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Original Article

Comparisons of precision and trueness of digital dental casts produced by desktop scanners and intraoral scanners

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Abstract *Background/purpose:* Different types of scanners are gradually used to produce digital dental casts in the current dental practice. This study tested the accuracy of the three desktop scanners and two intraoral scanners and evaluated whether the desktop scanners had higher precision than the intraoral scanners.

Materials and methods: This study used the three desktop and two intraoral scanners to scan a standard dental cast 5 times. The 5 digital casts produced by the same scanner were compared each other to study the precision errors of each scanner. Moreover, 5 sets of the 5 digital casts produced by the 5 different scanners were compared each other to investigate the trueness errors among these 5 different scanners.

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Results: This study showed a significant difference in the precision error of produced digital casts made by the 5 different scanners ($P < 0.0001$). The two intraoral scanners had significantly higher precision errors of produced digital casts than the three desktop scanners. However, there were no significant differences in the precision errors among the three desktop scanners and between the two intraoral scanners. The results of the whole cast or particular tooth surface trueness analyses demonstrated that the trueness errors were concentrated at the molar regions of produced digital casts when comparisons were performed between the intraoral and desktop scanners.

Conclusion: We conclude that the desktop scanners can achieve a better precision than the intraoral scanners. When the intraoral scanner is used, the dentist should notice the possible model errors at the molar regions.

Introduction

Dental care is transforming due to advancements in the digital technology.[1] The digital production has gradually replaced the traditional production in dentistry.[2] This includes applications of the artificial intelligence for dental prosthesis design and manifacture.[3] The production of traditional dental restorations involves complex steps, including taking impressions, producing plaster casts, and performing wax casting. This limitation restricts the range of materials that can be used for dental restorations.[4] Therefore, the digital technology, such as computer-aided design/computer-aided manufacturing (CAD/CAM) is being increasingly adopted in the current dental practice to produce different types of dental restorations.[5] A digital dental cast can be created by scanning either a plaster cast or the patient's teeth and oral soft tissues, then the dental design software is used to create a personalized restoration on the abutment teeth of the digital dental cast.[6] Finally, the CAM equipment is used to process the design and produce the dental restorations. The accuracy of the dental restorations primarily depends on the quality of the digital dental casts and the precision of the processing technology.[7] Current literature reports that the accuracy of CAD/CAM systems and three-dimensional (3D) printers is sufficient to meet the clinical demands.[8] In addition, adjustable production parameters are available for different materials to achieve the optimal dental restorations.[9] Therefore, verifying the accuracy of the scanner-produced digital casts is a critical factor in determining the quality of dental restorations.

Currently, the digital dental casts can be obtained by scanning plaster models through the desktop scanners. Alternatively, an intraoral scanner can also be used to directly capture both soft and hard tissues in the patient's oral cavity to create a digital dental cast.[10] The main difference between the two methods lies in the relative positioning of the camera. The desktop scanner mainly uses a fixed camera to scan through the machine's automatic moving cast. The intraoral scanner uses a handheld camera to capture the details of prepared teeth and the associated soft tissues inside the patient's mouth.[11] The impact of these two camera scanning methods on the accuracy of the produced digital dental casts has been less frequently discussed. Therefore, further researches are needed to optimize the quality of the scanner-produced digital dental casts.

A previous study reported that the resolution of the desktop scanners ranged from 8 μm to 15 μm, while the resolution of the intraoral scanners was approximately 4 μm.[12] Comparing the accuracy of the produced digital dental casts shows that the desktop scanners have the accuracy errors ranging from approximately 24 μm–33 μm, while the intraoral scanners have the accuracy errors ranging from 6.9 μm to 119 μm.[13–15] This indicates that the resolution is not parallel to the accuracy of the scanner. The actual resolution of a scanner refers to the smallest achievable resolution. However, factors affecting the accuracy of the digital dental cast also include the integrity of the plaster cast, variations in the intraoral environment, and the conversion between software and hardware systems.[16,17] Consistency between the plaster model and the oral environment can be ensured by following the standard procedures set by the dental technician.[18] Ensuring that the file conversions between software and hardware systems do not affect the accuracy is an important issue.[19,20] Currently, there are many different systems (e.g., desktop and intraoral scanner systems) for dental scanning equipment and the dental design software, such as 3Shape (Copenhagen, Denmark), Dentsply Sirona (Charlotte, NC, USA), and Zirkonzahn (South Tyrol, Italy).[21–23] It still requires further investigations to evaluate whether the scanning equipment in these digital dental systems can have similar accuracy to produce digital images from the same standard dental cast.

Therefore, this study used the three desktop scanners and two intraoral scanners to scan a standard dental cast 5 times. The 5 digital cast images produced by the same scanner were compared each other to study the precision errors of each scanner. Moreover, 5 sets of the 5 digital cast images produced by the 5 different scanners were compared each other to investigate the trueness errors of these 5 different scanners. In addition, we also evaluated whether there were significant differences in the trueness errors of the produced digital cast images among the three different desktop scanners (within the same system), between the two different intraoral scanners (within the same system), and between the two scanners with the same brand (3Shape or Dentsply Sirona) but with two different systems (desktop and intraoral scanner systems).

Materials and methods

This study used a standard dental cast (PRO2002-UL-SP-FEM-28, Nissin Dental Product Inc., Kyoto, Japan) for experiments.[24] In the standard dental cast, the right maxillary first premolar (tooth 14) to the right maxillary second molar (tooth 17) were replaced with four standard crown abutment teeth. This simulated the clinical status of a dental cast with 4 abutment teeth prepared for making the 4 crowns (for teeth 14, 15, 16, and 17).

This study used three desktop scanners and two intraoral scanners (Table 1). The three desktop scanners used were S3 (S300 ARTI, Zirkonzahn), E3 (E3, 3Shape), and X5 scanners (inEos X5, Dentsply Sirona), while the two intraoral scanners used were Trios 3 (Trios 3, 3Shape) and Primescan scanners (Prime scan, Dentsply Sirona).

All scanning operations were performed by the same dental technician who was a senior practitioner with more than three years of experience in operating dental scanners to reduce the operational errors. Before scanning, each scanner had completed a standard calibration process to ensure the accuracy. The standard dental cast was then digitally scanned following the manufacturer's instructions. Among the three desktop scanners and the two intraoral scanners, each scanner repeated the scan five times to obtain a total of the 25 digital cast files. Then, the precision analysis was conducted for evaluating the accuracy of the same scanner, while the trueness analysis was adopted by comparing the differences in the trueness errors among the 5 different scanners (Fig. 1).

For each set of scanners, the 5 digital cast files scanned by the same scanner were analyzed by the software of Medit Compare (Medit, Seoul, Republic of Korea).[25] The root mean square error (RMSE) value of the matched profiles could be obtained by overlapping any two of the 5 digital cast images. Moreover, the mean RMSE values could be calculated to estimate precision analysis of the same scanner and trueness analysis among different scanners. The trueness analysis included the whole cast surface trueness analysis and the particular tooth surface trueness analysis which were explored by the files of digital casts from different scanners (Fig. 2).

The RMSE value was calculated through the following Formula 1.[26]

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_i)^2} \qquad \text{Formula1}$$

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. Based on the same principle, the difference value was calculated through the error value of matched profiles at a particular tooth obtained by overlapping any two digital cast images.

The differences of the whole cast surface of the two overlapping digital casts were calculated and designated as the RMSE value of the whole cast in the whole cast surface trueness analysis, while the differences in the surfaces of the right maxillary first premolar (tooth 14), the right maxillary second molar (tooth 17), the left maxillary first premolar (tooth 24), and the left maxillary second molar (tooth 27) of the two overlapping digital cast images were calculated and designated as the RMSE value of the particular tooth in the particular tooth surface trueness analysis. In addition, the digital cast images made from different scanners were overlapped, and the whole cast surface trueness and the particular tooth surface trueness analyses were performed according to the above steps. Then, the differences in the mean RMSE values among different scanning devices could be explored.

Table 1 Introduction and specifications of various dental scanners.

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

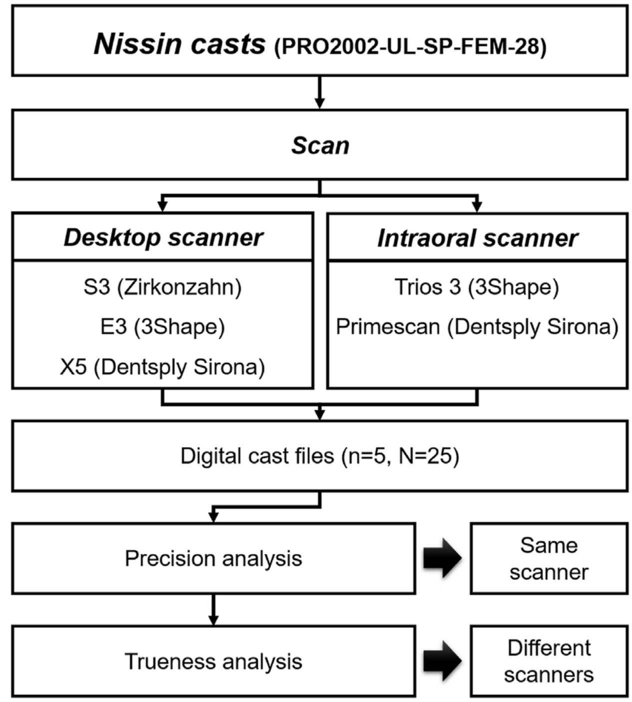

Figure 1 The experimental flow chart of this study.

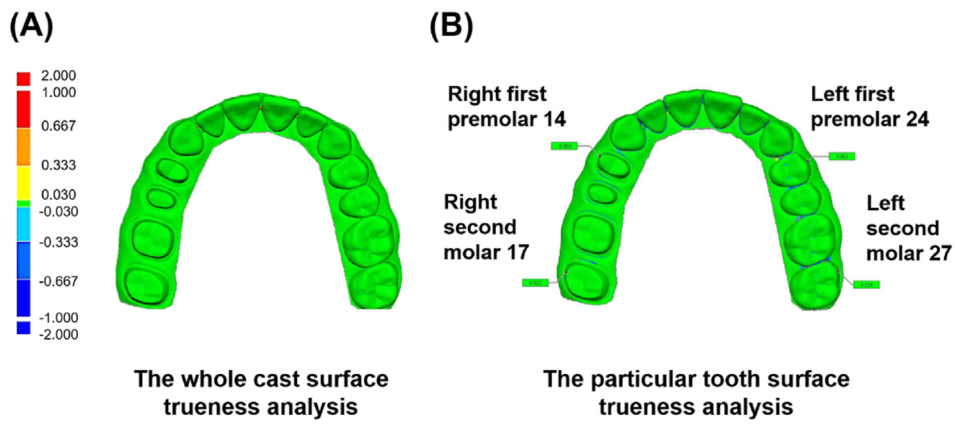

Figure 2 The schematic diagrams of trueness analysis between two digital cast files. (A) The whole cast surface trueness analysis. (B) The particular tooth surface trueness analysis.

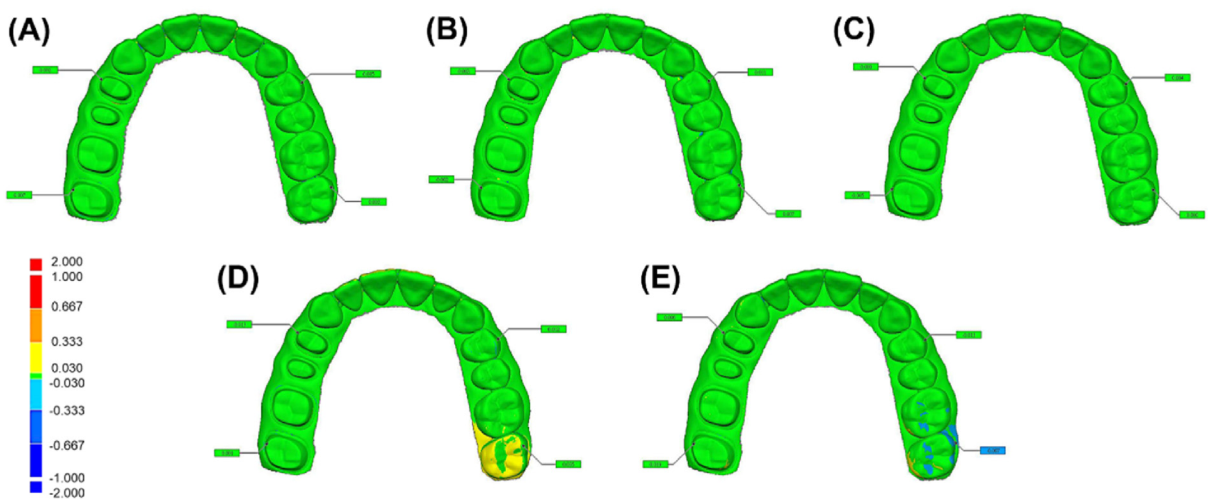

Figure 3 The results of the precision analysis of the same scanner. The five 3D color maps were obtained by overlapping the whole cast surfaces of two digital cast images made by the same scanner. (A) S3 scanner. (B) E3 scanner. (C) X5 scanner. (D) Trios 3 scanner. (E) Primescan scanner. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The collected data were analyzed by using the JMP 16 software (Statistics Analysis System, Charlotte, NC, USA). Mean RMSE values and standard deviations (SD) were calculated and compared in all tests. The Shapiro-Wilk test was applied to assess normality. The significance was evaluated by one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) post hoc test. The *P*-value of less than 0.05 was considered to be statistically significant.

Results

In the precision analysis of a particular scanner, the 3D color maps were obtained by overlapping the whole cast surface of two digital cast images made by the same scanner (Fig. 3). All three sets of the desktop scanners showed the green area coverage, indicating a high degree of matching between the two overlapping digital cast images. The two sets of the intraoral scanners had blue and yellow color distribution at the left maxillary molar areas, indicating that there are precision errors between the two digital cast images when overlapping (Fig. 3).

In the precision analysis of the same scanner, the root mean square error (RMSE) value represented the whole cast surface differences between two digital cast images and it was obtained by overlapping the two digital cast images and calculating their whole cast surface differences. Thus, the mean RMSE value was the average of the 10 RMSE values obtained by overlapping of any two of the 5 digital cast images made by the same scanner. There was a significant difference in the mean RMSE value among the 5 different scanners ($P < 0.0001$, Table 2). The Trios 3 scanner had the highest mean RMSE value (77.8 ± 6.3 μm), followed by the Primescan scanner (74.6 ± 5.7 μm), X5 scanner (56.0 ± 2.5 μm), E3 scanner (55.0 ± 10.1 μm), and S3 scanner (49.6 ± 4.7 μm) (Table 2).

Among the 5 different scanners, the mean RMSE values of the Trios 3 and Primescan scanners were significantly

Table 2 The precision analysis evaluated by comparison of the 5 mean root mean square error (RMSE) values obtained from 3 desktop scanners (S3, E3 and X5) and 2 intraoral scanners (Trios 3 and Primescan).

Type	Group	[a]Mean RMSE value ± SD (μm)	Lower 95 %	Upper 95 %	F Ratio	*P*-value
Desktop scanner	S3	49.6 ± 4.7	43.7	55.4	19.6948	<0.0001
	E3	55.0 ± 10.1	42.4	67.5		
	X5	56.0 ± 2.5	52.8	59.1		
Intraoral scanner	Trios 3	77.8 ± 6.3	69.8	85.7		
	Primescan	74.6 ± 5.7	67.4	81.7		

SD: Standard deviation.
The significant difference ($P < 0.05$) was determined by one-way analysis of variance (ANOVA).
[a] Mean RMSE value was the mean of the 10 RMSE values. Each RMSE value represented the whole cast surface difference between two digital cast images made by the same scanner. It should be noted that from the 5 digital cast images, 10 RMSE values could be obtained by overlapping any 2 of the 5 digital cast images made by the same scanner.

Table 3 The *P*-value outcome of the precision analysis by comparisons of the two mean root mean square error (RMSE) values between any 2 of the 5 different scanners including 3 desktop scanners (S3, E3 and X5) and 2 intraoral scanners (Trios 3 and Primescan).

Group	S3	E3	X5	Trios 3
E3	0.1972			
X5	0.1295	0.8074		
Trios 3	<0.0001	<0.0001	<0.0001	
Primescan	<0.0001	<0.0001	<0.001	0.4385

The significant difference ($P < 0.05$) was determined by Tukey's honestly significant difference (HSD) post hoc test.

higher than those of the S3, E3 and X5 scanners (all 6 *P*-values < 0.0001, Table 3). In other words, significant differences in the precision error were discovered between any one of the three desktop scanners and any one of the two intraoral scanners. However, there were no significant differences in the precision error among the three different desktop scanners and between the two intraoral scanners (Table 3). Moreover, it should be noted that the lower the mean RMSE value, the more accurate the scanner is, indicating the more matching between the two digital cast images made by the same scanner.

In the precision analysis of the same scanner evaluated by the surface difference of a particular tooth, the RMSE value of a particular tooth (tooth 14, 17, 24 or 27) represented the tooth surface differences (or the precision errors) between the two digital cast images made by the same scanner and it was obtained by overlapping the two digital cast images made by the same scanner and calculating their tooth surface differences (or the precision errors). There was a significant difference in the mean RMSE value of a particular tooth (tooth 14, 17, 24 or 27) among the 5 different scanners (all the *P*-values < 0.0001, Table 4). The mean RMSE value of a particular tooth ranged from 1.0 ± 0.7 μm to 4.6 ± 1.9 μm when using the S3 scanner ($P = 0.0610$), from 1.2 ± 1.3 μm to 2.8 ± 1.9 μm when using the E3 scanner ($P = 0.5301$), from 1.0 ± 3.6 μm to 3.4 ± 2.7 μm when using the X5 scanner ($P = 0.5250$), from 22.0 ± 4.5 μm to 41.2 ± 3.6 μm when using the Trios 3 scanner ($P < 0.0001$), and from 16.0 ± 2.1 μm to 36.4 ± 4.3 μm when using the Primescan scanner to produce the digital cast images ($P < 0.0001$), respectively (Table 4).

In the whole cast surface trueness analysis among the 5 different scanners, comparisons of any two of the 5 digital cast images made by the 5 different scanners

Table 4 The precision analysis evaluated by comparisons of the 4 mean root mean square error (RMSE) values of 4 particular teeth (tooth 14, 17, 24, or 27) obtained from 3 desktop scanners (S3, E3 and X5) and 2 intraoral scanners (Trios 3 and Primescan).

Group	[a]Mean RMSE value ± SD of a particular tooth (μm)				F Ratio	*P*-value
	Tooth 14	Tooth 17	Tooth 24	Tooth 27		
S3	4.6 ± 1.9	1.0 ± 0.7	3.8 ± 2.5	2.6 ± 2.3	3.0102	0.0610
E3	1.2 ± 1.3	2.0 ± 1.8	2.4 ± 1.8	2.8 ± 1.9	0.7650	0.5301
X5	2.8 ± 2.5	3.4 ± 2.7	1.0 ± 3.6	1.4 ± 2.4	0.7748	0.5250
Trios 3	22.0 ± 4.5	41.2 ± 3.6	30.0 ± 4.6	40.6 ± 2.9	26.4781	<0.0001
Primescan	16.0 ± 2.1	36.4 ± 4.3	18.4 ± 4.6	20.8 ± 4.0	27.4563	<0.0001
F Ratio	56.4731	232.2717	60.4721	181.0347		
P-value	<0.0001	<0.0001	<0.0001	<0.0001		

SD: Standard deviation.
The significant difference ($P < 0.05$) was determined by one-way analysis of variance (ANOVA).
[a] Mean RMSE value of a particular tooth was the mean of the 10 RMSE values of a particular tooth. Each RMSE value of a particular tooth represented the particular tooth surface difference between two digital cast images made by the same scanner. It should be noted that from the 5 digital cast images, 10 RMSE values of a particular tooth could be obtained by overlapping any 2 of the 5 digital cast images made by the same scanner.

could produce 10 combinations. Thus, the ten 3D color maps were obtained by overlapping the whole cast surfaces of two digital cast images made by any two of the 5 different scanners. From these ten 3D color maps, we found that the color change areas (changed from green to either blue or yellow) mainly appeared in the comparisons involving the two intraoral scanners, especially the comparison between the Trios 3 and Primescan scanners (Fig. 4). These color change areas were concentrated on the molar regions of the 3D color maps. Among the 10 comparison groups, the mean RMSE values obtained from comparison of the two digital cast images made by the two different scanners ranged from 45.8 ± 2.5 μm to 348.6 ± 4.8 μm ($P < 0.0001$, Table 5). Among the comparisons between the Primescan scanner and any one of the other four different scanners, the mean RMSE values ranged from 46.8 ± 2.1 μm (X5 versus Primescan) to 258.2 ± 6.0 μm (E3 versus Primescan). Moreover, among the comparisons between the Trios 3 scanners and any one of the other four different scanners, the mean RMSE values ranged from 57.0 ± 4.9 μm (X5 versus Trios 3) to 151.6 ± 3.2 μm (E3 versus Trios 3) (Table 5).

In the particular tooth surface trueness analysis among the 5 different scanners, the RMSE value of a particular tooth (tooth 14, 17, 24 or 27) represented the particular tooth surface differences between two digital cast images made by the two different scanners and it was obtained by overlapping the two digital cast images made by the two different scanners and calculating their tooth surface differences (or trueness error). Among 10 comparison groups, the four mean RMSE values of four teeth 14, 17, 24 and 27 were compared. In the comparison group between S3 and X5, the four mean RMSE values of four teeth 14, 17, 24 and 27 ranged from 6.6 ± 1.1 μm (for tooth 17) to 7.2 ± 0.8 μm (for tooth 24) and there was no significant difference in the four mean RMSE values of four teeth ($P = 0.8259$). However, in the other nine comparison groups between any two of the 5 different scanners except the comparison group between S3 and X5 scanners, the comparisons of the four mean RMSE values of four teeth 14, 17, 24 and 27 showed significant differences (all the P-values < 0.0001, Table 6). Moreover, in the comparison group between Trios 3 and Primescan scanners, the four mean RMSE values of four teeth 14, 17, 24 and 27 ranged from 7.4 ± 1.1 μm (for tooth 24) to 104.2 ± 6.0 μm (for tooth 27, Table 6). It should be noted that there were significant differences in the four mean RMSE values of four teeth 14, 17, 24 and 27, when the comparisons were performed between any one of the three desktop scanners and any one of the two intraoral scanners as well as between Trios and Primescan scanners (Table 6).

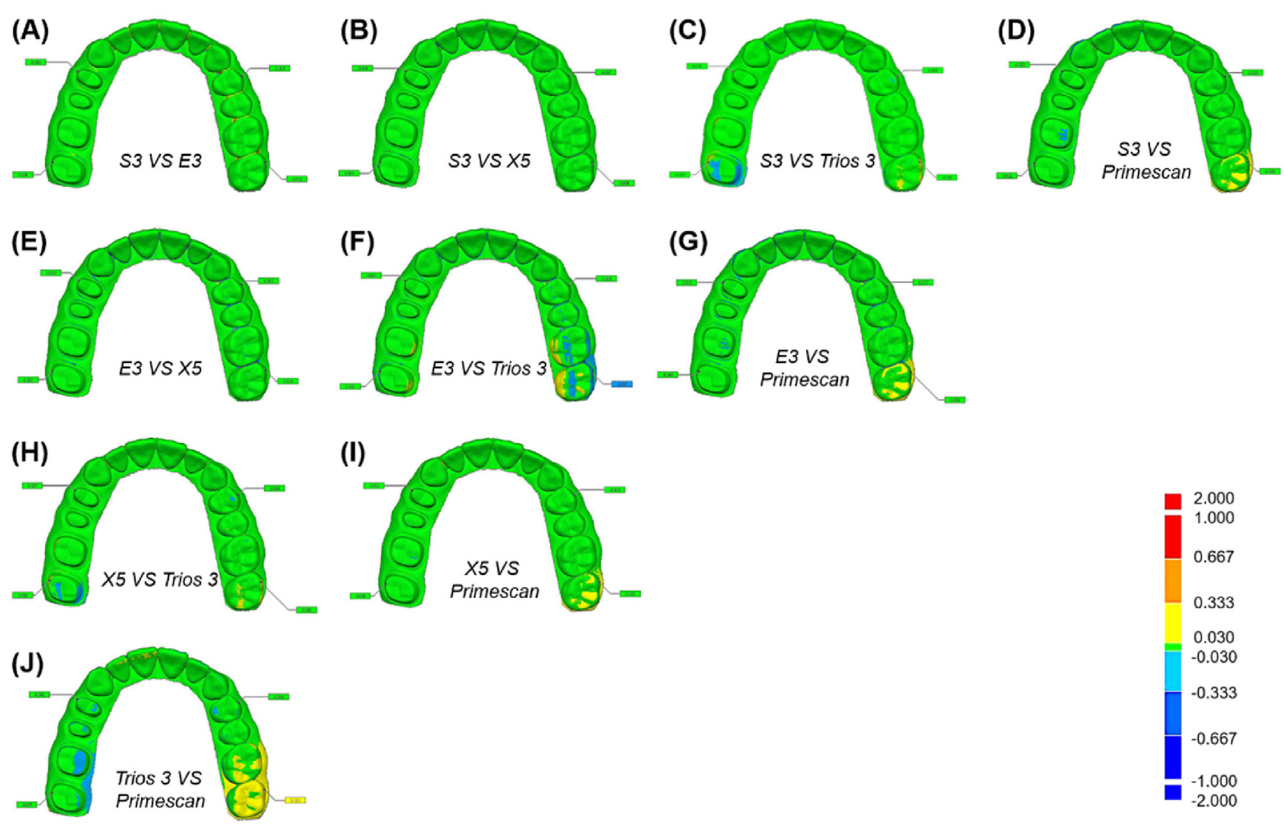

Figure 4 The results of the whole cast surface trueness analysis. The ten 3D color maps were obtained by overlapping the whole cast surfaces of two digital cast images made by the two different scanners. (A) S3 versus E3. (B) S3 versus X5. (C) S3 versus Trios 3. (D) S3 versus Primescan. (E) E3 versus X5. (F) E3 versus Trios 3. (G) E3 versus Primescan. (H) X5 versus Trios 3. (I) X5 versus Primescan. (J) Trios 3 versus Primescan. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5 The whole cast surface trueness analysis evaluated by comparison of the 10 mean root mean square error (RMSE) values obtained from 3 desktop scanners (S3, E3 and X5) and 2 intraoral scanners (Trios 3 and Primescan).

Reference	Target	[a]Mean RMSE value of the whole cast ± SD (μm)			F Ratio	*P*-value
		Mean ± SD	Lower 95 %	Upper 95 %		
S3	E3	45.8 ± 2.5	42.5	49.0	2021.670	<0.0001
	X5	245.8 ± 6.7	237.4	254.1		
	Trios 3	78.0 ± 6.6	69.7	86.2		
	Primescan	141.6 ± 6.2	133.8	149.3		
E3	X5	348.6 ± 4.8	342.6	354.5		
	Trios 3	151.6 ± 3.2	147.6	155.5		
	Primescan	258.2 ± 6.0	250.6	265.7		
X5	Trios 3	57.0 ± 4.9	50.8	63.1		
	Primescan	46.8 ± 2.1	44.1	49.4		
Trios 3	Primescan	138.8 ± 5.2	132.2	145.3		

SD: Standard deviation.
The significant difference ($P < 0.05$) was determined by one-way analysis of variance (ANOVA).
[a] Mean RMSE value of the whole cast was the mean of the 25 RMSE values of the whole cast. Each RMSE value of the whole cast represented the whole cast surface difference between any one of the one set of the 5 digital cast images made by the one scanner and any one of the other set of the 5 digital cast images made by the other scanner. It should be noted that from the 5 different scanners, 10 mean RMSE values of the whole cast could be obtained by comparisons of any two of the 5 different scanners.

Table 6 The particular tooth surface trueness analysis evaluated by comparisons of the 4 mean root mean square error (RMSE) values of 4 particular teeth (tooth 14, 17, 24, or 27) obtained from 3 desktop scanners (S3, E3 and X5) and 2 intraoral scanners (Trios 3 and Primescan).

Reference	Target	[a]Mean RMSE value of a particular tooth ± SD (μm)				F Ratio	*P*-value
		Tooth 14	Tooth 17	Tooth 24	Tooth 27		
S3	E3	5.4 ± 1.1	2.8 ± 1.9	4.2 ± 0.8	10.8 ± 2.5	19.7419	<0.0001
	X5	7.1 ± 1.4	6.6 ± 1.1	7.2 ± 0.8	7.0 ± 1.0	0.2986	0.8259
	Trios 3	30.8 ± 1.3	10.2 ± 1.3	8.8 ± 1.9	37.2 ± 1.3	470.9924	<0.0001
	Primescan	22.4 ± 1.1	23.0 ± 1.5	22.4 ± 1.5	28.4 ± 2.0	16.3289	<0.0001
E3	X5	3.6 ± 0.8	19.0 ± 2.9	2.4 ± 1.1	10.8 ± 2.3	71.9602	<0.0001
	Trios 3	5.0 ± 2.0	4.0 ± 1.5	14.0 ± 2.3	79.4 ± 3.5	1075.424	<0.0001
	Primescan	25.2 ± 3.4	7.2 ± 1.6	15.2 ± 1.0	29.0 ± 1.5	104.6703	<0.0001
X5	Trios 3	25.8 ± 0.8	10.6 ± 1.5	5.4 ± 1.1	39.4 ± 2.4	469.4125	<0.0001
	Primescan	6.4 ± 1.1	7.0 ± 1.2	14.2 ± 0.8	17.0 ± 1.0	123.4222	<0.0001
Trios 3	Primescan	39.4 ± 2.0	26.2 ± 0.8	7.4 ± 1.1	104.2 ± 6.0	821.8977	<0.0001

SD: Standard deviation.
The significant difference ($P < 0.05$) was determined by one-way analysis of variance (ANOVA).
[a] Mean RMSE value of a particular tooth was the mean of the 25 RMSE values of a particular tooth. Each RMSE value of a particular tooth represented the particular tooth surface difference between any one of the one set of the 5 digital cast images made by the one scanner and any one of the other set of the 5 digital cast images made by the other scanner. It should be noted that from the 5 different scanners, 10 mean RMSE values of a particular tooth could be obtained by comparisons of any two of the 5 different scanners.

Discussion

Based on our experimental results, we found that there was a significant difference in the precision error of the produced digital casts made by the 5 different scanners ($P < 0.0001$). The two intraoral scanners had significantly higher precision errors of the produced digital casts than the three desktop scanners. However, there were no significant differences in the precision errors of the produced digital casts among the three desktop scanners and between the two intraoral scanners.

Dental scanning technology was the most critical element of the digital treatment process.[27,28] The fabrication or imaging evaluation of all restorations relied on the accuracy of the produced digital dental casts. Therefore, the accuracy or precision of the scanners and the produced digital dental casts was a hot topic in dentistry.[29,30] This study explored the impact of different scanner systems and brands on the accuracy of the produced digital dental casts made by the three desktop scanners and the two intraoral scanners. The results showed significant differences in the precision error of the produced digital dental casts among the 5 different scanners, especially between any one of the three desktop scanners and any one of the two intraoral scanners. There was no significant difference in the precision error of the produced digital dental casts among the three different desktop scanners of the same system or between the two intraoral scanners of the same system

(Table 3). However, the precision errors of the intraoral scanners such as Trios 3 and Primescan scanners were 1.45-fold and 1.39-fold higher than the mean precision error (53.53 μm) of the three desktop scanners, respectively (Table 2). These results were consistent with those described in the literature, indicating that the desktop scanners are more accurate than the intraoral scanners.[31] The significant differences in the precision error of the produced digital casts among different scanners indicated that the scanning accuracy varied with the camera fixation modes. The desktop scanners with the fixed cameras had higher accuracy of the produced digital dental casts than the intraoral scanners with the mobile cameras. Perhaps, controlling the movement of the cast through the software in the computer allowed for a more accurate acquisition of the digital cast images. A previous study of the factors affecting the digital impression-taking using the intraoral scanners reported that the scan body visibility, the observer experience, and the scan length are the relevant factors affecting the accuracy of the produced digital casts.[32] Moreover, with further training, the dental technicians can have a significant improvement in using intraoral scanners and digital impressions.[33] This finding indicates that the camera stability may affect the accuracy of the produced digital dental casts.

The 3D color image comparisons showed that the different scanners could produce digital cast images with the tooth surface differences at different particular tooth positions (Fig. 3). These tooth surface errors may indicate the scanner-induced tooth surface differences. Analysis of the digital cast image errors at the different tooth positions showed that the four mean RMSE values of four teeth 14, 17, 24 and 27 for the three different desktop scanners were all lower than 5 μm, while those for the two intraoral scanners were all lower than 42 μm (Table 4). These four mean RMSE values of four teeth 14, 17, 24 and 27 were much lower than the five mean RMSE values of the whole cast in the whole cast surface precision analysis (Table 2). The reason causing the great differences in the mean RMSE values of the whole cast might be due to that the whole cast surface precision analysis included some smaller gaps which in turn caused the mean RMSE value to increase. Especially, there was a great difference in the mean RMSE value at the bilateral second molar regions (teeth 17 and 27 regions) of the digital dental cast (Table 4). Our findings were consistent with those reported in the previous study. The accuracy analysis of the digital cast images at different tooth positions showed that the anterior tooth images had better accuracy than the molar tooth images.[34] Another factor might be the impact of dental arch length on the accuracy of the intraoral and desktop scanners. The result was similar to that reported in another study showing that the scan span may affect only the accuracy of the intraoral scanners.[12]

Up to date, there was limited literature comparing the digital cast images made by either desktop or intraoral scanners.[35] The actual differences in the digital cast images made by the two different scanner types did not allow for an exact comparison. In this study, the digital cast images made by the three types of desktop scanners and two different types of intraoral scanners were compared each other for the trueness analysis. The 3D color image comparison showed that the digital cast image was mainly green in the color distribution (Fig. 4), which was similar to the precision analysis result. Only the molar regions of the digital cast image exhibited more yellow or blue areas. The realism results showed that the mean RMSE values were mainly different in the comparison groups of E3 versus X5 (348.6 ± 4.8 μm), E3 versus Primescan (258.2 ± 6.0 μm), and S3 versus X5 (245.8 ± 6.7 μm) ($P < 0.0001$, Table 5). However, the mean RMSE value in the comparison group of X5 versus Primescan was only 46.8 ± 2.1 μm (Table 5). Therefore, this might be caused by the differences in the operation of the scanner systems. The scanners of X5 and Primescan are different systems of scanning devices. However, both belonged to the Dentsply Sirona brand, which might reduce the difference in realism between both of them. In addition, there was still a difference in realism between the scanners of E3 and Trios 3, even though both of them were of the same brand (3Shape brand). Therefore, the differences in realism still existed when the digital dental casts were produced by scanners of the same brand. The difference in the trueness error between intraoral scanners and desktop scanners has ever been reported. The scanners of X5 and Primescan displayed a very clear and significant difference in the level of detail in the digital cast images compared to other scanners.[31] This caused the differences in the image grid numbers to affect the trueness result.

The trueness analysis for the different tooth positions showed that the tooth surface differences within the three desktop scanners was lower compared to the tooth surface differences observed within the two intraoral scanners (Table 6). Interestingly, the differences in the mean RMSE values also concentrated on the rear molar positions (teeth 17 and 27 regions) of the produced digital casts. There was a significant difference, especially in the position of the left maxillary second molar which was not an abutment tooth ($P < 0.0001$). The previous study examined the differences in the trueness errors of various tooth surfaces. It showed that simple abutment teeth exhibit less trueness errors compared to those teeth with a more complex morphology.[36] These findings indicate that the tooth surface complexity has an impact on the trueness error between two different scanners. The whole cast surface trueness analysis and the particular tooth surface trueness analysis showed that the realism consideration was not limited to the tooth surface. It also included the mesh distribution and gaps between teeth. Therefore, the surface of a single tooth on the digital model exhibited a smaller difference in the trueness error when comparing.

A limitation of this study was the use of a standard dental cast for comparisons, even though some teeth were replaced by the abutment teeth for crowns to simulate the patient's real oral condition under the status of clinical dental restorations. However, there were many types of other clinical dental restorations or prostheses that were not analyzed in this study. Therefore, it was necessary to further explore the impact of different types of dental restorations on the precision and trueness of the scanners of different systems or brands. In addition, the software version of the scanner needed to be considered to ensure that all scanners were up to date with the latest scanning technology at the same time.

In conclusion, the results of this study showed that the precision and trueness of both the desktop scanners and the intraoral scanners could be clinically accepted. The fixed camera of the desktop scanner achieved a better precision of the produced dental casts than the mobile camera of the intraoral scanner. The significant differences in the trueness error of the produced digital dental images were observed between any one of the three desktop scanners and any one of the two intraoral scanners. There were significant differences in the model fidelity among different scanners, even of the same brand. Therefore, future research will explore how to resolve the image errors in the digital dental casts produced by different dental scanners.

Furthermore, the focus of this study was to use a standard dental cast to compare the differences in the precision and trueness of the produced dental casts between the desktop scanners and the intraoral scanners to assist clinical workers who use dental scanners (such as dental technicians or dentists) to determine the location where errors are most likely to occur at a dental cast when operating a scanner in the clinical practice based on the comparison results. Therefore, the contribution of this study is to develop an analysis model for testing the accuracy of the dental scanners, which is clinically feasible and easy to operate. This analysis mode has the following functions and effects: (1) It can be used for various types or brands of scanners for the accuracy analysis and comparison. (2) For clinical workers who use scanners (such as dental technicians or dentists), it can be used to self-assess the stability and correctness of operating scanners and help to improve the quality of their dental clinical works. (3) For related workplaces (such as dental laboratories or dental institutions), it can be used to re-evaluate the functional accuracy of scanners and help to maintain the scanner equipment.

This study tried to perform the within-brand and inter-brand comparisons as well as the within-system and inter-system comparisons of the different scanners. The importance of this study lies in the fact that the digitization of dental practice is an inevitable trend, and the processing of dental X-ray images in Taiwan has almost reached the stage of comprehensive digitization. It is also foreseeable that the dental cast processing (especially using the intraoral scanners) will enter the stage of full digitization. Therefore, the use of dental scanners will become more and more common in the dental practice in the near future. For all dental technicians and dentists, the collaboration between them, the self-assessment of the stability and correctness of the scanner operations, and the maintenance of the accuracy of scanner equipment will become the important and basic abilities. This study also contributed to provide a feasible evaluation model for the related scanner operation.

Declaration of competing interest

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

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