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Original Article

Trueness and precision analysis of crown margins on digital casts produced by various dental scanning systems

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Abstract *Background/Purpose:* Digital dental scanning systems play a crucial role in producing precise dental restorations. This study aimed to evaluate the impact of different dental scanning devices on the trueness and precision of crown margins designed from digital models. It also focused on the influence of scanners and design software system alignment.
Materials and methods: A standard dental cast was scanned using two intraoral scanners (Trios 3, Primescan) and three desktop scanners (S3, E3, X5). Crown designs were created for each cast using dental design software (inLab SW 16.1, Dentsply Sirona), resulting in a total of 25 digital crown files. These files retained only a 1 mm height from the cervical margin toward the occlusal direction for margin analysis. Root mean square error (RMSE) values were calculated to assess trueness and precision.
Results: The trueness values for the same scanner ranged from 23.4 ± 4.1 μm to 42.1 ± 11.8 μm. Primescan (23.4 ± 4.1 μm) and X5 (29.7 ± 7.0 μm), which belonged to the same system as the design software, demonstrated superior accuracy ($P > 0.05$). No significant difference in trueness was observed between the intraoral scanner (Primescan) and the desktop scanner (X5) within the same system ($P > 0.05$). However, significant differences in trueness and precision were identified between systems ($P < 0.05$).

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Conclusion: The type of scanner and its system alignment significantly influenced the accuracy of crown margins. Ensuring compatibility between scanning devices and design software in clinical practice could enhance the precision of dental restorations.

Introduction

Dental digitization has introduced numerous conveniences and challenges, particularly in significantly reducing the time and complexity involved in fabricating dental restorations.[1,2] Digitized restoration workflows encompass fixed prostheses, removable prostheses, and orthodontic appliances.[3–6] Among these, dental crowns have progressively achieved faster production and treatment completion.[7] Digitization not only transforms traditional fabrication techniques into data—driven processes but also establishes a foundation for artificial intelligence (AI) model development.[8,9] Although there are existing reports on the application of AI in designing dental crown morphology, these AI models remain limited to the production of single restorations, such as crowns, inlays, and veneers.[10–13] Given the wide variety of restorations required in clinical practice, AI still needs further development to accommodate the diverse demands of all restoration types. Consequently, dental restorations' design and fabrication currently rely on dental technicians.

The fabrication of dental restorations involves obtaining digital models, designing crowns, and manufacturing crowns.[14–16] The process is completed when dental technicians finalize the crowns with staining and polishing.[17] A critical distinction between digitized and traditional workflows lies in the acquisition of models. Currently, digital models are created by scanning the patient's oral cavity or plaster models using scanning devices.[18–20] Dental scanning devices are primarily categorized into intraoral scanners and desktop scanners. Previous studies have reported significant differences among the models generated by these scanners.[21] However, the impact of scanner-induced errors on crown design has yet to be thoroughly investigated.

After the crown design is completed, a digital file is generated and used to fabricate the crown via computer-aided design/computer-aided manufacturing (CAD/CAM) systems or 3D-printers.[22–24] These digitized workflows rely heavily on robust hardware and software infrastructures.[25] While many dental equipment manufacturers are available today, few can provide a complete system capable of supporting the entire crown fabrication process. Additionally, individual preferences often influence system selection. Dentists and dental technicians may not necessarily use the same digital system for crown fabrication, raising concerns about potential discrepancies during hardware and software transitions between different systems.

For dental crown restorations, such transitions may affect the accuracy of the margins. This could potentially lead to gaps, resulting in secondary caries.[26] The integrity of crown margins is critical, and any compromise in accuracy can have significant clinical implications.[27,28] Consequently, many studies have focused on addressing the fit and sealing of crown margins to mitigate these issues.[29–31]

This study aimed to investigate whether the casts generated by different dental scanning devices influence the accuracy of digital crown margins. A single cast was scanned using two intraoral scanners and three desktop scanners to produce digital casts. A standardized crown design software was utilized to design crowns, and the differences in crown margins were compared. This study hypothesized that the accuracy of crown margins would not vary based on the casts generated by different scanners. Additionally, it was assumed that the consistency between scanning devices and digital design software systems would have no impact on crown margin accuracy.

Materials and methods

This study utilized a standard dental cast (PRO2002-UL-SP-FEM-28, Nissin Dental Product Inc., Kyoto, Japan) as the experimental model. The left mandibular first molar (tooth 36) in the dental cast was replaced with a standard crown abutment tooth (A25AN-LL62E). This setup simulated the clinical condition of a dental cast with abutment tooth prepared for crown fabrication (tooth 36).

This study employed three desktop scanners and two intraoral scanners (Table 1). The desktop scanners included the S3 (S300 ARTI, Zirkonzahn, South Tyrol, Italy), E3 (E3, 3Shape, Copenhagen, Denmark), and X5 (inEos X5, Dentsply Sirona, Charlotte, NC, USA). The intraoral scanners used were the Trios 3 (3Shape) and Primescan (Dentsply Sirona). According to previous studies, all scanning procedures were performed by senior dental technicians with over three years of experience operating dental scanners, minimizing the risk of operator errors. Prior to scanning, each scanner underwent a standard calibration process to ensure

Table 1 The introduction provided details about the experimental groups and the sources of digital casts.

Pattern	Brand	Code name
S300 ARTI	Zirkonzahn (South Tyrol, Italy)	S3
E3	3Shape (Copenhagen, Denmark)	E3
inEos X5	Dentsply Sirona (Charlotte, NC, USA)	X5
Trios 3	3Shape (Copenhagen, Denmark)	Trios 3
Prime scan	Dentsply Sirona (Charlotte, NC, USA)	Primescan

accuracy. Each scanner was used to perform five repeated scans, generating a total of 25 digital cast files.[21]

The prosthesis was designed using computer-aided design and computer-aided manufacturing (CAD-CAM) software (inLab SW 16.1, Dentsply Sirona). The cement space was standardized at 50 μm. A crown was designed for each digital cast, resulting in a total of 25 crowns (Fig. 1).

The crown margins generated for each cast model were analyzed using Medit Design software (Version 2.1.4.97, Medit, Seoul, Republic of Korea). This study focused on comparing the crown margins within a 1 mm distance extending from the cervical region toward the occlusal surface.[4] The root mean square error (RMSE) values of the matched profiles were obtained by overlapping any two of the five digital crown images. This study analyzed the differences in crown margins generated by the same scanner and by different scanners. Additionally, mean RMSE values were calculated to assess the precision of crown margins produced by the same scanner and the trueness of margins across different crowns.

The RMSE value was calculated through the following formula 1.[32]

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_i)^2} \qquad \text{formula1}$$

The meaning of each symbol was as follows: x_i for values of the reference cast, μ_i for values of the target cast; and n for the number of times.

The data were processed using JMP 16 software (SAS, Charlotte, NC, USA). Mean RMSE values along with standard deviations (SD) were calculated and analyzed across all test groups. The Shapiro–Wilk test was employed to examine the normality of the data distribution. Statistical comparisons were conducted through one-way ANOVA, followed by Tukey's HSD post hoc test to identify significant differences. A *P*-value below 0.05 was regarded as indicating statistical significance.

Results

The comparison of crown margins designed from casts obtained using the same scanner was shown in Fig. 2. The 3D overlapping images of different crown margins revealed that the S3 group had a more prominent yellow distribution (Fig. 2A), while the other groups predominantly displayed a green distribution (Fig. 2B – E). The trueness results of crown margins obtained from the same scanner were summarized in Table 2. The Trios 3 group exhibited the highest trueness (42.1 ± 11.8 μm) with a statistically significant difference ($P < 0.05$), followed by S3 (41.5 ± 14.6 μm), E3 (40.5 ± 17.2 μm), X5 (29.7 ± 7.0 μm), and Primescan (23.4 ± 4.1 μm). Similarly, the precision results of crown margins obtained from the same scanner aligned with the trueness rankings (Table 2). From highest to lowest, the groups were ranked as follows: Trios 3 (42.1 ± 11.8 μm), S3 (41.1 ± 14.7 μm), E3 (40.2 ± 17.3 μm), X5 (29.7 ± 7.0 μm), and Primescan (23.0 ± 4.0 μm), all showing statistically significant differences ($P < 0.05$).

The comparison of crown margins designed from casts obtained using different scanners was illustrated in Fig. 3. The 3D overlapping images of crown margins from different scanners predominantly showed yellow and green distributions (Fig. 3A–H). However, the X5 compared to Primescan group primarily exhibited green distributions (Fig. 3I).

The trueness results of crown margins obtained from different scanners ranged from 66.2 ± 8.8 μm to 22.6 ± 4.6 μm (Table 3). Among these, the S3 compared to E3 group showed the highest trueness value (66.2 ± 8.8 μm) with a statistically significant difference ($P < 0.0001$). The precision results were similar to the trueness results, ranging from 63.8 ± 9.7 μm to 22.4 ± 4.8 μm. The S3 compared to E3 group again exhibited the highest precision value (63.8 ± 9.7 μm), with a statistically significant difference ($P < 0.0001$). For both trueness and precision, the rankings from highest to lowest were as follows: Trios 3 (42.1 ± 11.8 μm), S3 (41.1 ± 14.7 μm), E3 (40.2 ± 17.3 μm), X5 (29.7 ± 7.0 μm) and Primescan (23.0 ± 4.0 μm). All showing statistically significant differences ($P < 0.0001$).

Discussion

The fabrication technology for dental restorations involves precision, aesthetics, and material properties.[33] Traditional

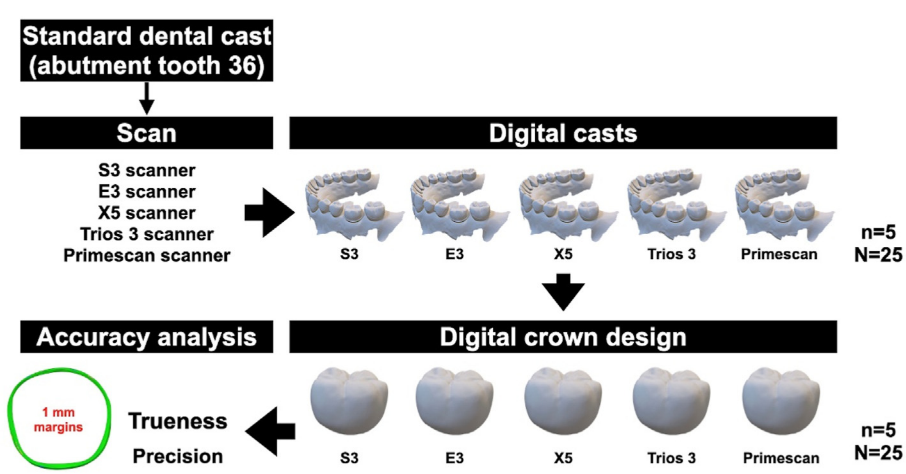

Figure 1 The flow chart illustrated the experimental design of this study.

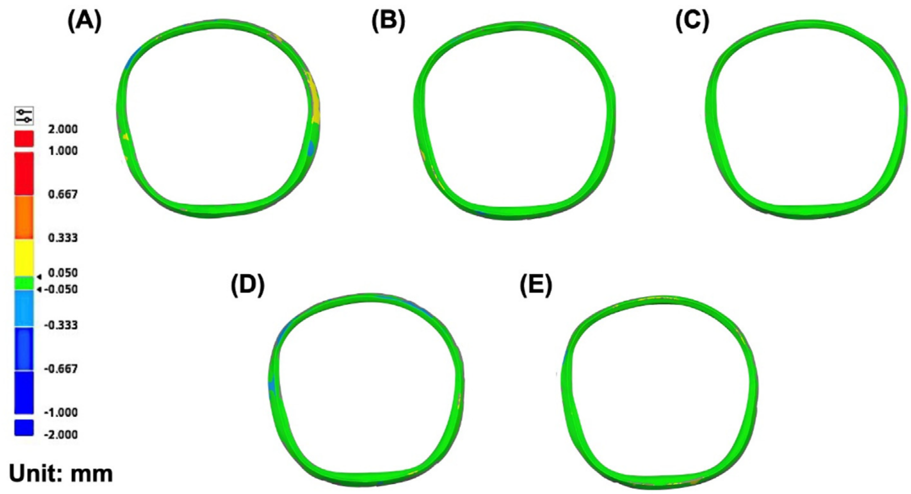

Figure 2 Representative color maps illustrated the marginal discrepancies. (A) S3 group. (B) E3 group. (C) X5 group. (D) Trios 3 group. (E) Primescan group.

Table 2 The trueness and precision of the margins were evaluated by comparing the mean root mean square error (RMSE) values derived from five digital casts.

Group	Trueness	Precision
	Mean ± SD (μm)	Mean ± SD (μm)
S3	41.5 ± 14.6[A]	41.1 ± 14.7[A]
E3	40.5 ± 17.2[A]	40.2 ± 17.3[A]
X5	29.7 ± 7.0[AB]	29.7 ± 7.0[AB]
Trios 3	42.1 ± 11.8[A]	41.2 ± 11.1[A]
Primescan	23.4 ± 4.1[B]	23.0 ± 4.0[B]
F Ratio	4.9789	4.8587
P-value	0.0021	0.0024

SD: Standard deviation.
The significant difference ($P < 0.05$) was determined by one-way analysis of variance (ANOVA).
Different capital letters indicate differences between groups.

manufacturing processes in the past limited the applications of dental restorations and made it difficult to analyze their accuracy during the design phase. Digitization has enabled greater stability and accuracy in the production of dental crowns. With advancements in digital technology, dental digital equipment has become widely utilized in dental clinics and dental laboratories. These software and hardware systems come in various brands and configurations, offering users a wide range of options. For dental crowns, the fabrication process is typically divided into four main steps: scanning, designing, manufacturing, and staining.

In previous research, this study analyzed the accuracy of casts obtained using dental scanning devices. The results indicated significant differences between intraoral scanners and desktop scanners.[21] Xin Wang et al. compared the accuracy of seven intraoral scanners with different types of casts.[34] Their findings demonstrated that trueness, precision, and scanning time were influenced by both the intraoral scanner (IOS) and the type of cast being scanned, showing significant variation among intraoral scanners. This suggests that dental scanning devices could impact the accuracy of the casts. Passent Ellakany et al. compared the accuracy of intraoral scanners and desktop scanners and found that both exhibited similar accuracy.[35] However, the study noted better accuracy for desktop scanners in the canine region. Thus, previous studies have primarily focused on the impact of different scanning devices on cast accuracy.

In the same year, Passent Ellakany et al. reported a comparison of the accuracy of various intraoral and extraoral scanners using different scanning technologies to produce 3D-printed casts and digital casts.[36] Their findings revealed that extraoral scanners demonstrated higher accuracy compared to intraoral scanners, and 3D-printed models exhibited greater accuracy than digital models. However, the impact of these differences on crown design files has not been sufficiently discussed in the literature. Therefore, this study focused on designing digital crowns using casts obtained from these scanners and comparing the differences in crown margins.

The surface morphology of crown designs varies based on the adjacent tooth and occlusal relationships. In this study, the surface data of these digital crown files were removed, retaining only a 1 mm height from the cervical margin toward the occlusal direction for crown margin comparison. The comparison of crown images from the same scanner demonstrated good margin accuracy (Fig. 2). The results for trueness and precision showed that all groups achieved values below 120 μm, meeting clinical requirements (Table 2).[37] No significant differences were observed between S3 (desktop scanner), E3 (desktop scanner), and Trios 3 (intraoral scanner) ($P > 0.05$), nor between X5 (desktop scanner) and Primescan (intraoral scanner) ($P > 0.05$). However, S3, E3, and Trios 3 showed significantly higher trueness and precision values compared to X5 and Primescan ($P < 0.05$).

The crown design software (inLab SW 16.1) used in this study and the two scanning devices (X5 and Primescan) belong to the same system by Dentsply Sirona. This system

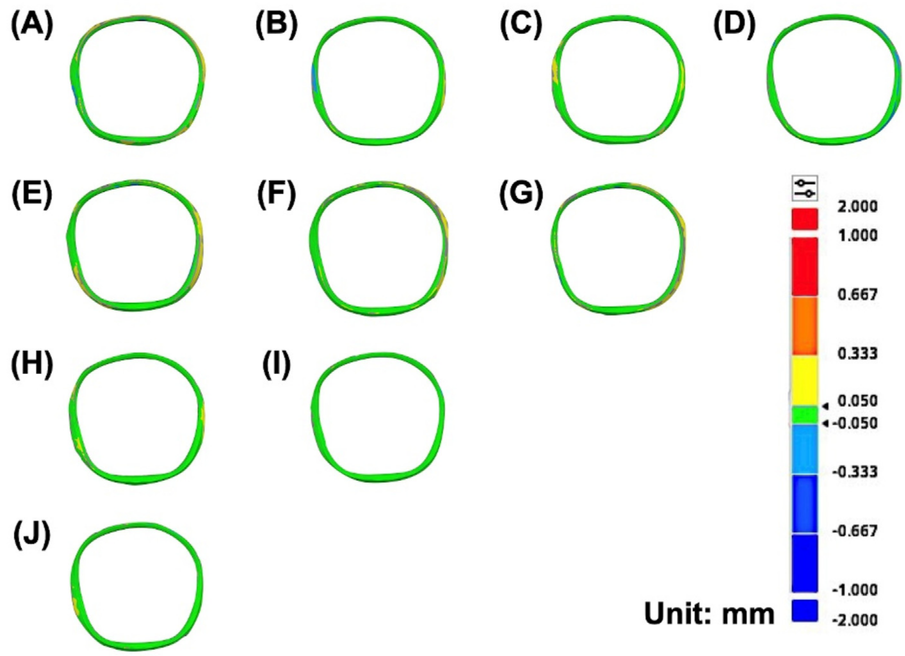

Figure 3 The results of the marginal discrepancy analysis were presented through 3D color maps, generated by overlapping the marginal discrepancies of two digital crowns in each comparison. (A) S3 compared to E3. (B) S3 compared to X5. (C) S3 compared to Trios 3. (D) S3 compared to Primescan. (E) E3 compared to X5. (F) E3 compared to Trios 3. (G) E3 compared to Primescan. (H) X5 compared to Trios 3. (I) X5 compared to Primescan. (J) Trios 3 compared to Primescan.

Table 3 The margins comparison was conducted among crowns designed from five digital casts.

Group		Trueness	Precision
Reference	Target	Mean ± SD (μm)	Mean ± SD (μm)
S3	E3	66.2 ± 8.8^{A}	63.8 ± 9.7^{A}
	X5	36.2 ± 12.4^{CD}	35.8 ± 12.1^{CD}
	Trios 3	47.8 ± 7.9^{BC}	47.0 ± 7.3^{BC}
	Primescan	37.0 ± 11.6^{CD}	36.4 ± 11.8^{CD}
E3	X5	55.2 ± 11.2^{AB}	52.0 ± 11.1^{B}
	Trios 3	59.0 ± 15.5^{A}	57.4 ± 15.6^{AB}
	Primescan	51.6 ± 8.3^{AB}	50.0 ± 9.0^{BC}
X5	Trios 3	34.8 ± 3.0^{CD}	34.2 ± 3.1^{CD}
	Primescan	22.6 ± 4.6^{D}	22.4 ± 4.8^{E}
Trios 3	Primescan	28.2 ± 11.5^{CD}	27.6 ± 10.3^{DE}
F ratio		9.8091	8.8209
P-value		<0.0001	<0.0001

SD: Standard deviation.
The significant difference ($P < 0.05$) was determined by one-way analysis of variance (ANOVA).
Different capital letters indicate differences between groups.

consistency may contribute to the superior trueness and precision observed for X5 and Primescan (Table 2). The comparison of crown margins designed from different casts showed that the X5 and Primescan groups displayed a better green distribution (Fig. 3I), while other groups showed more yellow areas (Fig. 3). This result aligns with the trueness and precision values (Table 3). Notably, the difference between X5 and Primescan remained the smallest among all groups. This finding is consistent with previous studies comparing digital casts, where the difference between X5 and Primescan within the same system was minimal (46.8 ± 2.1 μm).[21] For desktop scanners, trueness ranged from 36.2 ± 12.4 μm to 66.2 ± 8.8 μm, while intraoral scanners exhibited trueness values of 28.2 ± 11.5 μm, which were smaller than those of desktop scanners. This may be attributed to differences in the types of scanners used. Consequently, both hypotheses of this study were rejected. The accuracy of crown margins was influenced by the models generated from different scanners, and the consistency between scanning devices and digital design software systems affected crown margin accuracy.

Many dental clinics, hospitals, and dental laboratories faced a shortage of professionals skilled in fabricating dental restorations.[38,39] This issue provided a significant impetus for the digital transformation of dentistry. The development of dental digitization improved the efficiency, quality, and workforce demands associated with restoration fabrication. Recent studies demonstrated that digitally fabricated dental restorations sufficiently met clinical requirements, comparable to traditional manufacturing methods.[40] However, the selection of digital equipment and the compatibility between software and hardware remained critical factors in enhancing the quality of restorations.

This study has limitations, as the crown designs were generated using only a single design software, necessitating further investigation to compare the results across different digital systems. Additionally, this study focused solely on digital crown files without fabricating actual crowns for comparison. Future research could explore the effects of different digital design software on crown margin accuracy and conduct practical comparisons of crowns fabricated using CAD/CAM or 3D-printing.

In summary, dental scanning devices are critical factors influencing the accuracy of digital crown margins. Although most crown margins met clinical requirements, significant differences were observed between intraoral and desktop scanners. Furthermore, selecting dental equipment and software from the same system appears to be a potentially effective strategy for improving crown margin accuracy. This study aims into provide valuable insights for the clinical implementation of digital workflows in dentistry.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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