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Original Article

Evaluation of the marginal and internal fit of interim crowns fabricated using AI-based dental CAD software

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Purpose: This study aimed to assess the marginal and internal fit of interim crowns fabricated using artificial intelligence (AI)-based dental computer-aided design (CAD) software. **Materials and Methods:** The right maxillary first molar was prepared for an interim crown. Scan files were obtained using a desktop scanner and exported to three dental CAD software programs: a conventional software and two AI-based dental programs. A uniform cement gap of 60 μm was set across all software, and 10 interim crowns were designed. The crowns were fabricated using a 3D printer, and their marginal and internal fit was evaluated using the silicone replication technique. Statistical analysis was performed using the Kruskal-Wallis test and post hoc analysis ($\alpha = 0.05$). **Results:** A significant difference in marginal fit was observed among the three dental CAD software programs ($P < 0.05$). The marginal gap produced by 3Shape was significantly greater than that of the two AI-based programs ($P < 0.05$). No significant differences were observed in most areas regarding internal fit ($P > 0.05$), although Single-Pro exhibited a significantly larger occlusal gap ($P < 0.05$). **Conclusion:** The interim crowns fabricated using Dentbird and Single-Pro demonstrated excellent marginal fit. However, further refinement is necessary, as the occlusal area of the internal fit in Single-Pro exhibited a comparatively larger gap. **(J Dent Rehabil Appl Sci 2025;41(3):198-208)**

Key words: computer-aided design; artificial intelligence; marginal fit; internal fit

Introduction

Recent advancements in dental computer-aided design and computer-aided manufacturing (CAD/CAM) systems have significantly transformed the fabrication of dental prostheses.[1] These systems allow for precise prosthesis design and enhance workflow efficiency compared to conventional analog methods.[2-4] The success of crowns fabricated using CAD/CAM technology depends on several factors, including esthetics, fracture resistance, and marginal and internal fit.[5]

Marginal and internal fit are critical determinants of the long-term prognosis of a dental prosthesis.[6-9] Optimal marginal fit supports periodontal health and prevents cement dissolution.[8] Internal fit refers to the uniform adaptation between the crown and the tooth, with superior internal fit improving prostheses retention.[10] Clinically acceptable marginal fit values are reported to be under 100 - 120 μm, while internal fit is recommended to fall within the 50 - 100 μm range.[6-10] Therefore, achieving accurate marginal and internal fit is vital for the long-term success of dental prostheses.[11]

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Dental CAD/CAM technology includes scanning, design software, and milling procedures, each of which can affect the fit of dental prostheses.[11-13] Among these, dental CAD software plays a critical role by defining key structural elements of the prosthesis, such as the margin line, internal space parameters, and anatomical form; thus, the accuracy of the design process directly influences the final fit.[13]

Conventional dental CAD software extracts the margin line using predefined mathematical algorithms, which might be unreliable in areas with insufficient curvature features.[14,15] Furthermore, crown designs are generated based on templates from a tooth library without accounting for individual occlusion or adjacent dentition, often necessitating manual adjustments.[16] This increases the chairside working time and reduces fabrication efficiency.[16]

To address these limitations, artificial intelligence (AI)-based dental CAD software has been introduced. Trained on large datasets, these systems can more accurately replicate anatomical features, including patient-specific tooth morphology and occlusal relationships.[17] Automated margin detection further reduces the need for manual adjustments by the clinician.[16,18,19] As a result, AI-based CAD software is expected to significantly decrease working time and improve the efficiency of prosthesis design.[20-23]

Recent studies have evaluated the fit of dental prostheses using AI-based dental CAD software; however, most have focused on a single software program. Since differences in training data, automation algorithms, and design methods can affect prosthesis fit, it is essential to compare the performance of multiple AI-based CAD systems. Therefore, research comparing various AI-based dental CAD software is necessary.

This study evaluated the internal and marginal fit of interim crowns fabricated using various AI-based dental CAD software programs. By comparing one conventional and two AI-based software programs, the study sought to assess the clinical effectiveness of AI technology in prosthesis fabrication. The null hypothesis stated that no significant differences exist in the marginal and internal fit of interim crowns produced by the three software programs.

Materials and Methods

This study followed the workflow illustrated in Fig. 1. A prefabricated maxillary right first molar model (D85DP-500B.1; Nissin Dental, Kyoto, Japan) was used to fabricate a single interim crown. Tooth preparation involved a 1.5-mm reduction of the occlusal surface and a 1-mm reduction of the axial wall.[24] A 1.2-mm chamfer was created at the supragingival margin, and the preparation incorporated a 6° con-

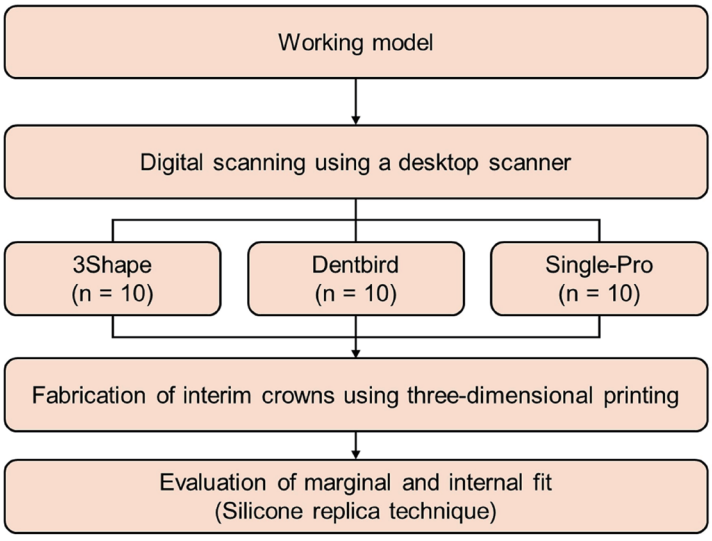

Fig. 1. Experimental procedure.

vergence.[24] The prepared maxillary and mandibular models were digitized using a desktop scanner (E1 scanner; 3Shape, Copenhagen, Denmark). The resulting scan files were imported into three different dental CAD software programs for interim crown design.

Dental CAD design was performed using a conventional CAD software program (3Shape Dental System; 3Shape) and two web-based AI software programs (Dentbird Crown; Imagoworks Inc., Seoul, Korea and Single-Pro; Xcube, Seoul, Korea). The design parameters were standardized across all software: cement gap of 60 μm, crown thickness of 0.6 mm, margin height of 0.1 mm, and margin angle of 45°.

The 3Shape software was used following the manufacturer's guidelines. Margin line extraction was initiated by selecting control points, after which the algorithm of the software automatically generated the margin path. If the extraction failed, the operator manually adjusted the control points. For crown design, the 3Shape C16 Bridge from the Smile Library was selected, and further modifications were made to ensure proper anatomical morphology and occlusal harmony.

Dentbird recognized the margin using a CNN-based segmentation model and automatically generated the tooth morphology through a StyleGAN-based generative model, with margin detection trained via supervised learning and tooth generation via unsupervised learning. In contrast, Single-Pro detected the margin based on the tooth axis using a principal curvature calculation algorithm and generated tooth morphology automatically using a transformer algorithm trained with supervised learning. Manual adjustments were made if necessary. The final crown design was then reviewed and refined as needed.

Ten interim crowns were designed using each software program, resulting in 30 crowns. This sample size is consistent with previous studies evaluating the marginal and internal fit of dental CAD software.[25] These designs were converted into G-code using slicing software (Raydent Studio; Raydent, Seoul, Korea) and printed with crown fabrication resin (Raydent C&B; Raydent) using a 3D printer (RAM500; Raydent). The printed crowns were rinsed under running water and post-cured for 5 min using a 405 nm light source in a post-curing unit (RPC 500; Raydent).

The silicone replica technique was employed to assess the marginal and internal fit of the interim crowns designed using each software (Fig. 2).[24] Light body silicone (Aquasil Ultra XLV; Dentsply Detrey

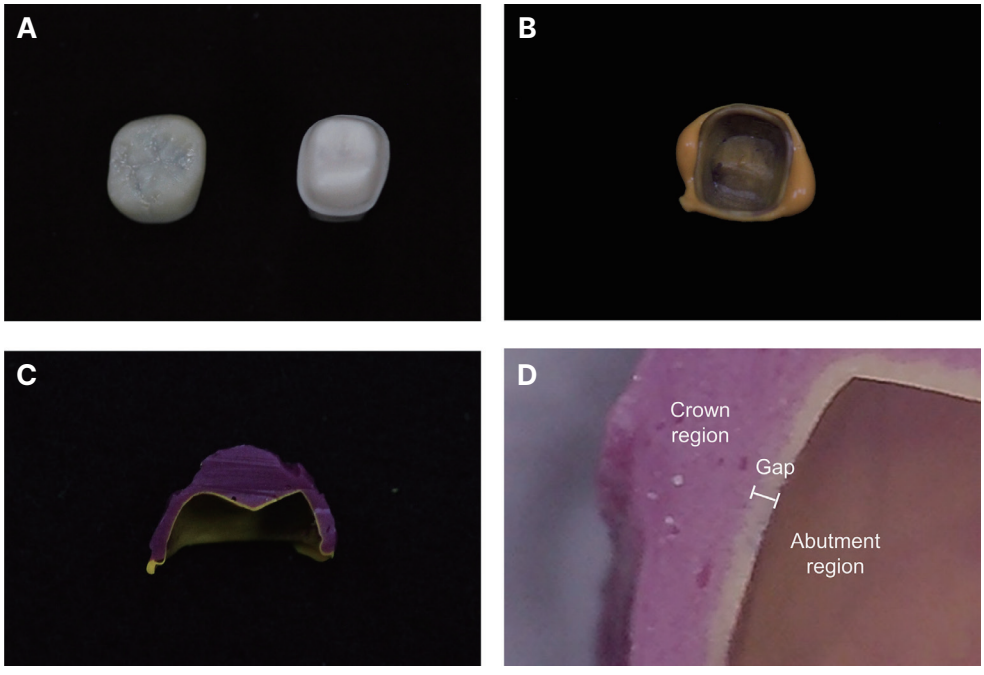

Fig. 2. Procedure of the silicone replica technique. (A) Prepared abutment tooth and interim crown, (B) Silicone injection and polymerization within the crown, (C) Sectioned silicone replica showing internal space, (D) Cross-sectional image of the silicone replica for gap measurement.

GmbH, Konstanz, Germany) was injected into the inner surface of each crown, which was then seated onto the abutment tooth under a constant force finger pressure until complete polymerization. After polymerization, the crown was carefully removed to preserve the silicone replica. Medium-body silicone (Aquasil Ultra Monophase; Dentsply Detrey GmbH) was subsequently applied over the replica to prevent deformation. The final replicas were sectioned mesiodistally and buccolingually using a stainless steel blade (Dorco stainless ST301 10; Dorco, Seoul, Korea).

Sectioned replicas were examined using a 60× industrial video microscope system (IMS 1080P; SOMETECH, Seoul, Korea), and images were analyzed for marginal and internal fit using measurement software (ITPlus 5.0; SOMETECH). The measurement sites for marginal and internal fit were illustrated in Fig. 3. The marginal fit was assessed using two parameters: marginal gap (vertical distance from the crown margin to the finish line of the abutment tooth) and absolute marginal discrepancy (AMD), defined as the distance between the crown margin and the finish line (Fig. 3A).[26] The internal fit was defined as the vertical distance between the axial surface of the abutment tooth and the corresponding inner surface of the crown. Internal fit was measured at four predefined points: chamfer gap (center of the chamfer), axial gap (midpoint of the axial wall), angle gap (junction of the chamfer and axial wall), and occlusal gap (midpoint between the occlusal surface and the angle) (Fig. 3B). All measurements were performed by a single operator.

All data were analyzed using statistical software (IBM SPSS Statistics, v25.0; IBM, Chicago, USA). To ensure the validity and consistency of the measurement protocol, intra-examiner reliability was assessed. A total of 40 randomly selected silicone replica sections were remeasured by the same examiner after a two-week interval. The intraclass correlation coefficient (ICC) was calculated using a two-way random-effects model with absolute agreement (ICC [2,1]) for both single and average measures. The normality and homogeneity of variance were tested using the Shapiro-Wilk test. The mean and standard deviation of the silicone replica measurements were calculated. Statistical differences among the groups were evaluated using the Kruskal-Wallis test, followed by post hoc analyses to determine between-group differences ($\alpha = 0.05$).

To evaluate the potential interaction effect between the type of dental CAD software and the measurement location on the marginal and internal fit of interim crowns, a two-way analysis of variance (ANO-

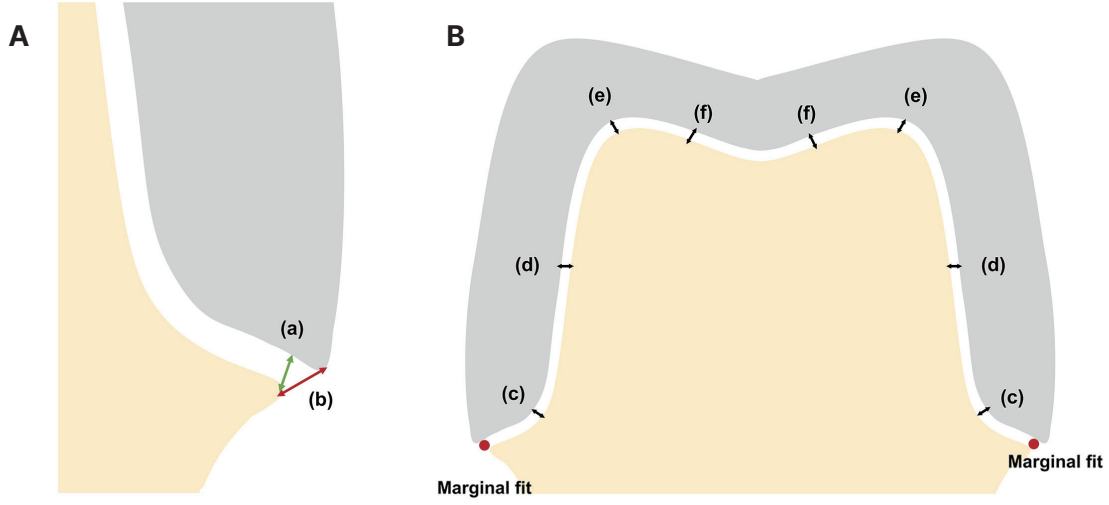

Fig. 3. Measurement sites for marginal and internal fit. (A) marginal fit, (B) marginal and internal fit. (a) marginal gap, (b) absolute marginal discrepancy, (c) chamfer gap, (d) axial gap, (e) angle gap, (f) occlusal gap.

VA) was conducted using a general linear model. The two fixed factors were the CAD software type (3Shape, Dentbird, and Single-Pro) and the measurement location, which consisted of six predefined regions: AMD, MG, chamfer, axial wall, angle, and occlusal gap. The dependent variable was the gap value (μm) measured at each location. A total of 1,440 measurements (n = 80 per condition) were included in the analysis. To account for potential deviations from normality, a bootstrap resampling method with 1,000 iterations was applied. The assumption of homogeneity of variances was verified using Levene's test. Post hoc pairwise comparisons were performed using Tukey's honestly significant difference test.

Results

The intra-examiner reliability analysis demonstrated excellent agreement. The ICC for single measures was 0.991 (95% CI: 0.984 - 0.995), and for average measures was 0.996 (95% CI: 0.992 - 0.998), indicating a high degree of repeatability in the measurement procedure. This result was statistically significant ($F = 225.186$; $P < 0.001$).

The results of the marginal and internal fit are summarized in Table 1. A statistically significant difference in marginal fit was observed among the three dental CAD software programs ($P < 0.05$; Table 1), while differences in internal fit were significant only in the occlusal area ($P < 0.05$; Table 1).

The AMD of interim crowns varied significantly among the three dental CAD software programs, with Dentbird exhibiting the lowest value (66.4 ± 11.4 μm) ($P < 0.001$; Fig. 4). Different superscript letters indicate statistically significant differences among groups, as shown in Fig. 4. For the marginal gap, Dentbird (60.2 ± 10.9 μm) and Single-Pro (62.4 ± 12.1 μm) demonstrated significantly lower values compared to 3Shape ($P = 0.009$; Fig. 4).

No significant differences were observed in the

Table 1. Comparison of marginal and internal fit (μm) of interim crowns fabricated using three dental CAD software programs

Marginal and internal fit		Dental CAD software	Mean (μm)	SD	95% confidence interval		*P*	Comparison
					Lower	Upper		
Marginal fit	AMD	3Shape	76.6	11.5	74.0	79.1	< 0.001*	A
		Dentbird	66.4	11.4	63.9	69.0		B
		Single-Pro	72.2	13.3	69.3	75.2		A
	MG	3Shape	66.0	12.6	63.2	68.8	0.009*	A
		Dentbird	60.2	10.9	57.8	62.6		B
		Single-Pro	62.4	12.1	59.7	65.1		AB
Internal fit	Chamfer	3Shape	69.1	13.4	66.1	72.1	0.067	-
		Dentbird	66.1	11.7	63.5	68.7		
		Single-Pro	71.0	14.7	67.7	74.3		
	Axial	3Shape	67.9	12.4	65.2	70.7	0.651	-
		Dentbird	66.1	15.4	62.7	69.5		
		Single-Pro	67.7	12.3	64.9	70.4		
	Angle	3Shape	62.1	11.3	59.6	64.7	0.057	-
		Dentbird	59.5	13.5	56.5	62.5		
		Single-Pro	57.6	11.1	55.1	60.1		
	Occlusal	3Shape	62.2	12.1	59.5	64.8	< 0.001*	A
		Dentbird	62.6	12.1	59.9	65.3		A
		Single-Pro	75.0	11.9	72.3	77.6		B

*Indicates a statistically significant differences determined using by the Kruskal-Wallis test ($P < 0.05$). Different uppercase letters denote indicate intergroup differences identified through pairwise comparisons in thebased on post- hoc pairwise analysis. CAD: computed-aided design; SD: standard deviation; AMD: absolute marginal discrepancy; MG: marginal gap

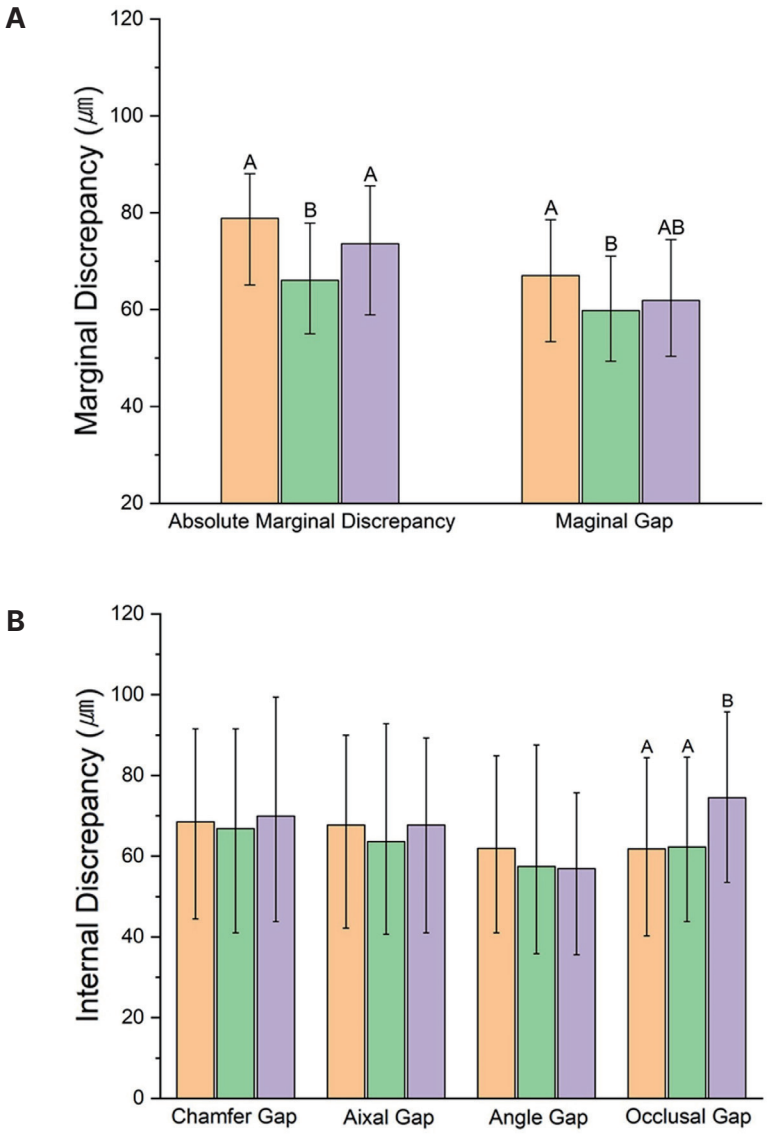

Fig. 4. Marginal and internal fit results by dental computer-aided design software type. (A) marginal fit, (B) internal fit. Different letters denote statistically significant differences between groups based on post hoc tests ($P < 0.05$).

internal fit at the chamfer, axial, and angle gaps ($P > 0.05$; Table 1). However, Single-Pro showed a significantly greater occlusal gap (75.0 ± 11.9 μm) than the other software programs ($P < 0.001$; Fig. 4).

The two-way ANOVA revealed a statistically significant interaction between CAD software type and measurement location (F (10, 1422) = 6.939, $P < 0.001$, partial $\eta^2 = 0.047$), suggesting that the fit accuracy of interim crowns varied depending on both the software used and the anatomical region measured. Significant main effects were also observed for CAD software (F (2, 1422) = 16.505, $P < 0.001$, partial $\eta^2 = 0.023$) and measurement location (F (5, 1422) = 28.200, $P < 0.001$, partial $\eta^2 = 0.090$). Levene's test confirmed the assumption of homogeneity of variances ($P = 0.247$). Post hoc analyses indicated that the occlusal gap in the Single-Pro group was significantly greater than those in the 3Shape and Dentbird groups ($P < 0.001$), while the Dentbird group consistently demonstrated the smallest gap values across all measurement locations.

Discussion

This study identified significant differences in the marginal and internal fit of interim crowns fabricated using the three dental CAD software programs ($P < 0.05$), leading to the rejection of all null hypotheses.

Previous research comparing CAD software programs such as Exocad, 3Shape, and B4D has shown discrepancies in cement space values,[27] indicating that differences in mathematical algorithms and scan data processing methods might affect accuracy.[28] Variations in the extraction and processing of control points and curves further highlight how software-specific design processes can impact the morphological accuracy of crowns.[29]

In the present study, the marginal fit of all three dental CAD software programs fell within the clinically acceptable range of 120 μm.[30-32] Notably, the AI-based software Dentbird (60.2 ± 10.9 μm) and Single-Pro (62.4 ± 12.1 μm) demonstrated superior fit. A previous study reported a significant difference in marginal fit between the Exocad group (103 ± 30 μm) and the Dentbird group (60 ± 32 μm) when a cement space of 50 μm was applied during the crown design process.[33] Consistent with previous findings, the present study demonstrated that the AI-based dental CAD software Dentbird and Single-Pro achieved comparable marginal fit values, suggesting that AI-based software might positively influence the marginal fit.

Specifically, Dentbird (66.4 ± 11.4 μm) exhibited the lowest AMD, indicating superior fit Performance among the evaluated software programs. While a previous micro-CT study comparing the AMD of crowns fabricated using Exocad and Dentbird found no statistically significant differences between the two systems, this contrasts with the findings of the present study.[33] Another study evaluated the accuracy of margin line extraction across several dental CAD platforms, namely 3Shape, Exocad, and MEDIT, compared with the AI-based Dentbird.[34] Using Hausdorff distance analysis, Dentbird demonstrated a lower mean value (0.543 ± 0.274 mm) relative to 3Shape (0.712 ± 0.325 mm), Exocad (0.635 ± 0.332 mm), and MEDIT (0.694 ± 0.372 mm),[34] meeting the clinically acceptable Hausdorff threshold of 0.566 mm.[34] This superior performance in margin line detection suggests that the AI-based algorithms of Dentbird might enhance the accuracy of crown design by precisely extracting margin lines, thereby contributing to reduced AMD values and improved clinical fit.

A previous study assessed the internal fit of crowns fabricated using AI-based dental CAD software by superimposing the intaglio surface of the crown onto the scan data of the abutment tooth.[35] Significant differences were reported among the software groups.[35] The cement space was set to 40 μm, with Automate demonstrating an internal fit of 83.1 ± 13.1 μm, Dentbird 59.4 ± 12.1 μm, and the technician-designed 3Shape group 65.4 ± 10.3 μm.[35] In contrast, the present study found no statistically significant differences in internal fit among the evaluated software programs at the chamfer, axial, and angle regions ($P > 0.05$), Likely due to the uniform parameter settings applied across all software platforms. An internal fit of 50 - 100 μm is considered clinically acceptable,[36] and all internal fit values observed in this study were within this range. However, a notable exception was identified in the occlusal region, where the Single-Pro group exhibited a significantly larger gap (75.0 ± 11.9 μm) compared to the other groups ($P < 0.05$). This value exceeds the widely ideal occlusal gap of < 70 μm.[37] Exceeding this range was reported to reduce the fracture strength of dental crowns.[38] These findings indicate that, while Single-Pro demonstrated acceptable performance overall, its crown design algorithm might benefit from further refinement to enhance accuracy in the occlusal region.

This study evaluated the fit of interim crowns fabricated using three different dental CAD software programs, highlighting the need for further research involving a broader spectrum of software solutions. Notably, the analysis was limited to the maxillary first molar, a posterior tooth with relatively uniform morphology. Future studies should incorporate a wider range of tooth types, including anterior teeth, which present more complex anatomical features. Moreover, as the present study employed an in vitro experimental model, the findings might not fully reflect

clinical performance. Therefore, additional research under in vivo conditions, such as multi-unit dental prostheses, subgingival margins, and chairside workflows, is recommended to more accurately assess the functionality and reliability of dental CAD systems in clinical practice.

Currently, AI-based dental CAD software has demonstrated superior performance in minimizing marginal fit, indicating enhanced accuracy in marginal adaptation. However, the Single-Pro software, which remains under development, exhibited limitations in internal fit, particularly in the occlusal area. Single-Pro uses a transformer-based algorithm, but this algorithm may not have fully captured the complex curvatures and irregular structures of the occlusal surface. Further optimization by incorporating more precise calibration parameters is necessary to enhance and improve its overall clinical reliability.

Conclusion

Variations in marginal and internal fit were evident based on the type of dental CAD software used.

The AI-based software programs, Dentbird and Single-Pro, demonstrated superior performance in terms of marginal gap adaptation. However, Single-Pro exhibited a significantly greater gap in the occlusal area of the internal fit, indicating limitations in internal adaptation. Therefore, as Single-Pro remains under development, further optimization is required to improve its internal fit.

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AI 기반 CAD 치과 CAD 소프트웨어를 사용하여 제작된 임시크라운의 변연 및 내면 적합도 평가

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목적: 본 연구의 목적은 인공지능 기반 치과 CAD 소프트웨어를 사용하여 제작된 임시 크라운의 변연 및 내면 적합도를 평가하는 것을 목표로 한다.

연구 재료 및 방법: 상악 우측 제1대구치를 임시 크라운 제작을 위해 준비하였다. 데스크탑 스캐너를 사용하여 스캔파일을 얻었고, 세가지 치과 CAD 소프트웨어 프로그램으로 내보냈다. 기존 소프트웨어와 두가지 AI 기반 치과 프로그램. 모든 소프트웨어에 걸쳐 60 μm의 동일한 시멘트 간격을 설정하고, 10개의 임시 크라운을 디자인하였다. 크라운은 3D 프린터를 사용하여 제작되었으며, 실리콘 복제 기법을 사용하여 변연 및 내부 적합도를 평가하였다. 통계 분석은 Kruskal-Wallis 검정과 사후 분석($\alpha = 0.05$)을 사용하여 수행하였다.

결과: 세 가지 치과용 CAD 소프트웨어 프로그램 간에 변연 적합도에 유의미한 차이가 관찰되었다($P < 0.05$). 3Shape에서 생성된 변연 간격은 두 가지 AI 기반 프로그램보다 유의미하게 컸다($P < 0.05$). 내부 적합도 측면에서는 대부분 영역에서 유의미한 차이가 관찰되지 않았으며($P > 0.05$), Single-Pro에서 교합 간극이 유의미하게 더 컸다($P < 0.05$).

결론: Dentbird와 Single-Pro를 사용하여 제작된 임시 크라운은 우수한 변연 적합도를 보였다. 그러나 Single-Pro의 내부 적합도 교합 영역에서 비교적 큰 간극이 나타났기 때문에 추가적인 개선이 필요하다.

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주요어: 컴퓨터 지원 설계; 인공지능; 변연 적합도; 내면 적합도

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