THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Accuracy of six intraoral scanners for scanning complete-arch and 4-unit fixed partial dentures: An in vitro study

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ABSTRACT

Statement of problem. The digital scan accuracy of different intraoral scanners (IOSs) for long-span fixed prosthesis and the effect of the starting quadrant on accuracy is unclear.

Purpose. The purpose of this in vitro study was to evaluate the accuracy of 6 IOSs for complete-arch and prepared teeth digitally isolated from the complete-arch and to determine the effect of the starting quadrant on accuracy.

Material and methods. A maxillary model containing bilaterally prepared canines, first molar teeth, and edentulous spans between the prepared teeth was used. The model was scanned by using a highly accurate industrial scanner to create a digital reference data set. Six IOSs were evaluated: TRIOS, iTero, Planmeca Emerald, Cerec Omnicam, Primescan, and Virtuo Vivo. The model was scanned 10 times with each IOS by 1 operator according to the protocols described by the manufacturers. Five scans were made starting from the right quadrant (ScanR), followed by 5 scans starting from the left quadrant (ScanL). All data sets were obtained in standard tessellation language (STL) file format and were used to evaluate accuracy (trueness and precision) with a 3D analyzing software program (Geomagic Studio 12; 3D Systems) by using a best-fit alignment. The prepared teeth were digitally isolated from the complete-arch and evaluated with the analyzing software program. The Kruskal-Wallis and Mann-Whitney U statistical tests were used to detect differences for trueness and precision (α=.05).

Results. Statistically significant differences were found regarding IOSs (P<.003) and scanning sequence (P<.05). The TRIOS showed the best trueness for the complete-arch, but not statistically different from Primescan, Virtuo Vivo, and iTero (P>.003). The lowest median values for precision of the complete-arch were also found using TRIOS, but no significant difference was found among the scanners (P>.003). In terms of trueness and precision, Primescan had the best accuracy for preparations. Emerald showed significant differences depending on the scanning sequence for complete-arch accuracy. ScanR for trueness (P=.021) and ScanL for precision (P=.004) showed improved results. However, Emerald, TRIOS, and Virtuo Vivo showed statistically significant differences in precision of preparations depending on scanning sequence. ScanL deviated less than ScanR when scanned with TRIOS (P=.025) and Emerald (P=.004), and the opposite with Virtuo Vivo (P=.008). In terms of preparations trueness, no significant difference was found between the ScanR and ScanL of any IOS (P>.05).

Conclusions. Based on this in vitro study, the accuracy of the complete-arch and prepared teeth differed according to the IOS and scanning sequence. (J Prosthet Dent 2022;128:187-94)

The use of digital technology in dentistry has been increasing in recent years,[1] with different computer-aided design and computer-aided manufacturing (CAD-CAM) systems being used to fabricate different types of prostheses.[2] With CAD-CAM systems, a workflow starting with indirect or direct digitalization can be followed.[3] Digital scanning techniques with intraoral scanners (IOSs) have been reported to have clinically acceptable results compared with those of conventional impression methods in the fabrication of crowns and fixed partial dentures (FPDs),[4-6] to provide time efficiency,[7] to eliminate potential error due to distortion of elastic impression materials,[8] and to improve patient acceptance.[9]

Accuracy can be specified as trueness and precision. Trueness is the closeness between the test object and the reference object, whereas precision is the variability of repeated measurements of the object.[10] In a completely digital workflow, an accurate digital scan is essential for a successful prosthesis.[6] The accuracy of a digital scan depends on the ambient light,[11] the head size of the IOS,[8] the scanning technology,[12-14] whether reflective powder is required,[15,16] the scanner software program,[17] the scanning protocol,[18,19] limited spacing,[20] and edentulous

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Clinical Implications

An accurate digital scan may lead to the better fit of fixed partial dentures. Variability in accuracy based on the IOS, software program, and scanning sequence should be considered in clinical practice.

span length.[21] Differences in digital scan accuracy have been reported depending on the scanners used.[13,16,22] Ender et al[23] reported that hardware or software developments can improve digital scan accuracy. Therefore, the accuracy of existing and new IOSs should be evaluated on prepared teeth and complete-arches.

The accuracy of different IOSs has been compared for single-crown preparations.[4,6,16,24-26] Recently, the accuracy of IOSs has improved for scanning larger regions. Sim et al[24] compared the accuracy of a single crown and 3-unit FPD preparations by using an IOS, reporting no significant difference in the accuracy among the different types of preparations. Fukazawa et al[21] evaluated the accuracy of digital scans in different edentulous span lengths between 2 implant abutments and concluded that a longer edentulous span resulted in more errors. The larger the scanned region, the more complex the merging of images because accuracy of IOS systems depends on the merging of single images.[27] However, information on the accuracy of long-span fixed prosthesis is sparse.

Intraoral scan strategies for quadrants and complete-arches have been described by manufacturers. Nevertheless, manufacturers have not provided guidelines for the quadrant in which scanning should begin during complete-arch scanning. The effect of scanning sequence on the digital scan accuracy in the complete-arch model has been reported.[28] However, evidence for whether the starting quadrant affects the accuracy of a digital scan is lacking.

Therefore, the purpose of the present study was to evaluate the accuracy of 6 representative IOSs for complete-arch and 4-unit FPD preparations and to examine the effect of scanning sequence. The null hypotheses were that there would be no difference in accuracy among IOSs and that scanning sequence would not affect accuracy.

MATERIAL AND METHODS

A maxillary complete-arch model (ANA-4V; Frasaco GmbH) was used. The canine and first molar teeth on the reference model were prepared for bilateral 4-unit FPDs with a 2.0-mm incisal edge and occlusal reduction, approximately 10 degrees of total angle of convergence, and with a supragingival chamfer margin. The sockets of the removed premolar teeth were filled with a silicone-based gingival simulation (Gingifast Elastic; Zhermack SpA) to provide appropriate residual ridge form.

The prepared model was scanned by using a highly accurate industrial reference scanner (ATOS Core 80; GOM GmbH) to create a digital reference data set. According to the manufacturer's data, ATOS Core uses a stereo camera set-up working on the principle of triangulation. Six IOSs were evaluated: TRIOS 3 (3Shape A/S), iTero Element 2 (Align Technology Inc), Cerec Omnicam (Dentsply Sirona), Planmeca Emerald (Planmeca Oy), Cerec Primescan (Dentsply Sirona), and Virtuo Vivo (Dental Wings Inc). One operator (B.D.) made all the scans with each IOS according to the protocols described by each manufacturer. An a priori power analysis was done by using a power analysis software program (G*Power 3.1.9.4), and the minimum sample size was determined as 3 (power:0.95, effect size:1.87). A sample size of 5 in each group was used to increase the power of the study.

Ten scans were made of the study model, with each IOS (N=60). The first 5 scans were started from the right maxillary quadrant (Scan Right- ScanR) and the following 5 scans were started from the left maxillary quadrant (Scan Left- ScanL) to evaluate the effect of scanning sequence.

For standardization, data sets from each scan were converted to the standard tessellation language (STL) file format. All data sets were loaded into a 3D analyzing software program (Geomagic Studio 12; 3D Systems). The unnecessary gingival area approximately 1 mm away from the free gingival margin was removed from the scan to measure the accuracy of the complete-arch, whereas the canine and first molar teeth were digitally isolated from the complete-arch to measure the accuracy of the preparations (Fig. 1). The trimmed scans were saved in STL file format. For the trueness measurement, these scans were superimposed with a best-fit algorithm of the software program on the reference model. The superimposition procedure aligned a test scan with a reference scan by using an iterative closest point algorithm, and this algorithm determined the minimal distance between 2 scans.[29] For the evaluation of precision, the final 3 scans (ScanR-ScanL 3, ScanR-ScanL 4, ScanR-ScanL 5) were selected and superimposed on each other within groups. A 2-way pairwise comparison was performed because reference scan data were not certain in the intragroup comparison. Each group contained a total of 6 combinations for precision measurement.

After the 3D comparison analysis, standard deviations, mean positive deviations, and mean negative deviations were separately recorded in micrometers for ScanR and ScanL. The absolute mean deviations were obtained by calculating the arithmetic mean of the absolute values of the positive and negative deviations.[13] The absolute mean deviation values to determine the

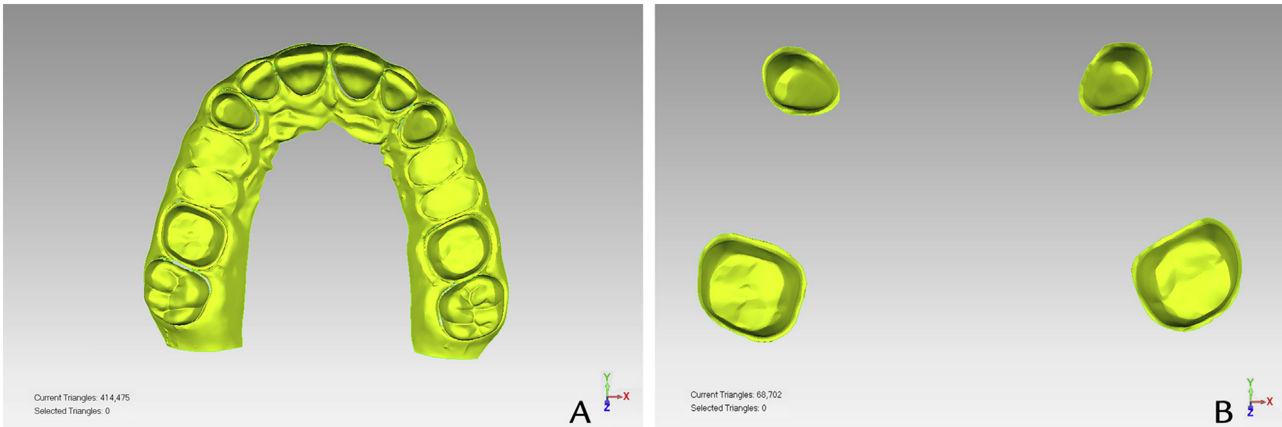

Figure 1. A, Trimmed complete-arch model. B, 4-unit FPD preparations bilaterally isolated from complete-arch.

trueness and standard deviation values were used to determine the precision. A color map representing visual deviation was set with 13 color segments. A positive deviation defined overestimation, and a negative deviation defined underestimation.

All scan data were statistically analyzed to measure trueness and precision. The homogeneity and normality of distributions were tested by the Kolmogorov-Smirnov and Shapiro-Wilk tests. The nonparametric Kruskal-Wallis test was performed to compare the trueness (n=10) and precision (n=12) differences among the scanner groups. The intergroup comparisons were performed with the Mann-Whitney U test with a Bonferroni correction to control for increased risk of Type I error by accounting for the number of comparisons. The Mann-Whitney U test was also used to compare the differences among scanning sequences (n=5) (α=.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 analyses were performed by using a statistical software program (IBM SPSS Statistics, v22.0; IBM Corp). The descriptive statistic values were given as median with interquartile range (IQR) (all values in µm).

RESULTS

The accuracy values of each scanner and *P* values of the interaction between ScanR and ScanL for the complete-arch and 4-unit FPDs preparations are given in Tables 1 and 2.

Trueness of digital scans for the complete-arch

Significant differences in the trueness of digital scans were found among IOSs (P<.05). The smallest median (IQR) deviations for the trueness measurements were obtained from TRIOS (48(8.25) µm), followed by Primescan (56(6.25) µm), Virtuo Vivo (59(5.75) µm), and iTero (60(11.5) µm). TRIOS, Primescan, Virtuo Vivo, and iTero had statistically significant differences ($P\leq$.001) when compared with Omnicam (84.5(16.25) µm) and Emerald (105.5(19) µm), but the comparison of trueness among the other groups showed no significant differences (P>.003). The boxplots of mean absolute deviations for each group are depicted in Figure 2.

Precision of digital scans for the complete-arch

No significant difference in the precision of digital scans was found between IOSs (P>.003). The median (IQR) precision values of the scanners were in the range of 41 (52.5) µm (TRIOS) to 84 (48.5) µm (Emerald) (Table 1). The boxplots of precision deviations for each group are depicted in Figure 3.

Trueness of digital scans for the prepared teeth

Primescan showed the highest trueness for the prepared teeth, with statistically significant differences from the other scanners. No statistically significant difference (P=.272) was found between Omnicam and Emerald, however, and other scanners showed statistically lower deviation than Omnicam and Emerald (P<.003). The boxplots of mean absolute deviations for each group are depicted in Figure 4.

Precision of digital scans for the prepared teeth

Primescan showed the highest median (IQR) precision value for preparations at 23(8) µm, but was not statistically different from Virtuo Vivo (P=.068), TRIOS (P=.214), or Omnicam (P=.007). Emerald had statistically lower precision (64(12) µm) than Primescan (P<.001), Virtuo Vivo (P<.001), and TRIOS (P<.001). No statistically significant difference was found between Omnicam and iTero (P=.083), Omnicam and Emerald (P=.06), or iTero and Emerald (P=.603). The boxplots of precision deviations for each group are depicted in Figure 5.

Table 1. Trueness and precision values of complete-arch for ScanR, ScanL, and total scans of each intraoral scanner (median [IQR] in micrometers)

	Accuracy for Complete-Arch							
	Trueness				Precision			
Intraoral Scanners	Scan R	Scan L	Total	*P*	Scan R	Scan L	Total	*P*
TRIOS	51 (6)	45 (9)	48 (8.25)[a]	.598	52 (37.25)	35 (65.5)	41 (52.5)[a]	.423
iTero	59 (5)	66 (12)	60 (11.5)[a]	.754	90.5(19.5)	53 (19.5)	70.5 (38.75)[a]	.190
Emerald	97 (10)	119 (13)	105.5 (19)[b]	.021*	113.5 (23)	62.5 (5.75)	84 (48.5)[a]	.004*
Omnicam	85 (11)	84 (36)	84.5 (16.25)[b]	.917	61 (21)	106 (35.75)	77 (49)[a]	.109
Primescan	55 (4)	57 (7)	56 (6.25)[a]	.445	75.5 (49.5)	68.5 (20.25)	68.5 (39.5)[a]	.873
Virtuo Vivo	54 (12)	59 (0)	59 (5.75)[a]	.990	60 (45.5)	51.5 (25)	58.5 (29.25)[a]	.260

Different superscript lowercase letters indicate statistically significant difference among the scanners by Mann-Whitney U test with Bonferroni correction ($P<.003$). *Statistically significant difference ($P<.05$) between Scan R and Scan L for trueness values.

Table 2. Trueness and precision values of FPD preparations for ScanR, ScanL, and total scans of each intraoral scanner (median [IQR] in micrometers)

	Accuracy for 4-Unit FPD Preparations							
	Trueness				Precision			
Intraoral Scanners	Scan R	Scan L	Total	*P*	Scan R	Scan L	Total	*P*
TRIOS	61 (5)	57 (3)	57.5 (4)[b]	.059	34.5 (18.25)	19.5 (10)	29 (9)[a]	.025*
ITero	61 (37)	60 (15)	60.5 (24)[b]	.675	73 (28.75)	50 (15.5)	60 (15)[b]	.109
Emerald	98 (9)	110 (7)	101 (12.75)[c]	.249	90 (24.75)	48 (10.25)	64 (12)[b]	.004*
Omnicam	98 (15)	83 (50)	92.5 (23.25)[c]	.600	39 (5.75)	65 (42.75)	45 (16)[a,b]	.337
Primescan	43 (2)	42 (3)	43 (3.5)[a]	.753	22 (8)	17 (15)	23 (8)[a]	.296
Virtuo Vivo	52 (4)	56 (7)	54.5 (7)[b]	.053	23 (3.75)	33.5 (5.25)	28 (3)[a]	.008*

FPD, fixed partial denture. Different superscript lowercase letters indicate statistically significant difference among the scanners by Mann-Whitney U test with Bonferroni correction ($P<.003$). *Statistically significant difference ($P<.05$) between Scan R and Scan L for trueness values.

Effect of scanning sequence on accuracy for the complete-arch

The scan sequence had no statistically significant ($P>.05$) effect on the trueness and precision values for the complete-arch, except for Emerald. The trueness and precision of ScanR and ScanL on the complete-arch are reported with *P* values in Table 1. In both scanning sequences, precision deviations were seen in the anterior segment and the most distal segment of the model with iTero, Omnicam, Emerald, and Virtuo Vivo. TRIOS and Primescan had more deviations in the most distal segment of the model and less deviation in the edentulous spans. More deviation in precision was found in the left quadrant in ScanR, as well as more deviation in the right quadrant in ScanL, except for Emerald. The deviation pattern between scans obtained from each IOS and reference model (trueness) can be seen in Figure 6.

Effect of scanning sequence on accuracy for the prepared teeth

No significant difference was found between the trueness values of ScanR and ScanL for the accuracy of the prepared teeth. However, precision was significantly influenced by scanning sequence ($P<.05$). Statistically significant differences were found between ScanR and ScanL with TRIOS ($P=.025$), Emerald ($P=.004$), and Virtuo Vivo ($P=.008$) (Table 2). The ScanL showed lower deviation than ScanR with TRIOS and Emerald, whereas ScanR had lower deviation than ScanL for Virtuo Vivo (Table 2).

DISCUSSION

The primary aim of this in vitro study was to evaluate the accuracy of 6 IOSs for the complete-arch and FPD preparations and to determine the effect of scanning sequence on accuracy. According to the results of the study, the null hypotheses that no difference in accuracy would be found among the scanners and between the scanning sequences were rejected.

STL is a digital format for recording the 3D geometry of an object and enables the transport of a triangulated mesh. Each triangle is defined by 3 points and a normal surface.[1] The size of these triangles varies between scanning systems by using different software algorithms,[30] obtaining different STL triangle resolutions and configurations from the same surface.[18] The accuracy of the IOSs should be assessed by using different software algorithms because the differences in the STL triangles may affect accuracy. The accuracy of a digital scan can be improved with a new software program.[23] The Primescan, Virtuo Vivo, and Emerald have been used to compare complete-arch accuracy in few studies,[19,22,23] and the authors are unaware of studies of the accuracy of prepared teeth scanned with these scanners. For this reason, the commonly preferred IOSs TRIOS, iTero, Omnicam, and the recently released IOSs Primescan,

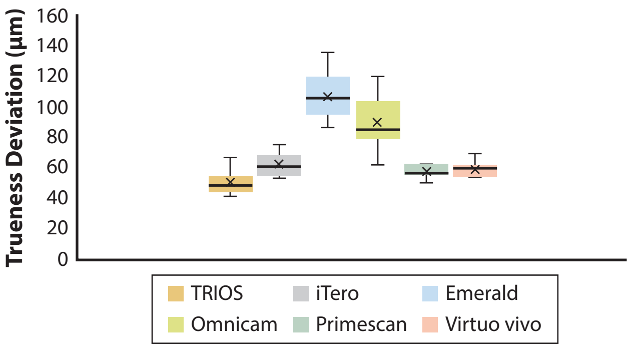

Figure 2. Trueness deviations (μm) of complete-arch among intraoral scanners.

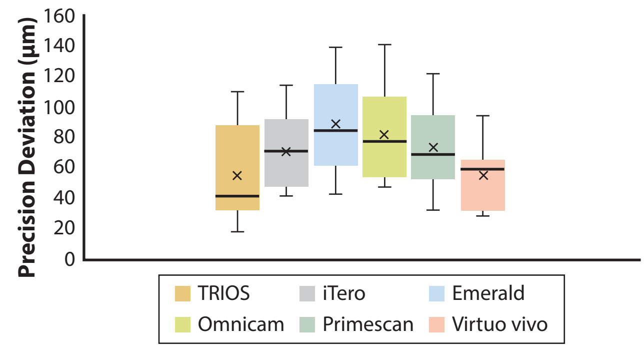

Figure 3. Precision deviations (μm) of complete-arch among intraoral scanners.

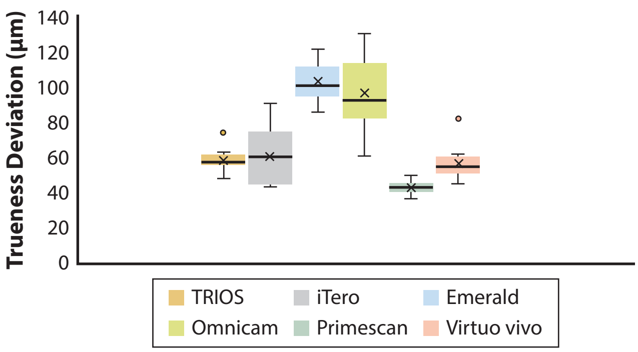

Figure 4. Trueness deviations (μm) of FPD preparations among intraoral scanners.

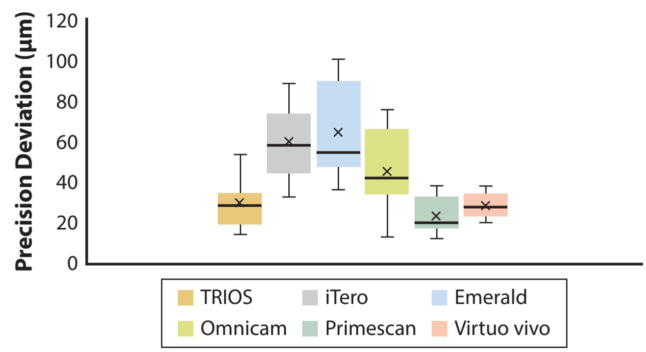

Figure 5. Precision deviations (μm) of FPD preparations among intraoral scanners.

Virtuo Vivo, and Emerald were used to evaluate the accuracy of the complete-arch and prepared teeth in the present study.

Several studies[12,14,23,31] reported that the accuracy of complete-arch scanning requires improvement. In the present study, the median (IQR) complete-arch trueness of TRIOS (48(8.25) μm) was higher than that of other scanners. Emerald (105.5(19) μm) and Omnicam (84.5(16.25) μm) showed significantly lower trueness than the others IOSs evaluated. No statistically significant difference was found between the median (IQR) trueness of TRIOS (48(8.25) μm), Primescan (56(6.25) μm), Virtuo Vivo (59(5.75) μm), and iTero (60(11.5) μm). For the precision of the complete-arch, the differences between the scanners were not statistically significant. Ender et al[23] evaluated complete-arch accuracy and reported that Primescan (33(7) μm) showed the best median (IQR) trueness, followed by TRIOS (51(16) μm), iTero (60(11) μm), and Omnicam (87(18) μm). Primescan was also reported to have the best precision value among the scanners tested. The difference with the present study may have been that a complete-arch model with unprepared teeth and, without an edentulous span was used. Prepared teeth involve various points that need high mesh density, making scans complex.[1] Also, the teeth were made of a feldspathic ceramic in the study of Ender et al.[23] The refractive index of feldspathic ceramic may be different from that of the typodont teeth used in the present study. Nevertheless, the trueness values of TRIOS, iTero, and Omnicam were similar in the study of Ender et al and the present study. Treesh et al[13] reported no statistically significant difference between the complete-arch trueness and precision values of TRIOS Color and Omnicam version 4.3.1. The software versions of IOSs used in this study were different from those used in the present study, which may have caused the difference in results. Haddadi et al[17] reported that software versions can have a significant impact on the accuracy of an IOS.

Few studies have evaluated the digital scan accuracy of long-span 4-unit FPDs.[27,32] A model representing the dental arch was not used in these studies. A complete-arch model was used in the current study to simulate the clinical situation, because accuracy may vary between complete and partial arch scans.[23] Similar to the results of the present study, although different scanners were used in these studies, the accuracy of 4-unit FPDs was reported to vary depending on the IOS.[27,32] Primescan showed the highest trueness and precision among all IOSs for the 4-unit FPDs preparations whereas Emerald showed the lowest trueness and precision for preparations in the present study. However, no statistically

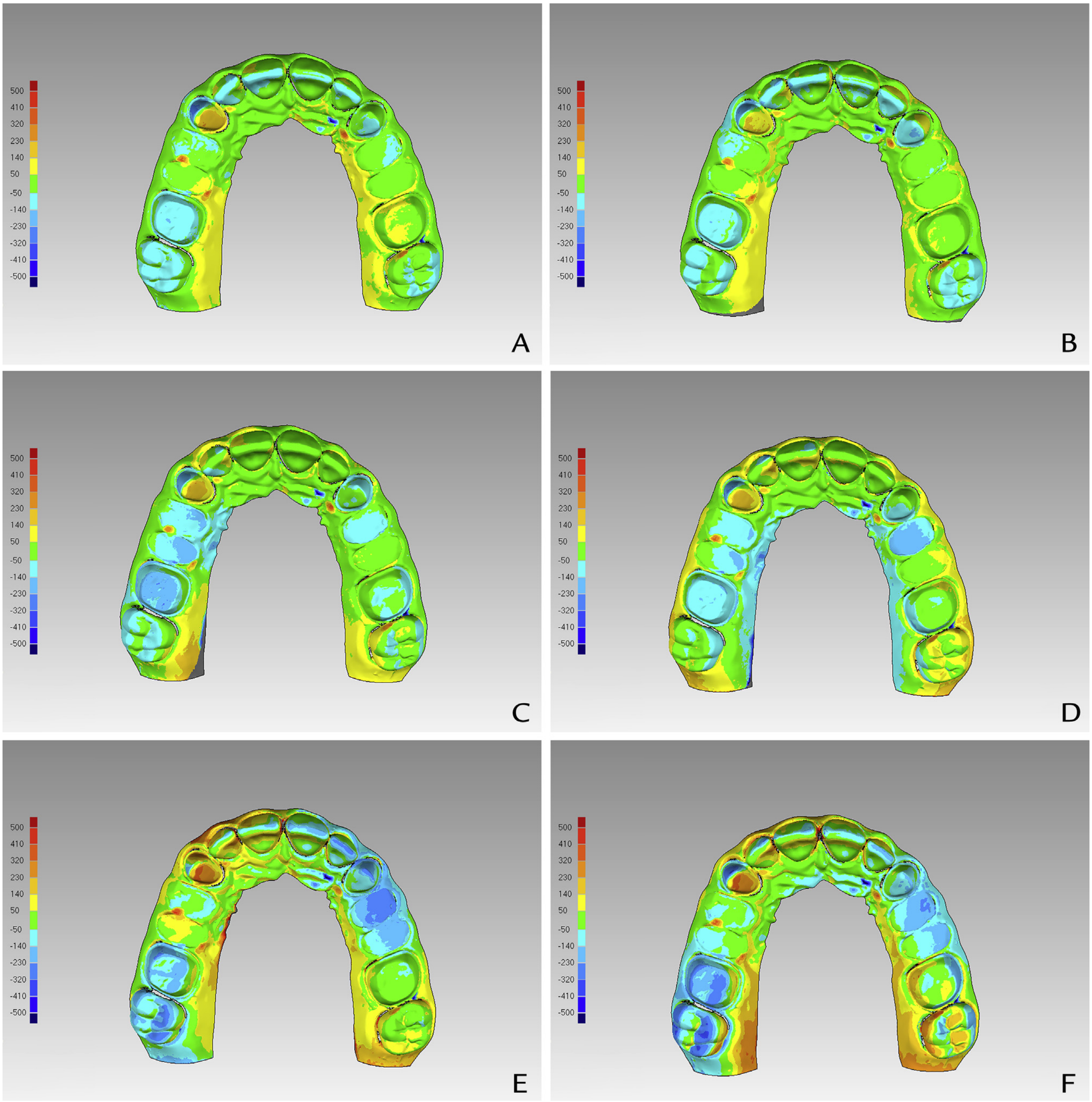

Figure 6. Deviation pattern showing trueness of complete-arch for ScanR and ScanL of each intraoral scanner. Max/min nominal ±50 µm and max/min critical ±500 µm. *Blue* represents negative deviation of reference file, *yellow*, *orange*, and *red* represent positive deviation, and *green* represents deviation within range of nominal values. A, TRIOS ScanR. B, TRIOS ScanL. C, iTero ScanR. D, iTero ScanL. E, Emerald ScanR. F, Emerald ScanL.

significant difference was found between Emerald and Omnicam. Kim et al[33] reported that Omnicam could not scan without an artificial landmark in the long edentulous span between the canine and second molar prepared teeth, because of problems with the stitching. Therefore, the accuracy of the IOSs should also be evaluated in models with a longer edentulous span.

The manufacturer for each scanner specifies a scanning strategy, although for complete-arch scanning, the quadrant where the scanning begins is not specified. If a local error occurs during the scanning, cumulative errors may be seen with the stitching process as the scanning continues toward proximal areas.[18] As differences in accuracy may occur between the regions where the scanning starts and ends, the effect of the scanning sequence on accuracy was evaluated in the present study. Emerald had statistically significant differences for accuracy of the complete-arch based on the scanning sequence (ScanR

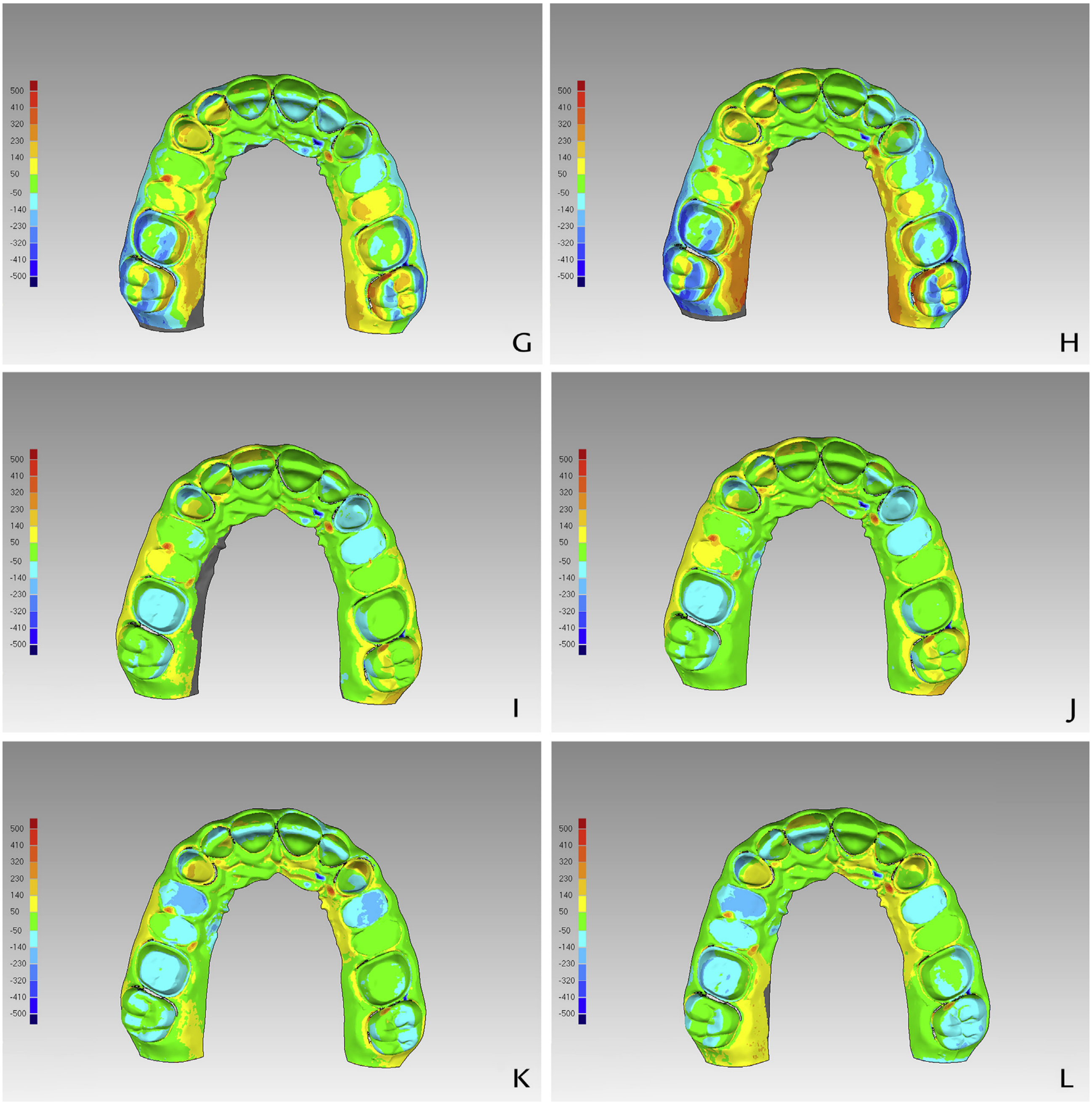

Figure 6. (*Continued*). G, Omnicam ScanR. H, Omnicam ScanL. I, Primescan ScanR. J, Primescan ScanL. K, Virtuo Vivo ScanR. L, Virtuo Vivo ScanL.

and ScanL). For the precision of 4-unit FPDs preparations, there were statistically significant differences between the ScanR and ScanL values of TRIOS, Emerald, and Virtuo Vivo. However, there was no significant difference in the trueness of preparations between the ScanR and ScanL. Anh et al[28] reported that the precision of complete-arch digital scans differed according to the scanning sequence for the iTero, but not for the TRIOS. And for the TRIOS, more errors were seen in the molar region opposite to the starting region. The deviation pattern of TRIOS showed similarity with that of the present study. In contradistinction to this study, iTero had no statistically significant difference for accuracy of the digital scan based on the scanning sequence in the present study. In clinical practice, it may be useful to consider the sequence when scanning the complete-arch with scanners in which the accuracy varies according to the scanning sequence.

Limitations of the present study included its in vitro design that did not simulate intraoral factors such as saliva, patient movement, or different reflective properties of the teeth and gingiva. Further studies that evaluate the accuracy of FPDs and complete-arch digital scans recorded in the oral cavity are required. Information about the effect of partially edentulous span length on accuracy is sparse, and future studies may focus on the effect of the length and location of the partially edentulous span on the accuracy of digital measurements.

CONCLUSIONS

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

1. The accuracy of complete-arch and 4-unit FPDs digital scans differed depending on the IOS and scanning sequence.
2. The TRIOS scanner had the lowest deviation in the trueness of the complete-arch, followed by Primescan, Virtuo Vivo, and iTero but with no significant difference among their trueness values. The precision values of scanners were not statistically different from each other in the complete-arch. In the accuracy (trueness and precision) of the 4-unit FPDs, Primescan presented the best results.
3. The accuracy of the complete-arch was affected by the scanning sequence when using Emerald. Additionally, the precision of the 4-unit FPDs was affected by the scanning sequence when using TRIOS, Emerald, and Virtuo Vivo.

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Burcu Diker: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Project administration. **Önjen Tak:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

https://doi.org/10.1016/j.prosdent.2020.12.007