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RESEARCH AND EDUCATION

Internal fit and marginal adaptation of digitally fabricated interim fixed dental prostheses

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ABSTRACT

Statement of problem. The clinical performance of interim fixed dental prostheses (FDPs) depends on their accuracy, which is influenced by manufacturing technique, material type, and span length. Rapid advancements in these factors warrant updated evaluation of their impact on FDPs accuracy.

Purpose. The aim of the present study was to assess the accuracy of stereolithography (SLA) and digital light processing (DLP) 3-dimensional (3D) printing of interim FDPs of different span lengths and compare these methods with the milling technique.

Material and methods. A maxillary typodont cast was used to simulate 3 clinical situations of missing maxillary anterior teeth. The abutment teeth were prepared, the cast was scanned using an intraoral scanner, and the scans were exported as standard tessellation language (STL) files into a software program for designing the FDPs. The designs were exported to a milling machine, SLA 3D printer, and DLP 3D printer for production. Specimens were divided into 3 groups according to manufacturing technique (n=24) and 3 subgroups according to span length (n=8), with a total number of 72 specimens. The FDPs were seated onto their corresponding casts, and the assemblies were scanned using micro-computed tomography (μCT). The produced scans were assessed for internal and marginal gaps using the Image J software program. Gaps were evaluated at the incisal, axial, and marginal regions. The data were analyzed using 2-way ANOVA models, and modeling was followed by post hoc comparisons of estimated marginal means using F-tests and pairwise *t* tests with Kenward-Roger degrees-of-freedom approximation.

Results. Milled FDPs exhibited higher incisal, axial and marginal gaps for all span lengths than the SLA and DLP 3D printed groups. For marginal gaps, the results were as follows: 3-unit FDPs: the highest mean gap was recorded in milling (112 ±9 μm), followed by DLP (99 ±19 μm), and the lowest in SLA (45 ±9 μm) *P* <.001; 4-unit FDPs: milling exhibited the highest mean gap (147 ±16 μm), with DLP (102 ±14 μm) and SLA (83 ±14 μm) following *P* <.001; 6-unit FDPs: the highest mean gap was reported in milling (135 ±14 μm), followed by DLP (104 ±19 μm), with SLA having the lowest (78 ±15 μm) *P* <.001.

Conclusions. 3D printed FDPs had fewer marginal and internal gaps than milled FDPs for different span lengths. All digitally fabricated FDPs exhibited marginal gap values within ranges commonly reported as clinically acceptable. (J Prosthet Dent 2026;136:220-228)

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Clinical Implications

Manufacturing technique and span length had a direct influence on the accuracy of the produced FDPs. Additive manufacturing can produce FDPs with higher accuracy than milling.

Interim fixed dental prostheses (FDPs) play a crucial role in maintaining stable oral conditions during the fabrication of definitive FDPs.[1–4] The advent of computer-aided design and computer-aided manufacturing (CAD-CAM) technology has revolutionized the production of interim FDPs, allowing for the fabrication of high-quality milled restorations with superior physical, esthetic, and mechanical properties.[3,5–7] More recently, advancements in 3-dimensional (3D) printing technology have gained significant attention in dentistry, offering notable advantages over traditional milling techniques regarding polymeric restoration production, including reduced production time, material efficiency, and the ability to fabricate complex structures with higher accuracy.[8–12]

Among the various 3D printing techniques, photopolymerization has been the most widely adopted in dentistry because of its ability to produce highly detailed objects with excellent resolution, smooth surface finishes, and faster production times. Techniques such as stereolithography (SLA) and digital light processing (DLP) use photopolymerization and are common in the production of dental casts[13–16] and interim FDPs.[17–23]

The clinical success of interim FDPs depends on 3 key factors: fracture resistance, esthetics, and accuracy.[23,24] Accuracy, which includes internal fit and marginal adaptation, is particularly critical as it directly impacts prosthesis functionality and longevity.[25–28] Ill-fitted interim FDPs can lead to a thick cement layer, lack of retention, plaque accumulation, and loss of function.[25,26,29–31]

Several methods have been used to assess the internal fit and marginal adaptation of FDPs, including the silicone replica technique, cross-sectioning method, digital scanning with superimposition, optical coherence tomography, and micro–computed tomography (μCT) scanning.[25,32] Among these, μCT has been considered the most accurate and reliable method of assessment[32] and has been increasingly implemented in evaluating the accuracy of FDPs fabricated from resin and hybrid polymer materials. This is attributed to its ability to produce high-resolution, detailed images that allow the 3D assessment of marginal and axial fit.[33,34]

One factor that can compromise the accuracy of FDPs is span length and the number of splinted units.[18,35] While previous studies have investigated the influence of span length and fabrication techniques on the accuracy of definitive FDPs,[35–37] only limited data are available on interim FDPs, especially those produced using digital manufacturing methods and materials. Therefore, the aim of the present study was to assess the accuracy of SLA and DLP 3D printed interim FDPs and compare them with milled FDPs. The null hypotheses were that the manufacturing technique or the span length would not affect the accuracy of interim FDPs.

MATERIAL AND METHODS

The materials used in this study, their description, product name, manufacturer, and lot numbers, are listed in Table 1. A maxillary typodont cast (Nissin acrylic cast; Nissin Dental Products Inc) was used to simulate 3 clinical situations of missing maxillary anterior teeth: missing right lateral incisor to be restored with a 3-unit FDP from the right central to the right canine, missing right lateral and central incisor to be restored with a 4-unit FDP from the left central to the right canine, and missing bilateral central and lateral incisors to be restored with a 6-unit FDP from the right canine to the left canine.

A measuring index was made prior to abutment preparation using a condensation silicone impression material (Zhermack condensation silicone; Zhermack GmbH). After complete setting, the index was sectioned buccolingually along each abutment's midline and used to evaluate the amount of reduction. Each abutment was prepared using blue coded tapered diamond stone size 13 with rounded end (TR13) and blue coded wheel stone (Komet diamond stones; Komet dental). The amount of reduction was 2 mm at the incisal edge or cusp tip, 1 mm axially, and 0.8 mm at the palatal fossae. The total convergence angle (TOC) between opposing axial walls was 25 degrees following a previous study.[38] The finish line was a 1-mm-deep chamfer margin placed approximately 0.5 mm supragingival for the convenience of scanning. To standardize the procedure, a single operator (N.A) performed all abutment preparations using the measuring index. For each span length, the cast was prepared by positioning the prepared abutment teeth and removing the pontic teeth. The socket of the missing

Table 1. Materials used

No.	Material	Product Name	Manufacturer	Lot no.
1.	CAD-CAM PMMA blanks	Dentsply Sirona Multilayer PMMA disc	Dentsply Sirona	00000007640000009139
2.	3D Printable composite resin for fixed partial dentures	GC Temp PRINT	GC Corp	23120812303281
3.	3D Printable composite resin for fixed partial dentures	Formlabs temporary CB	Formlabs	600695
4.	Light-polymerized resin for additive manufacturing of dental casts	P pro model	Straumann	210417B
5.	Intraoral latex Elastics	DentaurumOlympia	Dentaurum	772-126

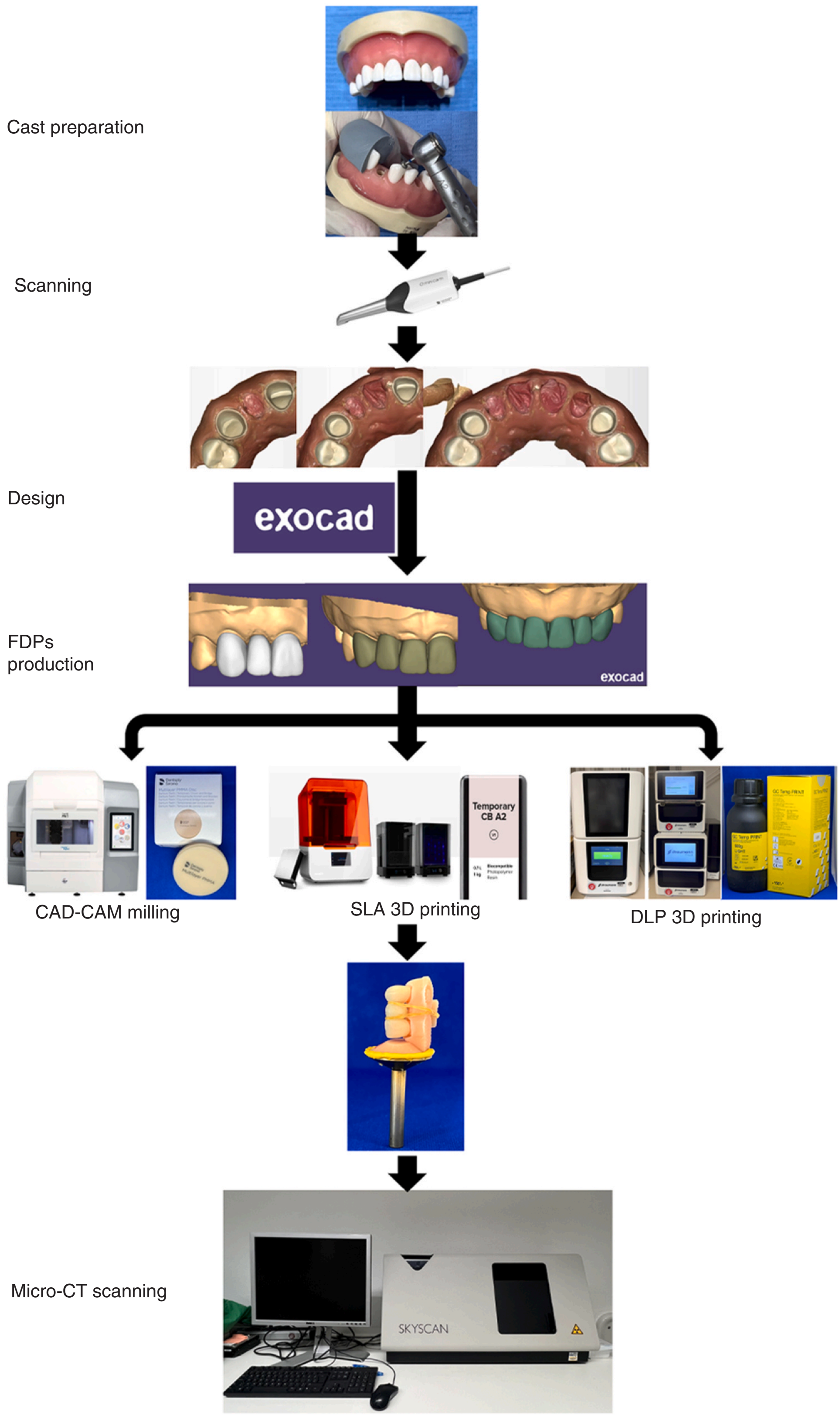

Figure 1. Schematic workflow of study methodology.

Table 2. Detailed FDP production techniques

Finishing and polishing	**After removal of sprues using acrylic resin finishing stone, restorations polished using universal acrylic polishing kit.**	**Restorations polished using pumice stone and polishing compound, followed by polishing using dental composite polishers to achieve high surface gloss.**	**Support attachments finished using acrylic finishing stone, followed by polishing using universal acrylic polishing kit.**
Post-processing procedures		**Washing:** Restorations washed in Form Wash with build platform submerged in clean isopropyl alcohol (≥99%) for 3 min, followed by drying with compressed air, producing white, powdery coating. **Post-polymerization:** After drying, restorations detached from build platform, placed raft-side down in Form Cure at 60 °C for 20 min, followed by separation from rafts and supports using handpiece.Restorations airborne-particle abraded using Perlablast with 50 µm glass beads at 0.15 MPa to remove powdery coating. Subsequent post-polymerization occurred in Form Cure at 60 °C for additional 20 min with occlusal plane facing upwards.	**Washing:** Restorations with intact supports underwent 2 washing cycles in Rapidshape (RS) wash using clean isopropyl alcohol (>96%) for 2 min using material-specific program, followed by drying with compressed air.**Post-polymerization:** Restorations polymerized in RS cure for 3 min with supports facing away from light source. Supports removed using tungsten carbide bur, followed by repeated polymerization for 3 min with opposite side facing light.
Manufacturer	Ivoclar AG	Formlabs Inc.	Straumann
Operating device	Ivoclar PrograMill PM7 milling machine	Formlabs Form 3B+ printer	Straumann p20+ dental 3D printer
Nesting/ Slicing software	PrograMill CAM nesting software program	Preform slicing software program	Netfab slicing software program
Material used	Dentsply Sirona Multi-layer PMMA disc	Formlabs interim CB 3D Printable composite for crown and fixed partial dentures	GC Temp PRINT 3D Printable composite resin for fixed partial dentures
Production steps	Milling	SLA 3D printing	DLP 3D printing

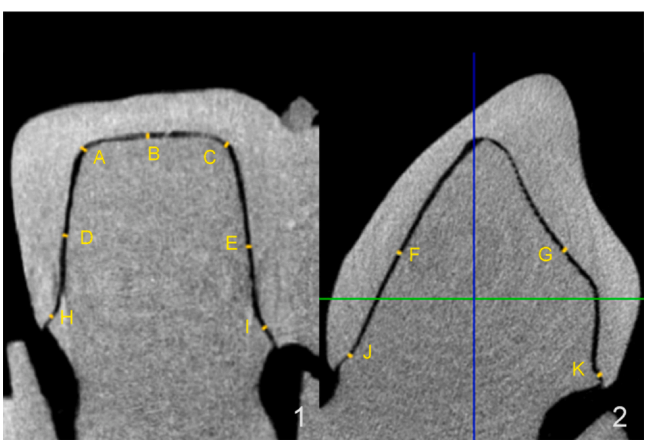

Figure 2. µCT sections for gap measurements; 1. Mesiodistal section along abutment midline, 2. Labiopalatal section along abutment midline. Incisal points: A. mesio-incisal angle, B. mid-incisal, C. disto-incisal angle. Axial points: D. mid-mesial, E. mid-distal, F. mid-labial, G. mid-palatal. Marginal points: H. mesial, I. distal, J. labial, K. palatal.

tooth/teeth was then filled with pink wax (Cavex pink wax; Cavex), and the cast was scanned using an intraoral scanner (Omnicam; CEREC Premium SW 4.4, Dentsply Sirona). The scans were exported as standard tessellation language (STL) files into a dental designing software program (exocad software program; exocad GmbH) (Fig. 1). For FDP designing, an experienced designer used a standardized tooth form from the exocad library for all designs with a 1-mm minimal restoration thickness and 80- µm cement gap.[20]

For the production of FDPs, a sample size calculation was performed based on the results of a previous study[17] using a software program (G*Power version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf).[39] Power analysis was calculated based on α=.05 and statistical power 0.80. A sample size of 6 specimens was found suitable to show significance between subgroups. In the present study, 72 specimens were used (n=8 per subgroup). FDP production proceeded as explained in Table 2.

The casts were 3D printed[13–15] using a DLP 3D printer (P20+; Straumann) with the default program settings for cast printing liquid (P pro Resin liquid; Straumann). Each cast was designed with a rounded, tapered cylinder base matching the dimensions of the µCT tray to ensure the precise positioning of the abutments along the tray's long axis. The produced casts were limited to include only the reduced abutments, pontic space, and underlying ridge for each span length, allowing straightforward placement of the specimens into the confined µCT chamber (Fig. 2).

The FDPs were seated onto their corresponding casts, and intraoral elastics were wrapped over the terminal connectors of each specimen for additional fixation. The assemblies were secured onto the µCT tray using light-body impression material (Honigum Light; DMG) (Fig. 3). µCT scanning was performed using a desktop X-ray µCT system scanner (SkyScan1174v2; Bruker) operating at 50-kV source voltage and 800-µA source current. The scanning parameters included a 360-degree sample rotation, 2-frame averaging, a rotation step of 0.40 degrees, and an exposure time of 2.2 seconds, with no filter applied. Following the scanning process, cone beam reconstruction was carried out using a reconstruction software program (NRecon version 1.6.1.5; Micro Photonics Inc), producing images with a pixel size of 25.50 µm. Reconstruction parameters included a ring artifact correction set at 10 and a beam hardening correction at 40%.

For analysis, mid-mesiodistal and mid-labiopalatal sections were obtained for each abutment. The internal

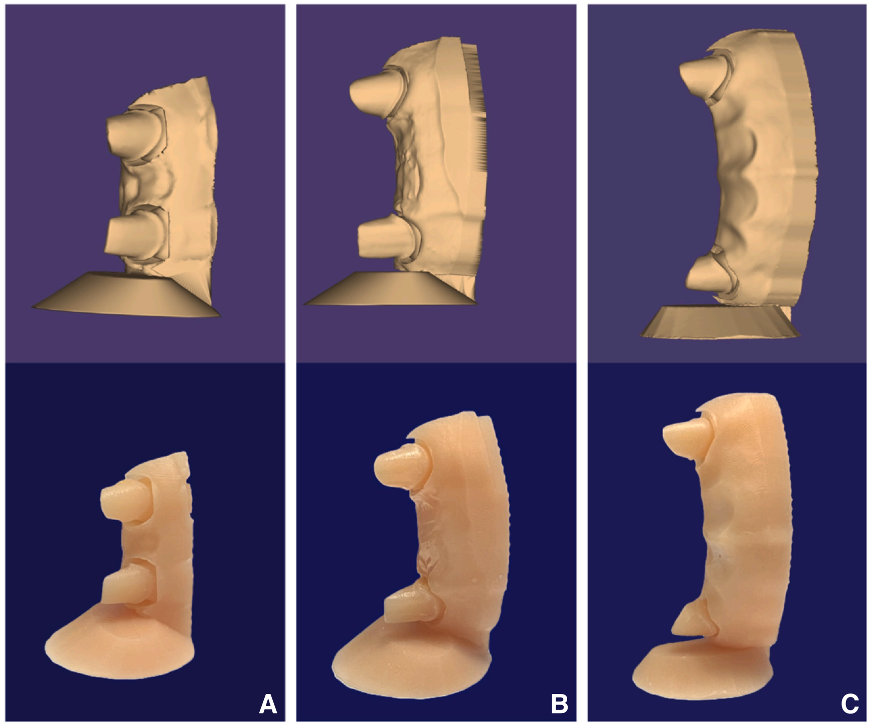

Figure 3. Designing and production of 3D printed casts for each span length; A. 3-unit FDP, B. 4-unit FDP, C. 6-unit FDP. FDP, fixed dental prosthesis; 3D, 3-dimensionally.

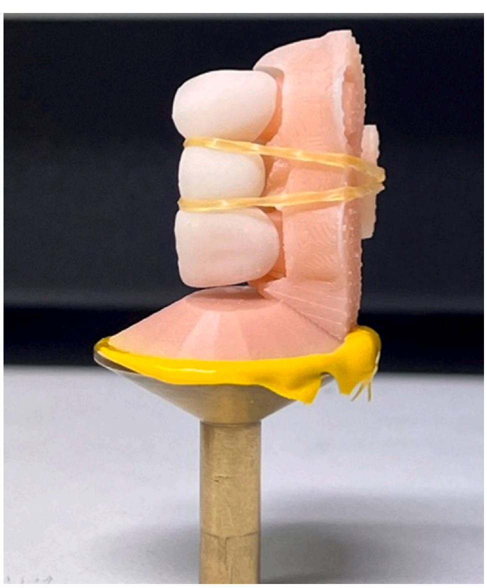

Figure 4. Fixing FDP to cast using elastics and securing assembly to µCT tray holder using light-body impression material, FDP, fixed dental prosthesis; µCT, microcomputed tomography.

gap distance was measured at 3 incisal points (mesio-incisal angle, mid-incisal, disto-incisal angle) and 4 axial points (mid-labial, mid-palatal, mid-distal, mid-mesial). Marginal gap distance was defined as the vertical distance between the restoration and the tooth finish line margin. Measurements were made at 4 central points along each surface margin (Fig. 4). Gap distances were measured using a software program (ImageJ; National Institutes of Health).

Statistical analysis was performed with statistical analysis software program (R statistical analysis software version 4.4.3 for Windows; R Foundation for Statistical Computing). Numerical data are presented as mean and standard deviation values. They were checked for normality and variance homogeneity by viewing the distribution and using the Shapiro-Wilk and Levene tests, respectively. The data were found to be normally distributed with homogenous variances across groups. They were analyzed using 2-way ANOVA models. Modeling was followed by post hoc comparisons of estimated marginal means using F-tests and pairwise *t* tests with Kenward-Roger degrees-of-freedom approximation. *P* values were adjusted for multiple comparisons using the false discovery rate (FDR) method. Effect sizes were expressed as partial eta squared (ηp^2) (α=.05 for all tests).

RESULTS

The 2-way ANOVA revealed that manufacturing technique had a significant main effect on incisal gap ($F(2,63)=41.97$, $P<.001$, $\eta p^2=0.57$), with milling demonstrating the highest mean gap, followed by DLP and SLA. Span length also showed a significant main effect on incisal gap (F(2,63)

Table 3. Effect of different variables and their interaction on incisal, axial, and marginal gaps (μm)

Source	df_1	df_2	F-value	*P*	ηp^2 (95% CI)	Effect Size
Incisal Gap						
Manufacturing technique	2	63	41.97	<.001*	0.57 (0.40 to 0.68)	Large
Span length	2	63	6.75	.002*	0.18 (0.03 to 0.33)	Medium
Manufacturing technique × Span length	4	63	0.90	.467	0.05 (0.00 to 0.15)	Small
Axial gap						
Manufacturing technique	2	63	56.01	<.001*	0.64 (0.49 to 0.73)	Large
Span length	2	63	17.89	<.001*	0.36 (0.17 to 0.51)	Large
Manufacturing technique × Span length	4	63	1.65	.172	0.09 (0.00 to 0.21)	Small
Marginal gap						
Manufacturing technique	2	63	45.93	<.001*	0.59 (0.43 to 0.70)	Large
Span length	2	63	12.08	<.001*	0.28 (0.10 to 0.43)	Large
Manufacturing technique × Span length	4	63	3.85	.007*	0.20 (0.02 to 0.34)	Medium

CI, confidence interval; df_1, numerator degrees of freedom; df_2, denominator degrees of freedom; ηp^2, partial eta squared.
* Statistically significant at *P*<.05.

Table 4. Comparisons and summary statistics of incisal, axial, and marginal gaps (μm) for different variables

Span Length	Incisal Gap (μm) (Mean ±SD)			*P*
	Milling	SLA	DLP	
3-unit	124 ±17^{Ab}	54 ±9^{Ca}	89 ±9^{Bb}	<.001*
4-unit	152 ±19^{Aa}	69 ±10^{Ca}	111 ±15^{Ba}	<.001*
6-unit	143 ±17^{Aa}	70 ±13^{Ca}	118 ±23^{Ba}	<.001*
P	.002*	.072	<.001*	
	Axial gap (μm) (Mean ±SD)			
3-unit	127 ±15^{Ab}	50 ±10^{Cb}	90 ±14^{Bb}	<.001*
4-unit	167 ±16^{Aa}	71 ±11^{Ca}	104 ±10^{Bab}	<.001*
6-unit	163 ±18^{Aa}	79 ±13^{Ca}	117 ±21^{Ba}	<.001*
P	<.001*	<.001*	.002*	
	Marginal gap (μm) (Mean ±SD)			
3-unit	112 ±9^{Ab}	45 ±9^{Bb}	99 ±19^{Aa}	<.001*
4-unit	147 ±16^{Aa}	83 ±14^{Ca}	102 ±14^{Ba}	<.001*
6-unit	135 ±14^{Aa}	78 ±15^{Ca}	104 ±19^{Ba}	<.001*
P	<.001*	<.001*	.793	

Values with different upper and lowercase superscripts within same horizontal row and vertical column, respectively, significantly different
* significant (*P*<.05)

=6.75, *P*=.002, ηp^2 =0.18). The interaction between manufacturing technique and span length was not statistically significant (F(4,63)=0.90, *P*=.467); therefore, the main effects were interpreted independently.

For axial gap, manufacturing technique demonstrated a significant main effect (F(2,63)=56.01, *P*<.001, ηp^2 =0.64), with milling exhibiting the highest mean gap, followed by DLP and SLA. Span length also had a significant main effect (F(2,63)=17.89, *P*<.001, ηp^2 =0.36). The interaction effect was not statistically significant (F (4,63)=1.65, *P*=.172); thus, the main effects were interpreted independently.

For marginal gap, both manufacturing technique (F (2,63)=45.93, *P*<.001, ηp^2 =0.59) and span length (F(2,63) =12.08, *P*<.001, ηp^2=0.28) demonstrated significant main effects. Unlike incisal and axial gaps, a significant interaction was observed between manufacturing technique and span length (F(4,63)=3.85, *P*=.007, ηp^2=0.20); therefore, the comparisons were interpreted at the level of simple effects. Comparisons and summary statistics of the incisal gap, axial gap, and marginal gap (μm) for different variables are presented in Tables 3, 4 and Figure 5.

DISCUSSION

Manufacturing techniques and span length are among the key factors influencing the accuracy of interim FDPs.[37] Direct acquisition system was selected for this study for its better accuracy compared with indirect methods of digitization of elastomeric impressions and poured gypsum casts.[6,7] To ensure standardization, an identical STL file for each span length was used across all production techniques.[10,18,19] FDPs were produced using materials validated on each device following the manufacturer's recommendation to ensure optimum production accuracy.[11,21,22] Sectional 3D printed casts were used to facilitate positioning within the constrained μCT chamber while maintaining the same refractive index as the tested FDPs.[10] A DLP printer was used for cast fabrication, as DLP printing has been considered the most accurate technique for producing 3D casts.[13–15] The Straumann printer specifically offers high precision accuracy.[16] During pilot tests, scanning cemented specimens resulted in reduced image quality. This necessitated the addition of an aluminum filter, which significantly increased scanning time. Consequently, noncemented specimen scanning was conducted following previous studies.[26,40] To secure the specimens during scanning, intraoral elastics were applied over the terminal connectors of each specimen.

This study demonstrated that both manufacturing techniques and span length significantly influenced the accuracy of interim FDPs; accordingly the null hypotheses that the manufacturing technique or the span length would not affect the accuracy of interim FDPs were rejected. Overall, milling resulted in greater internal and marginal gaps than 3D printing techniques (SLA and DLP) across different span lengths. This finding was consistent with previous studies.[17,18,23,26] However, other studies[19,24] reported that milling achieved lower internal and marginal gaps. These discrepancies may stem from variations in 3D printers, resins, and less accurate gap measurement techniques such as superimposition and silicon replica techniques.[25]

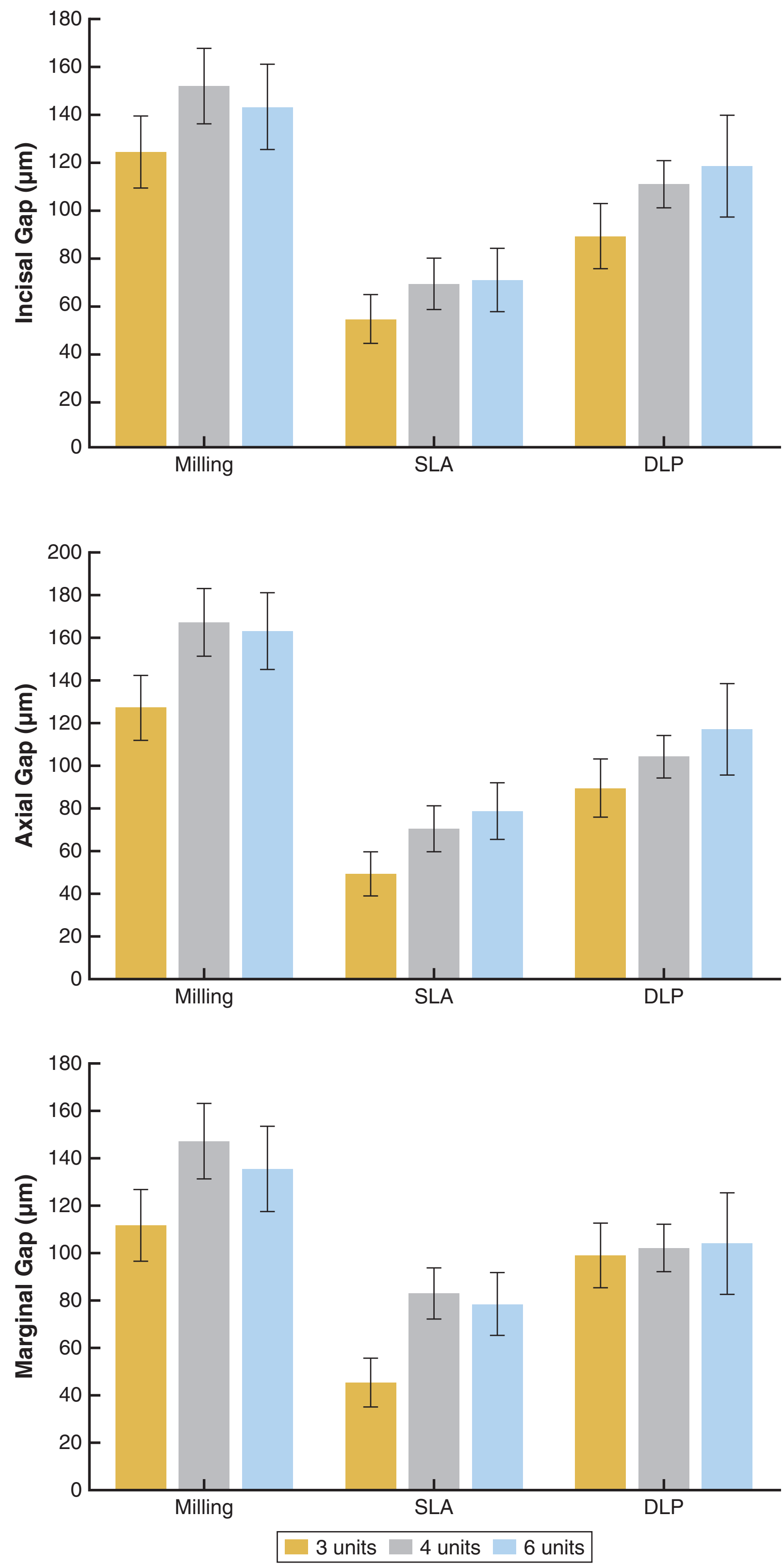

Figure 5. Bar charts for different variables. A, Average incisal gap (µm). B, Average axial gap (µm). C, Average marginal gap (µm).

Yılmaz et al[34] compared the accuracy of milled and 3D printed interim crowns and 3-unit FDPs and concluded that improved marginal and axial fit was observed in 3D printed interim crowns than in milled crowns. In contrast, for 3-unit FDPs, milled FDPs showed fewer internal and marginal gaps than 3D printed FDPs. The discrepancy between the findings of that study and the present study may be attributed to differences in restoration design. Specifically, Yılmaz et al used FDPs with a retainer thickness of 2 mm, whereas the present study used a retainer thickness of 1 mm. The increased thickness may have induced greater polymerization shrinkage in the 3D printed FDPs, resulting in increased internal and marginal gap discrepancies.[34]

Larger internal and marginal gaps of the milled restorations could be attributed to the inherent limitations of the CAM unit milling path and the dimensions of the milling burs, which can result in wider grooving of the fitting surface equivalent to the size of the cutting tip, thereby resulting in slightly oversized restorations.[17,18,26] In the present study, marginal gap values within the DLP-fabricated interim FDPs showed relatively small variation across the evaluated span lengths. This observation may be attributed to the higher precision accuracy associated with DLP technology when compared with milling and SLA techniques, as reported in previous studies.[14,41] However, span length significantly influenced incisal and axial gaps within the DLP, milling, and SLA groups, with all manufacturing techniques demonstrating increased internal gap values as span length increased. The smallest internal gaps and marginal gaps were noticed among all span lengths of SLA printed FDPs, consistent with the findings of Wadhwani et al[12] and Alharbi et al.[26] However, the internal gap was smaller than the designed cement gap, which indicates shrinkage of the printed FDPs that might result in tightly fitted restorations and mandates designing restorations with a wider cement gap. Different gaps produced by DLP and SLA 3D printing can result from different building and postprocessing polymerization techniques. Each manufacturer recommends a postprocessing polymerization process suitable for its material.[42] According to each manufacturer's recommendation, Formlabs interim FDPs were subjected to longer polymerization time (40 min) at higher temperature (60 °C), while GC interim FDPs were subjected to a 6-minute polymerization time. Polymerization time and temperature have a direct effect on the degree of polymerization, and increasing both factors can result in a higher degree of polymerization and higher polymerization shrinkage.[42]

Span length also influenced the outcomes of the present study. Milled and SLA-fabricated 4- and 6-unit FDPs demonstrated significantly larger marginal gaps than 3-unit FDPs. This finding can be attributed to the impact of arch curvature on the marginal adaptation of FDPs. Komine et al[27] reported that more curved FDP designs exhibit poorer marginal adaptation than straight designs. In the anterior region, increasing span length increased the curvature of the FDP, thereby adversely affecting its marginal adaptation. In contrast, marginal gap values within the DLP-fabricated FDPs did not differ significantly among the evaluated span lengths.

Previous studies have proposed that a clinically acceptable marginal gap is approximately 120 μm.[3,23,30] Other studies, however, suggest a broader range of 100 to 150 μm.[19,43] Based on these latter references, all manufacturing techniques evaluated in this study produced marginal gaps within acceptable limits across all span lengths. However, according to the former references, unacceptable marginal gaps were noted in 4- and 6-unit milled interim FDPs surpassing 120 μm. Regarding the incisal and internal fit gaps, clinically recommended values have yet to be established as the literature reports inconsistent findings.[28,30,44]

Limitations of the study included that the specimens were not subjected to an aging process, which would better simulate the service period and its impact on dimensional accuracy. Different resins were not tested for each printing technique, limiting the ability to assess the influence of material variations on accuracy. This study simulated the clinical workflow of FPD fabrication by checking the accuracy of the produced FDPs on the definitive cast as the first step of accuracy checking. However, further studies are required to check accuracy on the initially prepared cast, resembling intraoral accuracy checking.

CONCLUSIONS

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

1. 3D printed interim FDPs had fewer marginal and internal gaps than milled interim FDPs for different span lengths.
2. DLP 3D printing produced interim FDPs with relatively similar marginal gaps across the evaluated span lengths.
3. Increasing span length ≥4 units increased the internal and marginal gaps for milled and SLA 3D printed interim FDPs.
4. All digitally fabricated interim FDPs exhibited marginal gap values within ranges commonly reported as clinically acceptable.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used the ChatGPT AI tool to improve the readability of the English language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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