



Comparing the accuracy of six intraoral scanners on prepared teeth and effect of scanning sequence

Burcu Diker*, Önjen Tak

Department of Prosthodontics, Faculty of Dentistry, Istanbul Okan University, Istanbul, Turkey

PURPOSE. The aim of this study was to evaluate the accuracy of six recently introduced intraoral scanners (IOSs) for single crown preparations isolated from the complete arch, and to determine the effect of scanning sequence on accuracy. **MATERIALS AND METHODS.** A complete arch with right and left canine preparations for single crowns was used as a study model. The reference dataset was obtained by scanning the complete arch using a highly accurate industrial scanner (ATOS Core 80, GOM GmbH). Six different IOSs (Trios, iTero, Planmeca Emerald, Cerec Omnicam, Primescan, and Virtuo Vivo) were used to scan the model ten times each. The scans performed with each IOS were divided into two groups, based on whether the scanning sequence started from the right or left quadrant (n=5). The accuracy of digital impression was evaluated using three-dimensional analyzing software (Geomagic Studio 12, 3D Systems). The Kruskal Wallis and Mann-Whitney U statistical tests for trueness analysis and the One-way ANOVA test for precision analysis were performed ($\alpha=.05$). **RESULTS.** The trueness and precision values were the lowest with the Primescan (25 and 10 μm), followed by Trios (40.5 and 11 μm), Omnicam (41.5 μm and 18 μm), Virtuo Vivo (52 and 37 μm), iTero (70 and 12 μm) and Emerald (73.5 and 60 μm). Regarding trueness, iTero showed more deviation when scanning started from the right ($P=.009$). **CONCLUSION.** The accuracy of digital impressions varied depending on the IOS and scanning sequence used. Primescan had the highest accuracy, while Emerald showed the most deviation in accuracy for single crown preparations. [J Adv Prosthodont 2020;12:299-306]

KEYWORDS: Trueness; Precision; Digital impression

INTRODUCTION

Obtaining accurate impression is a critical step in prosthetic workflow. In addition to conventional impression techniques, digital impressions made with IOSs have been used in clinical practice for over thirty years. Digital impression techniques show clinically acceptable results compared to conventional impression techniques for fixed prosthesis fab-

rication.¹⁻³ Using digital impression techniques is time efficient⁴, eliminates many clinical and laboratory steps such as selecting the tray, preparing impression material, and pouring a stone model, eliminates potential error due to distortion and deformation of elastic impression materials,⁵ and improves patient acceptance.⁶

The accuracy is specified as trueness and precision according to the International Organization for Standardization. The trueness is defined as ‘the closeness between the test object and the reference object’ and precision is defined as ‘the variability of repeated measurements of the object’.⁷ A scan obtained from a reference scanner is required to evaluate trueness of investigated IOS. *In vitro* studies⁸⁻¹¹ commonly use a highly accurate industrial or laboratory scanner as a reference scanner. Three-dimensional comparative analysis software programs using a best-fit alignment method have been used by researchers to evaluate the accuracy of IOSs.¹²⁻¹⁶

Recent technological advances have made digital impressions and crown manufacturing in clinical practice increas-

Corresponding author:

Burcu Diker
Faculty of Dentistry, Istanbul Okan University, Istanbul Okan University
Tuzla Campus, Faculty of Dentistry, 34959, Akfırat- Tuzla/ Istanbul- Turkey
Tel. +902166771630: e-mail, burcu.diker@okan.edu.tr
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ingly common. The chair-side computer-aided design and manufacturing technology utilizing IOSs ensures restoration delivery to the patient within one appointment.¹⁷ However, the marginal fit of the restoration may vary depending on IOS accuracy.¹⁸ The acceptable maximum marginal gap was defined as 120 μm . Data on the effect of digital impression accuracy on the fit of the single crown restoration is lacking in the literature. However, previous studies noted that when evaluating whether the IOS accuracy is within the clinically acceptable range, the digital impression accuracy should be below 120 μm .^{11,16} There are few studies in the literature evaluating the accuracy of different IOSs for obtaining digital impression of single crown preparation.^{8,9,11,18,19} The differences in digital impression accuracy were found among IOSs used for single crown preparation. Sim *et al.*⁹ reported better accuracy for impression obtained by digital method compared to conventional method for the single crown preparation. However, the results of an *in vitro* study showed that the conventional workflow was more precise than the digital workflow for transferring the implant position in single implant analog models.²⁰ Kim *et al.*²¹ demonstrated that accuracy of IOSs differed depending on their data capture principle for a complete arch model, including single crown preparations. Today, there are many IOS systems using various scanning technologies on the market, with and new ones being introduced. In addition to the different scanning technologies used by various manufacturers, new versions of hardware or software may also improve the accuracy of IOSs.^{12,22} To the best of our knowledge, although edentulous or complete arch models were used in the studies evaluating accuracy of digital impression by using Primescan, Virtuo Vivo, and Planmeca Emerald as new introduced scanners,^{12,13,23,24} no study has compared the accuracy of these IOSs for prepared teeth.

Manufacturers describe intraoral scan strategies for single crown preparation, quadrant, and complete arch impression. Nevertheless, the manufacturers have not provided any guidelines about the quadrant in which scanning should begin, especially in cases where both quadrants have prepared teeth. The effect of scanning sequence on digital impression accuracy in the complete arch model was shown in a previous study.²⁵ The authors determined a difference in accuracy depending on whether the scans started from the right or left quadrant when using iTero. This difference may be related to using the image stitching process and scan strategy in which the two quadrants are scanned separately and then merged. However, there is a lack of information in the literature as to whether the quadrant where the scan starts affects the accuracy of the digital impression.

The aim of the present study was to evaluate accuracy of six IOSs, and to examine the effect of scanning sequence on digital impression of single crown preparation. The null hypotheses of the study were that (1) there are no differences in accuracy between intraoral scanners; and (2) the scanning sequence does not affect accuracy.

MATERIALS AND METHODS

A maxillary complete arch model (ANA-4V, Frasaco, Tettngang, Germany) was used in the present study. The right and left canine teeth on the reference model were prepared for single crowns. The preparations were simulated by a 2.0 mm incisal edge reduction, approximately 10 degree convergence angle, and a 1.0 mm wide supragingival chamfer margin. All of the sharp angles of the preparations were rounded.

First, the prepared model was scanned using a highly accurate industrial reference scanner (ATOS Core 80, GOM GmbH, Braunschweig, Germany) to create a digital reference dataset. The reference scanner was calibrated and tested. The maximum deviations found were a 1 μm probing error form, 3 μm probing error size, 5 μm sphere spacing error, and 7 μm length measurement error. According to the manufacturer's data, this reference scanner uses a stereo camera set-up working on the principle of triangulation.²⁶ Six IOSs were used to investigate the precision and trueness of different intraoral scanning systems, as follows: Trios 3 version 1.4.7.5 (3Shape A/S, Copenhagen, Denmark), iTero Element 2 version 1.9.3.3 (Align Technology Inc, San Jose, CA, USA), Cerec Omnicam version 4.6.1 (Dentsply-Sirona Dental Systems, Bensheim, Germany), Planmeca Emerald version 6.0 (Planmeca Oy, Helsinki, Finland), Cerec Primescan version 5.0.0 (Dentsply-Sirona Dental Systems, Bensheim, Germany) and Virtuo Vivo version 3.0 (Dental Wings Inc., Montreal, Canada). One investigator (BD) performed all scans with each intraoral scanner according to the protocols described by each manufacturer. The scan strategies are demonstrated via a representative illustration in Figure 1. Ten scans were taken of the model using each intraoral scanner (a total of 60 scans). The first 5 scans started from the right maxillary quadrant (Scan Right-ScanR) and the following 5 scans started from the left maxillary quadrant (Scan Left-ScanL) to evaluate the effect of the scanning sequence.

For standardization and subsequent digital processing, datasets from each scan were converted to a standard tessellation language (STL) file format. All of the STL-formatted datasets were loaded into three-dimensional analyzing software (Geomagic Studio 12, 3D Systems, Morrisville, NC, USA) to evaluate the accuracy of the tooth preparations. The left and right canine teeth were digitally isolated from the complete arch to reduce the possible errors that could result from the superposition of large datasets (Fig. 2).¹⁶ The trimmed left and right canine data was saved as a STL-formatted file. The obtained STL data was aligned with the reference STL data while the two canine teeth were connected. For the trueness measurement, these models were superimposed on the reference model using a best-fit algorithm of the software. For the evaluation of precision, 5 scans in the ScanR and ScanL groups were superimposed on each other within groups. A two-way pairwise comparison was performed because reference scan data were not clear in the intra-group comparison.²⁷ For example, the

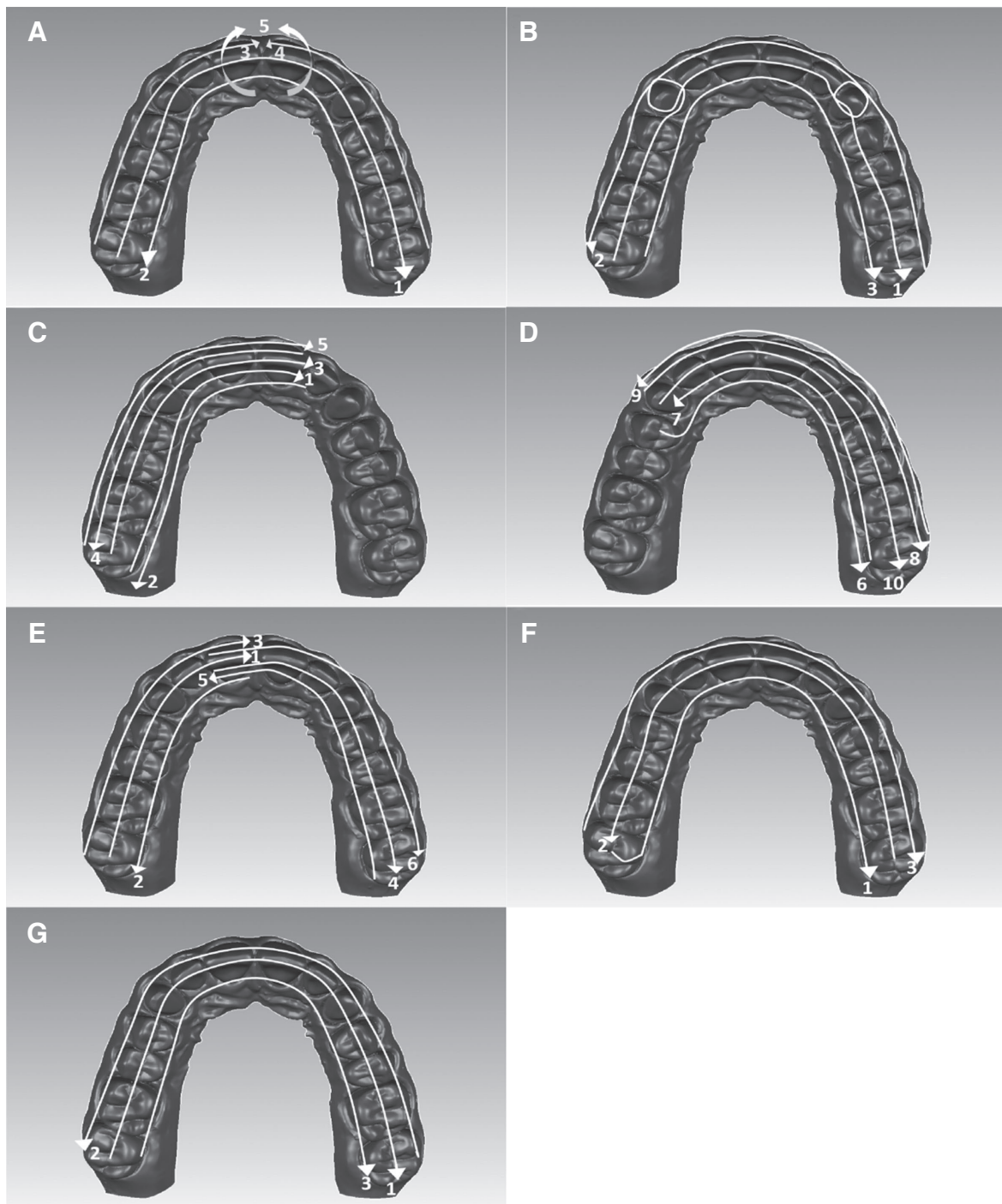


Fig. 1. Scan strategy for the ScanR. (A) iTero Element 2. The scan was started from the occlusal side of the right molars to the left occlusal side (1), continued the palatal side in the reverse direction (2), and toward the buccal side to the midline (3), moved to the opposite side and scanned to the midline (4), scanned by rolling over the anterior teeth (5). (B) Trios 3. Started from the occlusal side of the right molars to the left occlusal side by rolling over palatal, buccal, distal, and mesial side of preparations (1), continued the buccal side in the reverse direction (2), and toward the palatal side (3) (C) Omnicam, first half of arch. Started from the occlusal side of the right molars and tilted the scanner by 45° in palatal direction (1), continued the palatal side (90°) from the left lateral to the right molar (2), toward the occlusal side in the reverse direction (3), scanned the buccal side with 45° tilt (4) and 90° tilt (5). (D) Omnicam, second half of arch. Started from the occlusal side of the right premolar and continued the palatal side with 90° (6) and 45° (7) tilt, followed the buccal side with 45° (8) and 90° (9) tilt, and finally occlusal side (10). (E) Planmeca Emerald. Started from occlusal side of the right molar to the midline (1), continued the palatal side (2), and buccal side (3), scanned the second half similar to the first half, starting from the central tooth. (F) Primescan. Scanned the palatal side (1), occlusal side (2), and buccal side (3), respectively. (G) Virtuo Vivo. Scanned the occlusal side (1), buccal side (2), and palatal side (3), respectively (not defined a specific scan strategy by manufacturer).

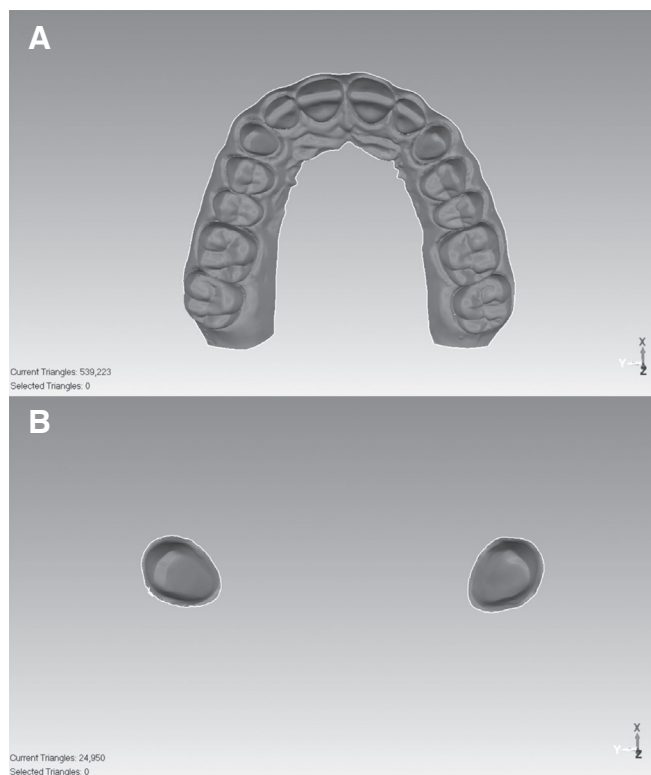


Fig. 2. The model scanned with the industrial reference scanner. (A) Complete arch, (B) Bilaterally prepared canine teeth digitally isolated from the complete arch.

ScanR 1 was determined as a reference scan and compared with the ScanR 2. Then the ScanR 2 was determined as a reference scan and was compared with the ScanR 1. There were a total of 20 precision measurement combinations in each group. The necessity of performing the two-way pairwise comparison was mentioned because of the part comparison algorithm in the three dimensional software in a previous study.²⁸

After the 3D comparative analysis, standard deviations and mean positive/ negative deviations were recorded in micrometers. For each IOS, the ScanR and ScanL values were recorded separately. The absolute mean deviations were obtained by calculating the arithmetic mean of the absolute values of the positive and negative deviations as mentioned by Treesh *et al.*²⁸ Values for trueness and precision were calculated using absolute mean deviation values and standard deviation values, respectively.

All scan data were statistically analyzed to measure trueness and precision. The homogeneity and normality of distributions were tested by Kolmogorov-Smirnov and Skewness-Kurtosis tests. The Kruskal Wallis test for non-normal distributed data and one-way ANOVA for normal distributed data were used. The Kruskal Wallis test was performed to compare the trueness differences between IOSs (n = 10). The pairwise comparisons were performed via the Mann-Whitney U test with a Bonferroni correction to control for

the increased risk of Type I error by accounting for the number of comparisons. The Mann-Whitney U test was also used to compare differences among scanning sequences (n = 5). One-way ANOVA and a post-hoc Tukey test were used to assess the precision differences between IOSs (n = 20). The level of significance was set $\alpha = .05$ (except when the Bonferroni adjustment was used). After Bonferroni correction, the level of significance of 0.003 (0.05/15) was considered. All statistical analysis was performed by using SPSS software (PASW Statistics 18.0, SPSS Inc., Chicago, IL, USA).

RESULTS

There were significant differences among IOSs for trueness and precision of digital impressions. The median trueness and mean precision values of each scanner and the p values of the interaction between scanners for trueness and precision of single crown preparations are shown in Table 1 and Table 2. The statistically higher trueness was obtained from Primescan (25 μm), followed by Trios (40.5 μm), Omnicam (41.5 μm), Virtuo Vivo (52 μm), iTero (70 μm), and Emerald (73.5 μm) (Fig. 3). There was no statistically significant difference between Trios, Omnicam, Virtuo Vivo, and iTero ($P > .003$). iTero did not exhibit statistically significant differences from Emerald and Virtuo Vivo for trueness. However, Emerald had statistically the lowest trueness among the all IOSs, except for iTero.

The highest precision was obtained from Primescan (10 $\pm 2 \mu\text{m}$), followed by Trios (11 $\pm 3 \mu\text{m}$), iTero (12 $\pm 3 \mu\text{m}$), Omnicam (18 $\pm 5 \mu\text{m}$), Virtuo Vivo (37 $\pm 19 \mu\text{m}$), and Emerald (60 $\pm 27 \mu\text{m}$). There was no statistically significant difference between Primescan, Trios, iTero, and Omnicam. The Emerald and Virtuo Vivo had statistically lower precision than Primescan, Trios, iTero, and Omnicam. Pairwise analysis revealed a statistically significant difference between Virtuo Vivo and Emerald.

Table 1. Trueness and precision values for each intraoral scanner

	Trueness		Precision	
	Median	First quartile - Third quartile (Q1 - Q3)	Mean	Standard deviation
Trios	40.5	39 - 42	11	3
iTero	70	45 - 87.25	12	3
Emerald	73.5	64 - 76	60	27
Omnicam	41.5	33.5 - 43.75	18	5
Primescan	25	23.25 - 26.75	10	2
Virtuo Vivo	52	44.75 - 55.25	37	19

Table 2. P value results of Mann-Whitney U test with Bonferroni correction for trueness and one-way ANOVA with post-hoc Tukey test for precision between intraoral scanners for single crown preparations

Scanner		Trueness	Precision
Trios	iTero	.025	.998
	Emerald	.002*	< .001**
	Omniscam	1	.238
	Primescan	< .001*	.999
	Virtuo Vivo	.017	< .001**
iTero	Trios	.025	.998
	Emerald	.705	< .001**
	Omniscam	.010	.471
	Primescan	< .001*	.967
	Virtuo Vivo	.344	< .001**
Emerald	Trios	.002*	< .001**
	iTero	.705	< .001**
	Omniscam	.002*	< .001**
	Primescan	< .001*	< .001**
	Virtuo Vivo	.002*	< .001**
Omniscam	Trios	1	.238
	iTero	.010	.471
	Emerald	.002*	< .001**
	Primescan	< .001*	.102
	Virtuo Vivo	.009	< .001**
Primescan	Trios	< .001*	.999
	iTero	< .001*	.967
	Emerald	< .001*	< .001**
	Omniscam	< .001*	.102
	Virtuo Vivo	< .001*	< .001**
Virtuo Vivo	Trios	.017	< .001**
	iTero	.344	< .001**
	Emerald	.002*	< .001**
	Omniscam	.009	< .001**
	Primescan	< .001*	< .001**

*Statistically significant difference among the scanners ($P < .003$)

** Statistically significant difference among the scanners ($P < .05$)

Table 3. Trueness and precision values of single crown preparations for Scan R and Scan L of each intraoral scanner (mean ± standard deviation in micrometer)

	Accuracy for the single crown preparations					
	Trueness			Precision		
	Scan R	Scan L	P value	Scan R	Scan L	P value
Trios	42 ± 3	38 ± 4	.206	11 ± 3	11 ± 3	1
iTero	74 ± 4	44 ± 7	.009*	10 ± 2	15 ± 4	.995
Emerald	67 ± 21	67 ± 6	.114	59 ± 30	61 ± 14	.727
Omniscam	39 ± 6	42 ± 7	.754	16 ± 5	21 ± 6	.999
Primescan	26 ± 3	24 ± 3	.248	9 ± 3	11 ± 2	1
Virtuo Vivo	44 ± 8	60 ± 16	.059	43 ± 14	31 ± 24	.381

*Statistically significant difference ($P < .05$) between Scan R and Scan L

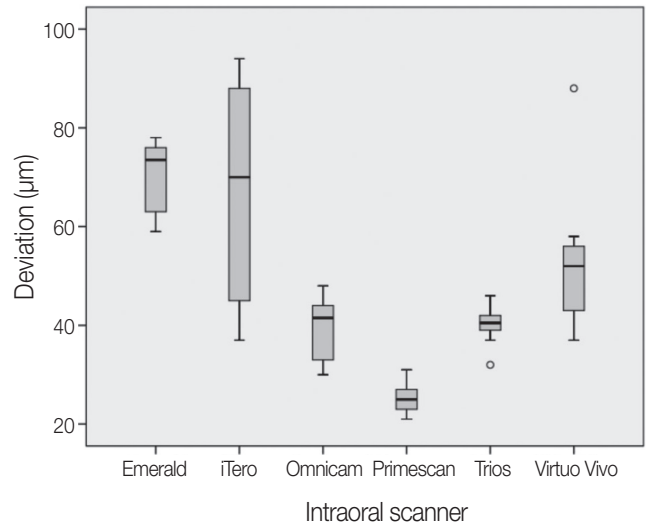


Fig. 3. Boxplot for trueness values of each intraoral scanner.

No significant difference was found between the precision values of the ScanR and ScanL obtained from each IOS for the prepared teeth. However, trueness was significantly affected by scanning sequence when using iTero. The ScanR had statistically lower trueness than the ScanL, for iTero ($P = .009$). The trueness and precision values of the ScanR and ScanL for each IOS are shown in Table 3.

DISCUSSION

The aim of the present study was to evaluate the accuracy of single crown preparations using six IOSs, and to determine the effect of scanning sequence on accuracy. Based on the results of the present study, the first null hypothesis that there are no significant differences between digital impression accuracy of single crown preparations obtained by six IOSs was rejected. The second null hypothesis, that scan-

ning sequence does not affect accuracy, was partially rejected (for iTero).

The IOS accuracy varies with the quality of the point cloud obtained depending on the hardware and software algorithms. The mesh decimation algorithm regulates the total number of triangles by increasing the triangle density in curved surfaces and decreasing the triangle density on flatter surfaces.²⁹ The size of the triangle varies depending on the scanning systems using different software algorithms.¹⁴ For this reason, different triangle configurations from the same surface may be obtained.¹⁵ It is important to evaluate the accuracy of the IOSs using different hardware and software algorithms because these differences in triangles may affect accuracy. Therefore, the present study focused on the accuracy of new and actual intraoral scanners, and the software version of each scanner was specified. IOS accuracy can be evaluated directly through three-dimensional comparisons of digital impressions, and indirectly through internal and marginal fit measurements of the fabricated restoration after scanning. The maximum clinically acceptable marginal gap was reported as 120 μm .⁴ Although a clinically acceptable deviation value for digital impressions is not clear in literature, their accuracy must be below 120 μm .

Several studies^{12,13,23,24} evaluated the accuracy of digital impressions obtained from the recently introduced Emerald, Virtuo Vivo, and Primescan IOSs.^{12,22} In these studies, edentulous or complete arch models with unprepared teeth were used as reference models. However, intraoral scanning of the prepared teeth is a commonly used and preferred procedure in daily clinical situations. This may be more complex than scanning unprepared teeth, because the prepared teeth involve various points which require high mesh density.³⁰ For this reason, a reference complete arch model with right and left canine abutment teeth for single crowns was used in the present study. The commonly preferred Trios, iTero, and Omnicam IOSs, and the recently introduced Primescan, Virtuo Vivo, and Emerald IOSs were selected to evaluate the accuracy of the single crown preparations.

The recently introduced IOSs did not display similar accuracy. In the present study, Primescan showed the highest accuracy among all scanners tested, whereas Emerald had the lowest accuracy. However, the trueness of Virtuo Vivo was not statistically different from that of Omnicam, Trios, and iTero. Ender *et al.*¹² reported that Primescan showed the highest trueness for digital impressions of the complete arch model with unprepared teeth, with statistically significant differences compared to iTero and Omnicam, but not Trios. The authors found that, similar to the results of the present study, Primescan had the highest trueness for the anterior segment. Latham *et al.*¹³ evaluated effect of scan strategy on complete arch scans using Cerec Omnicam, Planmeca Emerald, iTero Element, and Trios scanners. The accuracy of iTero, Emerald, and Trios were similar when four different scan strategies, guided by the various manufacturers' instructions, were used. The differences between

those results and the ones found in the present study may relate to the use of different scan strategies. In the present study, the scan strategy described by its manufacturer was performed for each intraoral scanner. Another study²³ reported that in an edentulous acrylic model with scan abutment, Emerald showed middle-low performance and Virtuo Vivo showed low performance when compared to Trios and Omnicam. Although the study models were different, results were similar to those found in the present study. Osnes *et al.*²⁴ reported similar results in an edentulous model and stated that Emerald and Virtuo Vivo showed higher deviation than Trios and Omnicam.

Previous studies evaluating accuracy of single crown preparation reported that the accuracy varies depending on the IOSs utilized.^{8,9,11,18,19} In the present study, statistically significant differences were found between accuracy of six IOSs for single crown preparation. The most accurate scanner was Primescan (median trueness deviation 25 μm , mean precision deviation $10 \pm 2 \mu\text{m}$), followed by Trios (40.5 μm , $11 \pm 3 \mu\text{m}$), Omnicam (41.5 μm , $18 \pm 5 \mu\text{m}$), Virtuo Vivo (52 μm , $37 \pm 19 \mu\text{m}$), iTero (70 μm , $12 \pm 3 \mu\text{m}$), and Emerald (73.5 μm , $64 \pm 27 \mu\text{m}$). Medina-Sotomayor *et al.*¹⁶ found Trios (trueness 9.7 μm , precision 15.1 μm) to be the most accurate scanner for a single tooth scan, when compared with iTero (trueness 11.2 μm , precision 18.4 μm) and Omnicam (trueness 20.6 μm , precision 33.2 μm). Another study¹¹ showed that trueness of Trios was between $15.8 \pm 0.9 \mu\text{m}$ and $20.6 \pm 1.0 \mu\text{m}$, and precision was between $10.0 \pm 2.1 \mu\text{m}$ and $13.4 \pm 1.8 \mu\text{m}$, depending on convergence angles of the preparation's mesial and distal walls. The root mean square values were statistically analyzed, and mean and standard deviation values for accuracy were presented. The numeric discrepancies in the results may be due to the use of different data types for statistical analysis and different reference model designs. In the studies of Medina-Sotomayor *et al.*¹⁶ and Carbajal Mejía *et al.*,¹¹ a single prepared tooth (unattached to a model) or a model that also included onlay preparation and implant scan body were scanned, while single crown preparations on a complete arch were scanned in the present study. Thus, the distortion that occurs during a complete arch scan was taken into account when prepared teeth in different quadrants needed to be scanned. The trueness of IOS for single crown preparation was evaluated at four points determined by the sectional analysis method in an *in vitro* study.³¹ Although the evaluation methods and generation of IOSs used were different, Trios showed higher trueness than iTero, similar to the results of the present study. Boeddinghaus *et al.*¹⁸ evaluated *in vivo* accuracy of single crown restorations via marginal fit of the copings. The Omnicam group showed statistically higher marginal gap than the Trios group. Contrary to this finding, in the present study, there was no statistically significant difference between accuracy of Omnicam and Trios. This may be related to the different study designs (*in vivo* and *in vitro*), potential processing errors during design and manufacture of the crown, and different version of IOS software. However, the study of Boeddinghaus *et al.*¹⁸

was standardized using the same workflow, design principles, software, material and milling machine to fabricate restorations and focused on IOS performance. Based on the different results obtained, the present study's authors have considered that IOSs may behave differently in *in vivo* and *in vitro* situations.

For each IOS, there is a scanning strategy specified by the manufacturer. However, manufacturer's instructions do not specify where scanning should begin, which is a concern especially in cases where both quadrants have prepared teeth. There may be differences in accuracy between the regions where scanning starts and ends; because cumulative errors may be seen with the stitching method as scanning moves from the starting point and continues towards proximal areas.^{15,27} Therefore, the effect of the scanning sequence on accuracy was evaluated in the present study. iTero had statistically significant differences based on scanning sequence (ScanR and ScanL) for accuracy of the prepared teeth. ScanL ($44 \pm 7 \mu\text{m}$) showed higher trueness than ScanR ($74 \pm 4 \mu\text{m}$). However, there were no statistically significant differences in precision of prepared teeth between ScanR and ScanL of IOSs. Anh *et al.*²⁵ compared the precision of the digital impressions obtained by iTero and Trios. This study showed that iTero produced less precise digital impressions when scanning started from the right rather than from the left, similar to the trueness findings of the present study. Kim *et al.*³² designed a multiple implant model and observed that iTero Element showed more deviation than Trios at the opposite side of the scans' starting region. Although different generations and softwares of iTero were used in the studies of Anh *et al.*²⁵ and Kim *et al.*,³² the region where scanning started affected the deviation in the opposite or complete arch. The result may be related to iTero's scan strategy, which merges left and right buccal scan data on the anterior region.

Like other *in vitro* studies evaluating IOS accuracy, the present study has some limitations. Intraoral factors such as saliva, limited mouth opening, patient movement, and different refractive indexes of teeth and gingiva were not considered. Further studies that evaluate the accuracy of newly introduced hardware and/or software of IOSs for single crown preparation under *in vivo* conditions are required. It will also be clinically useful to evaluate the IOS accuracy by comparing the marginal fit of the crown. The accuracy of actual and new IOSs should be evaluated on prepared teeth for long-span prostheses as well as for single crown preparation. In addition to the IOSs evaluated in the present study, the accuracy of IOSs recently introduced to the market, including Trios 4, Medit i500, and iTero Element 5D, should be evaluated.

CONCLUSION

Within the limitations of the present study, the accuracy of digital impressions for single crown preparations differed depending on the IOS and scanning sequence used. Primescan showed the highest trueness for single crown

preparations. In terms of precision, Primescan, Trios, iTero, and Omnicam had better results than Emerald and Virtuo Vivo. Emerald showed the most deviation in trueness and precision. iTero resulted in more trueness deviation when scanning started from the right.

ORCID

Burcu Diker <https://orcid.org/0000-0001-5367-9369>

Önjen Tak <https://orcid.org/0000-0002-3578-9078>

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