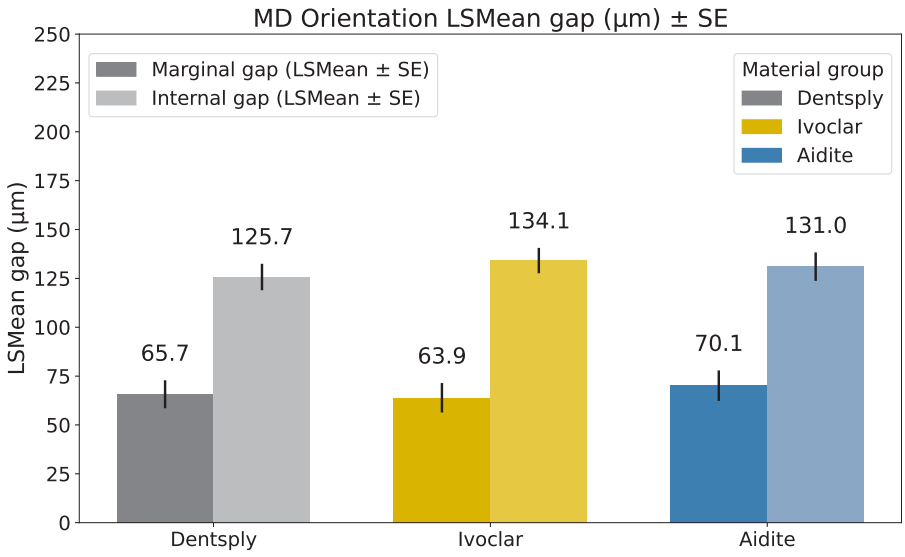

Figure 8. Least-squares mean (LSMean) marginal and internal gap values in the mesio-distal (MD) orientation for Dentsply, Ivoclar, and Aidite wax patterns. Error bars represent standard error (SE). Three-way ANOVA showed that orientation and fit type significantly affected gap values ($p < 0.001$), with a significant orientation × fit type interaction ($p < 0.001$), while material type was not statistically significant ($p = 0.4196$). Darker shade representing the Marginal gap and lighter shade the internal gap.

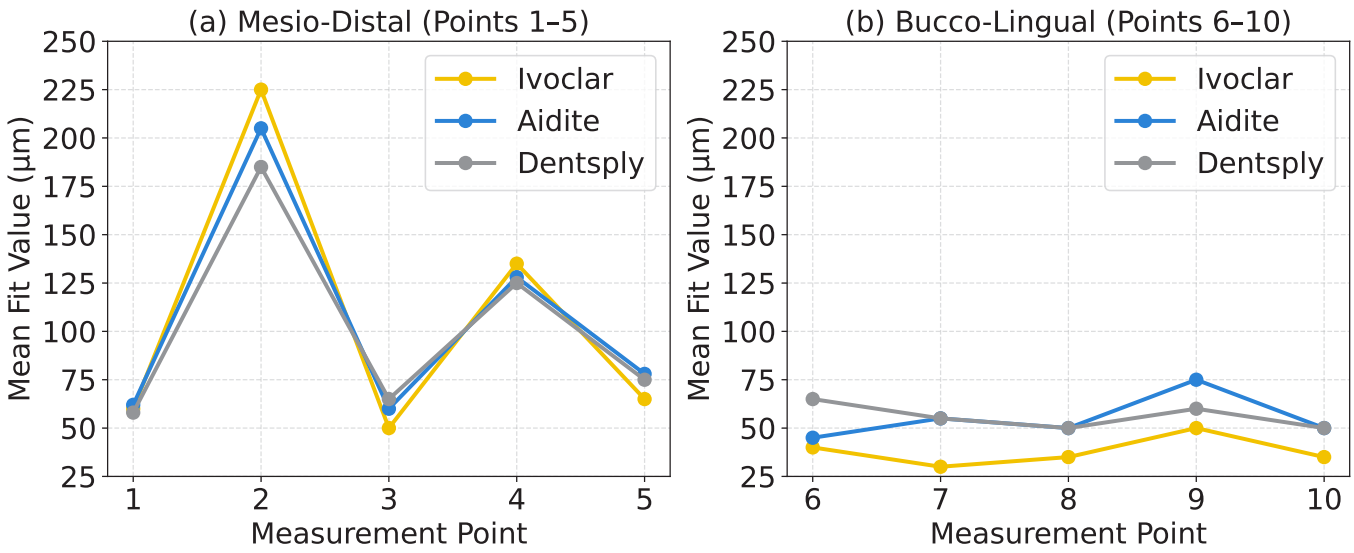

Figure 9 (a) and (b). Mean fit values (µm) recorded at the predefined measurement points for the three CAD/CAM milling wax materials. (a) Mesio-distal section showing measurements at points 1–5. (b) Bucco-lingual section showing measurements at points 6–10. Each plotted point represents the mean gap measurement obtained at the respective location on the sectioned crown–die interface. Ivoclar, Aidite, and Dentsply wax patterns are shown for comparison. Three-way ANOVA demonstrated significant effects of orientation and fit type on the measured gap values ($p < 0.001$), with a significant interaction between orientation and fit type ($p < 0.001$), while material type did not show a statistically significant effect ($p = 0.4196$).

No other interactions were significant: Material × Orientation, $F(2, 288) = 0.94$, $p = .391$; Material × Fit Type, $F(2, 288) = 0.33$, $p = .722$; and the three-way interaction, $F(2, 288) = 0.91$, $p = .404$. Across all materials, the same qualitative pattern was observed: BL sections and marginal sites consistently produced smaller gaps than MD sections and internal sites.

Nanoindentation testing revealed measurable differences in the hardness and elastic modulus of the three waxes ($p < 0.05$). Ivoclar (2.44 ± 0.21 GPa) and Aidite (2.27 ± 0.44 GPa) exhibited higher moduli compared with Dentsply (1.52 ± 0.31 GPa). For hardness, Aidite recorded the highest values (0.074 ± 0.018 GPa), followed by Dentsply (0.066 ± 0.017 GPa), while Ivoclar showed the lowest hardness (0.059 ± 0.008 GPa).

Discussion

The precision of marginal and internal adaptation plays a fundamental role in ensuring the biomechanical stability and biological outcomes of indirect restorations. Unlike most studies which evaluated fit accuracy only at the final restoration stage (Kokubo *et al.*, 2011; Colpani *et al.*, 2013), the present study focused on the interim precursor phase by assessing the fit accuracy of full-coverage wax patterns milled from three CAD/CAM wax materials. The results indicated no statistically significant differences in marginal or internal discrepancies among Dentsply Sirona Gray, Ivoclar ProArt CAD Yellow, and Aidite Blue Milling Wax. All materials produced fits that remained within commonly cited clinical thresholds (<120 µm marginal;

<300 μm internal), suggesting comparable performance across materials under standardised conditions.

Nanoindentation confirmed that the three waxes differ in their mechanical properties. Differences in hardness and stiffness are relevant, as these mechanical properties may influence milling behaviour and thereby affect the dimensional precision and reproducibility of the resulting wax patterns. Ivoclar and Aidite exhibited a higher elastic modulus than Dentsply, while Aidite demonstrated the highest hardness and Ivoclar the lowest. These differences suggest that the waxes vary in how they may respond to milling forces; however, under the standardised workflow of this study, such variations in material mechanics did not translate into significant differences in marginal or internal fit.

Both measurement orientation and fit type were found to significantly influence adaptation. Mesio–distal sections demonstrated greater discrepancies than bucco–lingual sections, a finding that aligns with Chaiamornsup *et al.* (2022), who also reported orientation-dependent differences, though in the opposite direction, highlighting the complexity of this methodological variable. This variation may be explained by the more intricate morphology along the mesio–distal axis, which complicates scanner capture and restricts milling bur access (Kim *et al.*, 2024). In addition, internal gaps were consistently larger than marginal gaps across all materials. This result is consistent with earlier studies (Martins *et al.*, 2012; Shamseddine *et al.*, 2017; Homsy *et al.*, 2018; Skordou *et al.*, 2021).

From a clinical perspective, the findings emphasise how the geometry of tooth preparation and the limitations of milling tools directly affect internal adaptation. The smallest bur available in the inLab MC X5 system, a 0.5 mm bur, was used in this study, yet internal features sharper than its radius could not be reproduced, resulting in unavoidable rounding or over-milling of internal line angles, as illustrated in Figures 1c and 5. This explains why, even with the smallest bur size, Measurement Point 2 consistently exhibited larger internal discrepancies. Such constraints are inherent to all subtractive systems and underscore an important clinical message: overly sharp internal line angles or narrow axial walls may exceed the milling machine's ability to reproduce them with precision. However, only using one milling machine in this study was a distinct limitation, as different machines have different milling pathways which could be a distinct variable influencing the internal contours of milled restorations. Future studies may shed more light on this issue by including several different milling systems. Accordingly, designing and preparing restorations with smooth internal transitions not only facilitates optimal milling but also improves the likelihood of achieving a more accurate internal fit.

Most previous investigations into fit accuracy have focused on the definitive restorative materials, such as metal alloys, ceramics, or hybrid resins, with marginal and internal adaptation commonly measured after the final casting or milling stage (Shamseddine *et al.*, 2016; Akçin *et al.*, 2018; Homsy *et al.*, 2018). By contrast, there has been little to no emphasis on the interim wax pattern stage, despite its critical role in the lost-wax workflow. The wax pattern serves as the direct precursor to the definitive restoration, and any inaccuracies introduced at this stage are likely to be transferred or even amplified during subsequent investment and casting processes (Manappallil, 2016). The present study therefore contributes new insight by evaluating adaptation at the wax pattern phase itself, before casting or pressing, allowing for a more direct assessment of how different milling waxes influence fit. This highlights the importance of material selection not only for the final prosthesis but also at the intermediate stages of digital workflows.

A strength of this study was the high level of standardisation across the experimental workflow. A single typodont preparation and digital design were used for all specimens, eliminating anatomical variability and ensuring direct comparability between materials. Furthermore, all experimental procedures were carried out by a single operator, reducing the risk of inter-operator variability. The same intraoral scanner and consistent milling protocol were applied, minimising workflow heterogeneity. The use of multiple measurement points across both mesio-distal and bucco-lingual planes also enhanced the spatial resolution of the fit assessment, providing a more comprehensive evaluation of adaptation than single-point methods. Importantly, the measurement protocol relied on stereomicroscopy, a well-established and highly sensitive technique for evaluating marginal and internal fit in vitro. Previous studies have demonstrated that stereomicroscopic analysis provides accurate, reproducible, and clinically relevant results (Nawafleh *et al.*, 2013; K. Son *et al.*, 2019), making it a robust choice for assessing adaptation in this experimental setting.

It is important to note that the "clinically acceptable" threshold for marginal gaps (<120 μm) most frequently cited in the literature originates from the classic study of McLean and von (1971). While widely adopted, this benchmark was established more than fifty years ago under clinical conditions and cementation protocols that differ substantially from contemporary adhesive systems. Advances in luting agents, bonding techniques, and restorative materials may alter what constitutes a truly acceptable marginal discrepancy today. In contrast, no universally accepted reference values exist for internal fit. Reported ranges vary considerably between studies, with many authors refraining from specifying any threshold at all (Contrepois *et al.*, 2013; Kim *et al.*, 2018). These inconsistencies underscore the need for ongoing reassessment of adaptation standards in light of modern restorative technologies.

Conclusion

Within the limitations of this in-vitro study, three commonly used CAD/CAM milling waxes (Dentsply Sirona Gray, Ivoclar ProArt CAD Yellow, and Aidite Milling Wax Blue) demonstrated comparable marginal and internal adaptation, with all measurements falling within clinically accepted thresholds. Therefore, material selection alone had little influence on fit accuracy under standardised conditions. By contrast, methodological factors such as section orientation and fit type significantly affected adaptation, with mesio–distal sections and internal sites showing larger discrepancies. These findings highlight the importance of carefully controlling experimental design and recognising that workflow variables may exert greater influence on

adaptation than wax brand choice. Collectively, these findings indicate that although material choice exerted little influence under the present experimental conditions, methodological factors such as orientation and fit type and production factors such as milling burr radius had a measurable effect on adaptation outcomes and should be carefully considered in both in-vitro design, clinical interpretation and application.

Author contributions

Conception and design of the study – LJvV, WJvV
Data collection – MM
Data analysis and interpretation – MM, LJvV, WJvV
Drafting the article – MM
Critical revision of the article – LJvV, WJvV
Final approval of the version to be published – MM, LJvV, WJvV

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Conflict of interest statement

The authors declare no conflicts of interest.

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