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RESEARCH AND EDUCATION

Accuracy of 4 digital scanning systems on prepared teeth digitally isolated from a complete dental arch

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ABSTRACT

Statement of problem. The accuracy of digital scanners is acceptable for scanning a complete dental arch. However, whether that accuracy is sufficient for only 1 tooth within the dental scan of a complete dental arch is unclear.

Purpose. The purpose of this in vitro study was to evaluate and compare the accuracy of 4 intraoral scanners on a complete dental arch and on prepared teeth digitally isolated from the digital scan in terms of trueness and precision.

Material and methods. A model of a complete dental arch with tooth preparations was scanned 40 times with each of the 4 digital scanners. Their accuracy was evaluated by using 3-dimensional (3D) software to compare the test models with a highly accurate reference model. The data were digitally processed to isolate the prepared teeth and evaluate them in the same way. The data were statistically analyzed using the Levene test and the Tamhane's T2 test (α=.05).

Results. In scans of a complete dental arch, the True Definition scanner had the best accuracy values, followed by TRIOS, iTero, and Omnicam. For prepared teeth isolated from the dental arch, both True Definition and TRIOS had the best values, followed by iTero and Omnicam.

Conclusions. In both long-span scans of the complete dental arch and isolated prepared teeth, the True Definition scanner had the greatest accuracy, closely followed by TRIOS. (J Prosthet Dent 2019;121:811-20)

The introduction of digital dentistry in the 1980s was a major advance and an important trend in prosthetic dentistry. These systems can capture 3-dimensional (3D) images of tooth preparations from which restorations are directly manufactured with computer-aided design and computer-aided manufacturing (CAD-CAM).[1-3]

A major problem with intraoral scanners is obtaining exact and precise images of extensive areas and thus simplifying the workflow. Not all intraoral scanners are optimized for every clinical situation. However, accuracy studies on intraoral scans in the complete dental arch are scarce,[4,5] and few have measured the accuracy of prepared teeth.[6,7] More studies are needed to ensure the accuracy of digital scanning systems.

The long-term survival of a dental restoration depends on the precision of the fit between the restoration and the abutment. According to the American Dental Association, the clinically accepted fit for an indirect restoration is between 50 and 100 μm, values obtained in a study conducted in 1971.[8] Other studies have suggested an increased discrepancy of 150 μm,[9] and some authors have reported that a fit below 200 μm is associated with long-term clinical survival.[10-15]

Because the precision of the marginal fit includes errors during the fabrication of the definitive restoration, the deviation produced in a digital scan must be below these values. The mean marginal fit of the restoration obtained by intraoral scanning is less than 120 μm, a clinically acceptable value.

According to ISO 5725,[16] possible sources of error from systematic and random geometric defects of the digital processing of data incorporated into digital dentistry that may occur during the digital workflow should be

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Clinical Implications

The accuracy of the digital scanning systems for a complete dental arch was found to be lower than that for a single tooth. To ensure more accurate scans, clinicians should know which digital scanning system works best in each clinical situation.

determined. The size of some of these errors can be controlled by the clinician during the intraoral scanning, design, milling, and cementation of the restoration.[8,13,15,17-21]

The True Definition scanner requires powdering with titanium dioxide to create digitally measurable surfaces. The layer of powder applied increases the thickness of the dental surface by 13 to 85 μm.[22] However, the powdering and the experience of the dentist have not been reported to generate significant accuracy differences.[1,23-25]

Accuracy studies of 1 to 4 restorations have been reported.[21,26-29] A digital scan of the complete dental arch does not enable the clinician to know the accuracy of the prepared tooth. The deviations between the generated cast and the reference model on long-span scans differ significantly from the mean obtained on a single tooth.[30] Therefore, the smaller data sets that result from the small selection of a single tooth may reduce the number of possible errors that could result from the superposition of large data sets because the number of points analyzed by the comparison software is reduced.[31] Therefore, this study analyzed accuracy in both complete-arch scans and each digitally isolated prepared tooth from the digital scanning systems and superimposed them onto the same dental structure of the computer-assisted design (CAD) reference model (CRM).

The definitive fit of the restoration can only be as good as the accuracy of the scan.[32] The accuracy of 4 digital scanning systems for the complete dental arch and for digitally isolated teeth was measured in terms of trueness, which describes the discrepancy between the measurement values of the reference scanner and the study scanners, and precision, which describes the discrepancy between the study scanners.

The purpose of this in vitro study was to evaluate and compare the accuracy of 4 intraoral scanners on a complete dental arch and on prepared teeth digitally isolated from the digital scan, in terms of trueness and precision. The null hypothesis was that no significant difference would be found in the accuracy of the digital scans on a complete dental arch or a single tooth in each digital scanning system.

Figure 1. Master model in methacrylate box to carry out digital scans.

MATERIAL AND METHODS

A maxillary dental arch was fabricated from epoxy resin (Exakto-Form; Bredent), an opaque and dimensionally stable material with good mechanical and chemical resistance. The tested scans were for the complete dental arch (CDA) and a digitally isolated right maxillary second molar onlay preparation (SM) and a fixed dental prosthesis (FDP) with right maxillary first molar (FM) and first premolar (FP) complete crown abutments, both with a supragingival chamfer finish line and a veneer preparation on the right maxillary central incisor (CI). Analogs were inserted with a Straumann tissue level internal connection at the left maxillary FM, left maxillary canine, left maxillary central incisor, and right maxillary canine, and then, a Straumann RN antirotational Core3D scan body was screwed into place (Avinent Implant System). The scans were made with the master model inserted into an opaque black methacrylate box measuring 140 mm wide, 100 mm deep, and 80 mm high with a cutout in the base measuring 80 mm wide by 60 mm deep for coupling of the master model (Fig. 1).

The following digital scanning systems were evaluated: TRIOS (software v1.4.5.3, 3Shape Dental Systems), iTero (software OrthoCAD 5.7.0.301 Cadent LTD), Cerec AC Omnicam (software CEREC SW 4.4.4; Dentsply Sirona), and the True Definition (software v4.2; 3M ESPE Dental Products) (Table 1). The occlusal surfaces were powdered (3M High-Resolution Scanning; 3M ESPE) in the True Definition scans. Forty scans were made with each intraoral scanner, with the master model inside the box. The scan data were subjected to postprocessing (TRIOS, iTero, True Definition) and then exported in standard tessellation language (STL) file format for their subsequent digital processing. Dental Exchange 2016 R3 software was used for the Omnicam files conversion.

Table 1. Digital scanning systems tested

Intraoral Scanner	Company	Scanning Principle	Scan Procedure	Light Source	Imaging Type	Surface Conditioning	In-Office Milling	Output Format
TRIOS	3Shape	Ultrafast Optical Sectioning	Light source provides illumination pattern to cause light oscillation on object. Continuous images to form 3D model	Blue LED light	Video	No	No	Proprietary or STL
iTero	Cadent LTD	Parallel confocal microscopy.	Illuminates surface of object with 3 beams of different colored light (red, green, or blue) which combine to provide white light, 5 scans of prepared area. Shot of single image.	Red Laser	Multiple images	No	Yes	Proprietary or STL
Omnicam	Dentsply Sirona	Active triangulation	Video, continuous images to create a 3D model.	White light	Video	No	Yes	Proprietary
True Definition	3M ESPE	Active wave front sampling	Measuring out-of-plane coordinates of object points by sampling, makes continuous images in various positions.	Pulsating blue light	3D in motion video	Yes	Yes	Proprietary or STL

LED, light-emitting diode; STL, standard tessellation language.

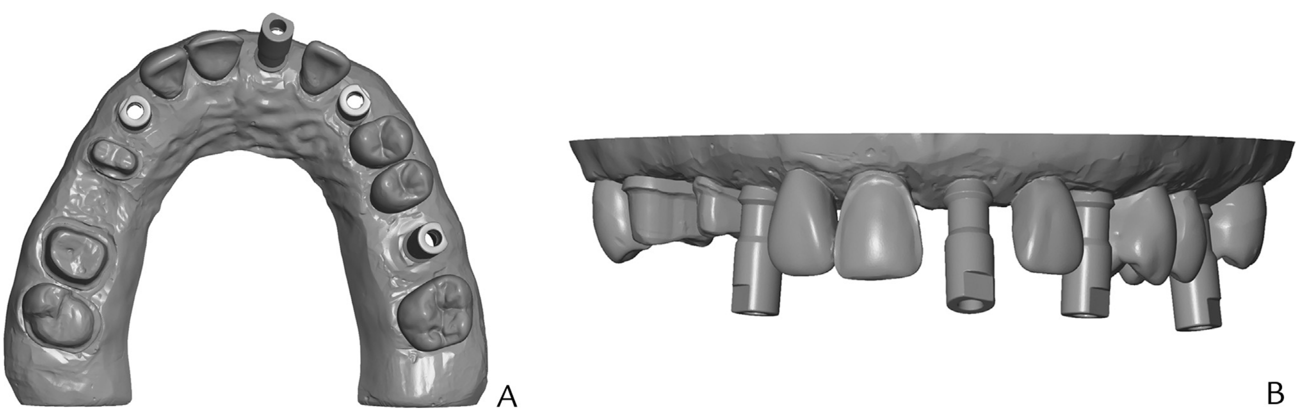

Figure 2. CRM scanned with ATOS II Triple Scan industrial scanner: A, Occlusal view. B, Frontal view. CRM, CAD reference model.

To compare these STL files dimensionally with a master model, a CRM[31,33] was made with ATOS II Triple Scan (GOM Technologies; Metronic). An industrial structured blue light 3D scanner was shown to be accurate to 3 μm, with a demonstrated repeatability of 2 μm used for the jaw-sized scans (Fig. 2).[24,34,35]

Software (Geomagic Control 2013; 3D SYSTEMS)[10,31,34,36,37] was used to analyze discrepancies and the digital processing of the files. All scanning artifacts attributing to soft tissue were removed, and the digital isolation of the tooth preparation was made with the "cut with planes" tool (Fig. 3).

Each STL file was aligned with the CRM using a best-fit alignment algorithm. The command used 300 randomly selected points to obtain an initial orientation. After the first pass, the sample size was automatically increased to 1500 points, and fine adjustment only was activated to achieve final alignment to the specified 1-μm tolerance. The files were then compared by superimposing them on the reference model to calculate the total number of 3D deviations (X, Y, and Z) among the data sets obtained from the reference scanner for both the complete arch and the tooth preparations. This software provided discrepancies in micrometers and color-coded deviation map of each match (Figs. 4-9).

The total mean discrepancy calculated from the average of the mean internal and external discrepancies corresponds to trueness, and the standard deviation that indicates the dispersion of the points of the study scanner around the mean of the CRM corresponds to precision. The lower the standard deviation, the greater the precision.

The level of Type I error was calibrated at α=.05. The Levene test was used to assess the equality of variances for all test groups (α=.05). A nonparametric Kruskal-Wallis test followed by the Tamhane T2 test for multiple post hoc comparisons were used to evaluate the data.

RESULTS

The descriptive results of the data from the digital scanning systems tested are presented in terms of mean, standard deviation, minimum, and maximum in

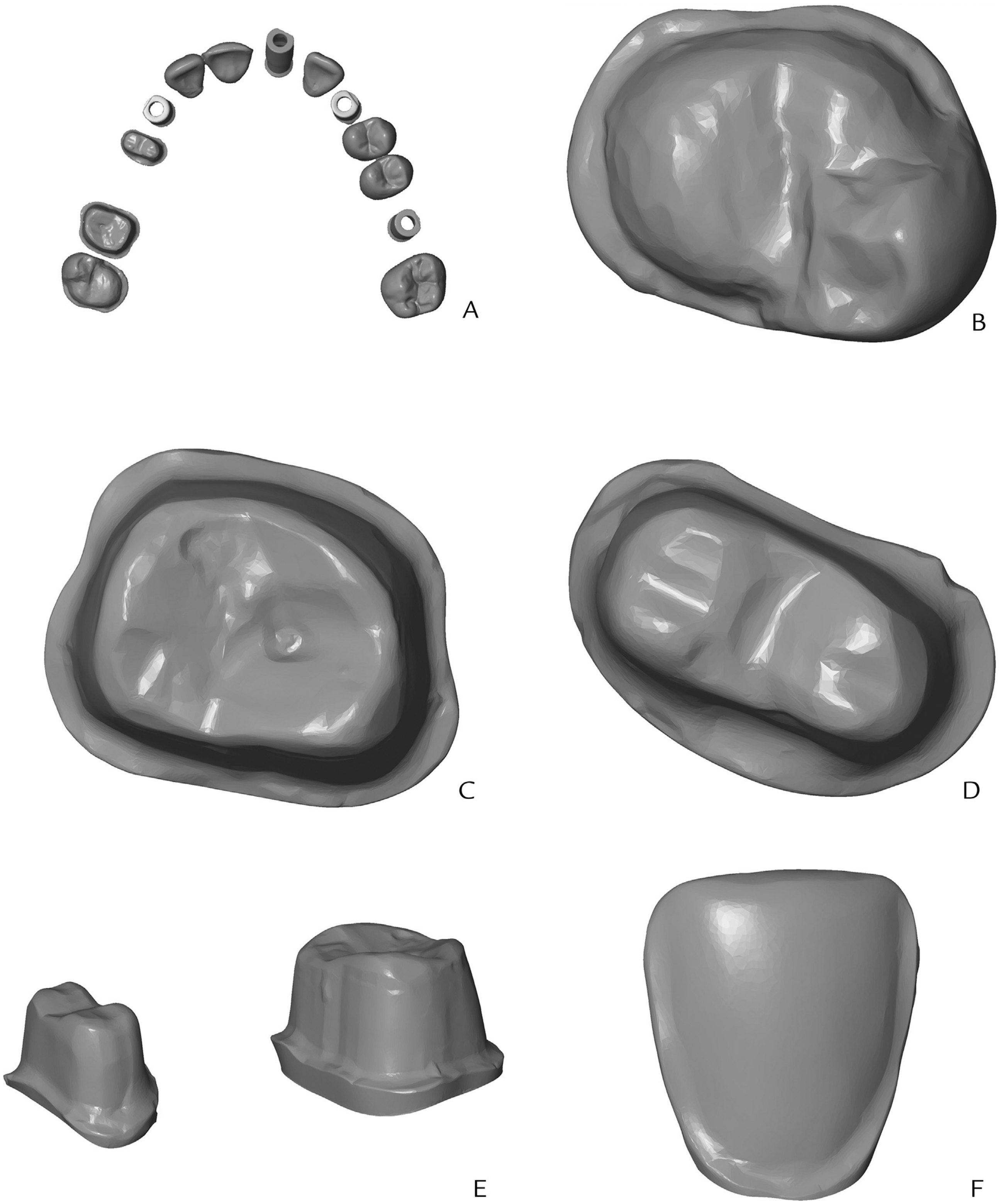

Figure 3. Scans evaluated. CDA, complete dental arch; CI, veneer preparation on right maxillary central incisor; FDP, fixed dental prosthesis; FM right maxillary first molar complete crown abutment; FP first premolar complete crown abutment; SM, right maxillary second molar onlay preparation.

Tables 2 and 3. The Levene test did not indicate any equality of variances ($P<.05$), the nonparametric Kruskal-Wallis test was used to analyze whether there were differences among scanners ($P<.05$), and post hoc comparisons were performed with the Tamhane T2 test for unequal variance.

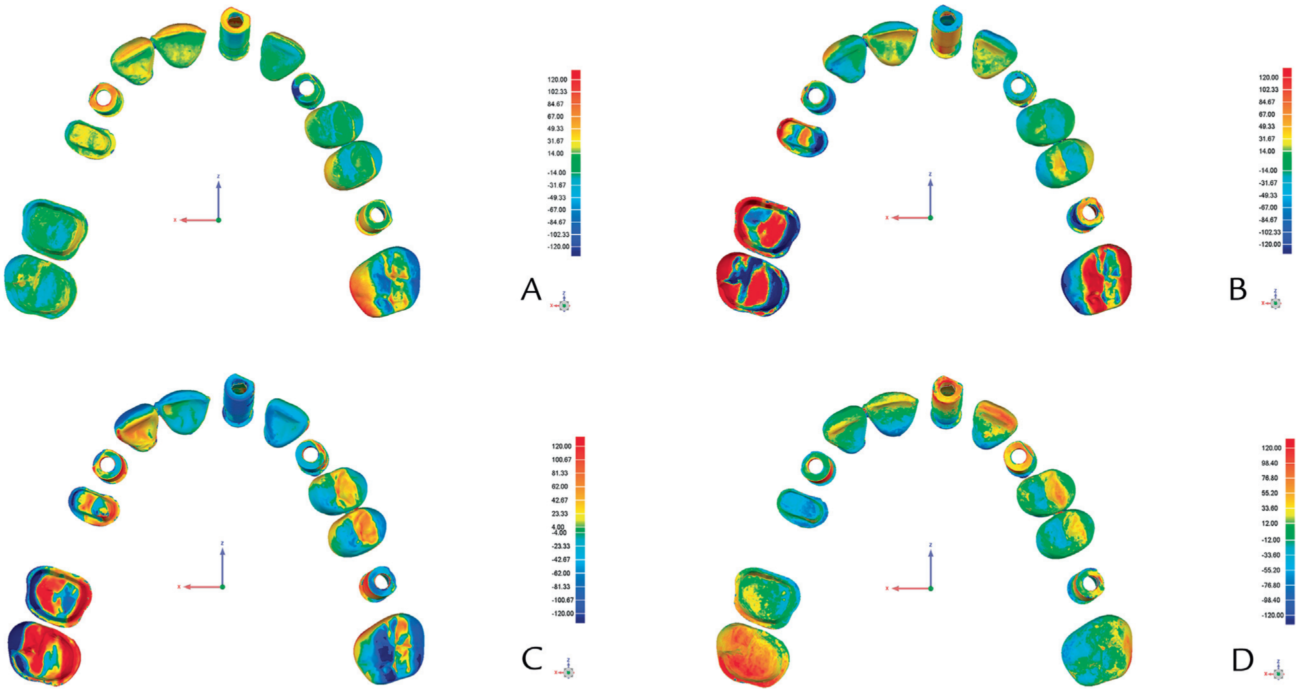

Figure 4. Color-coded map of deviations between CRM and test models in arrangement CDA (Geomagic Control software). Color indicates from -120 µm (*blue*) to + 120 µm (*red*), representing contraction (*blue*) and expansion (*red*). A, TRIOS. B, iTero. C, Omnicam. D, True Definition. CRM, CAD reference model.

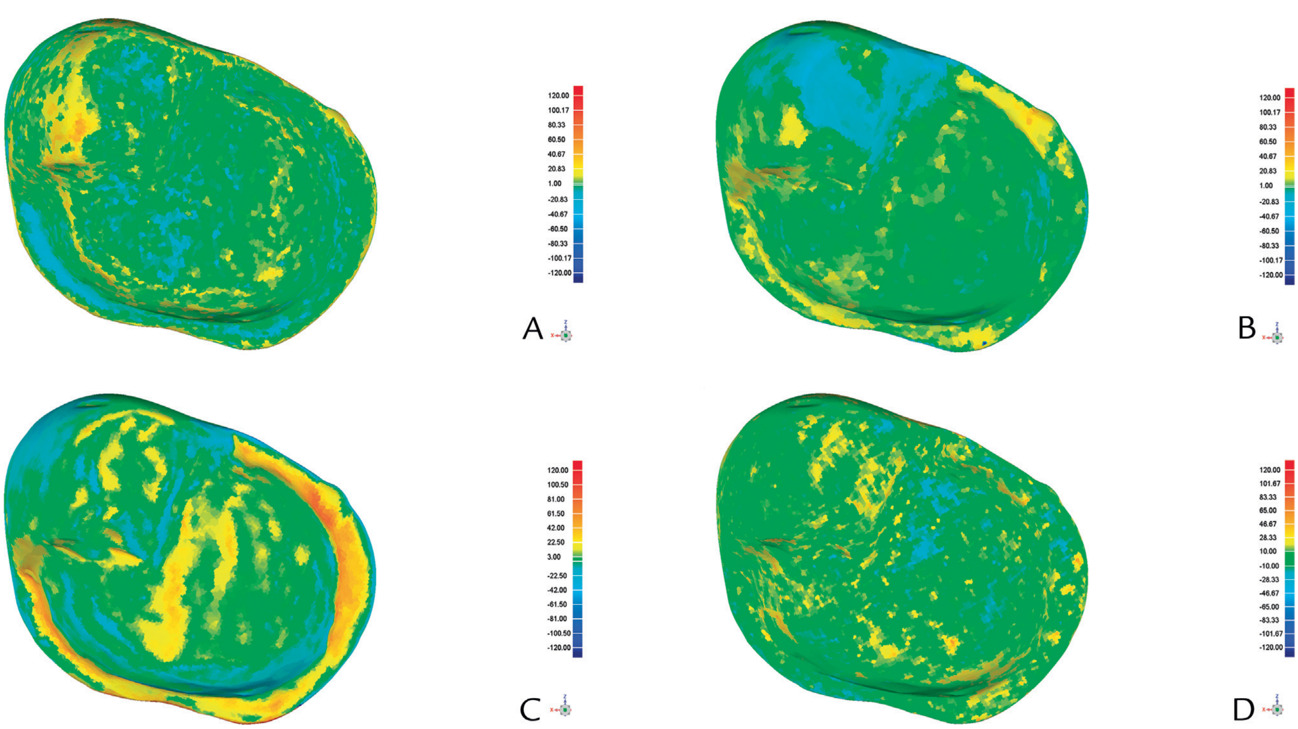

Figure 5. Color-coded map of deviations between CRM and test models in arrangement SM (Geomagic Control software). Color indicates from -120 µm (*blue*) to + 120 µm (*red*), representing contraction (*blue*) and expansion (*red*). A, TRIOS. B, iTero. C, Omnicam. D, True Definition. CRM, CAD reference model.

In the CDA scans, the True Definition had the best trueness (32.1 ±13.7 µm) and precision (98.8 ±40.4 µm), followed by TRIOS, iTero, and Omnicam with significantly the lowest accuracy in CDA scans. In the SM and FM scans, the TRIOS had the best accuracy. In the FP scans, the TRIOS had the best trueness, and the True

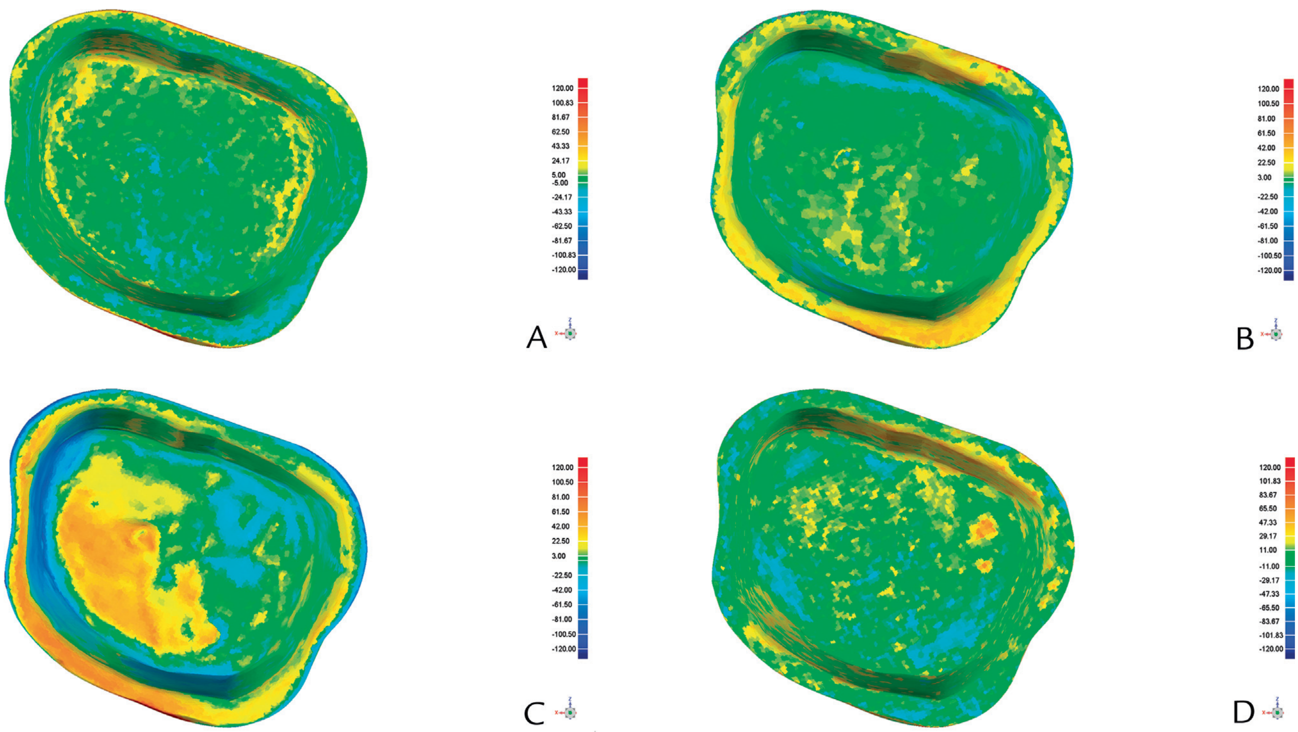

Figure 6. Color-coded map of deviations between CRM and test models in arrangement FM (Geomagic Control software). Color indicates from -120 µm (*blue*) to + 120 µm (*red*), representing contraction (*blue*) and expansion (*red*). A, TRIOS. B, iTero. C, Omnicam. D, True Definition. CRM, CAD reference model.

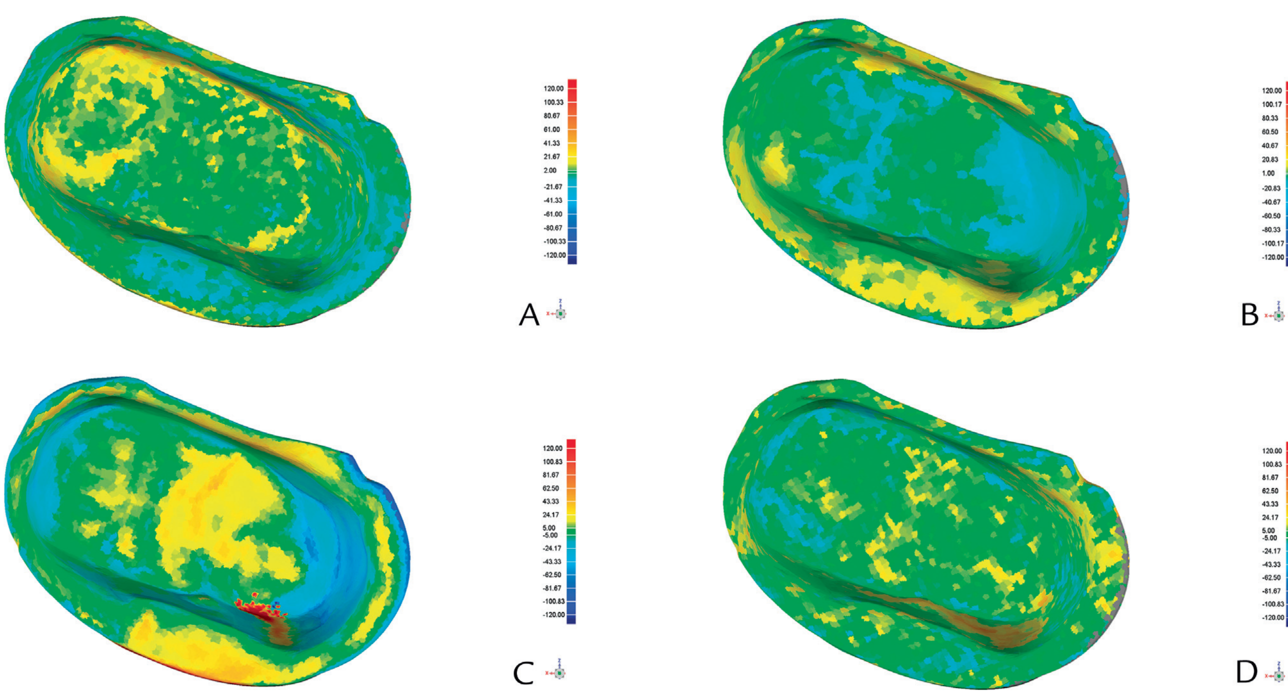

Figure 7. Color-coded map of deviations between CRM and test models in arrangement FP (Geomagic Control software). Color indicates from -120 µm (*blue*) to + 120 µm (*red*), representing contraction (*blue*) and expansion (*red*). A, TRIOS. B, iTero. C, Omnicam. D, True Definition. CRM, CAD reference model.

definition had the best precision but with no significant difference (P>.05) between them. In the FDP and the CI scans, the True Definition had the best accuracy, but in the FDP scans, the TRIOS did not differ significantly (P>.05) and reached the same high level of accuracy as the True Definition. Accuracy in terms of trueness and

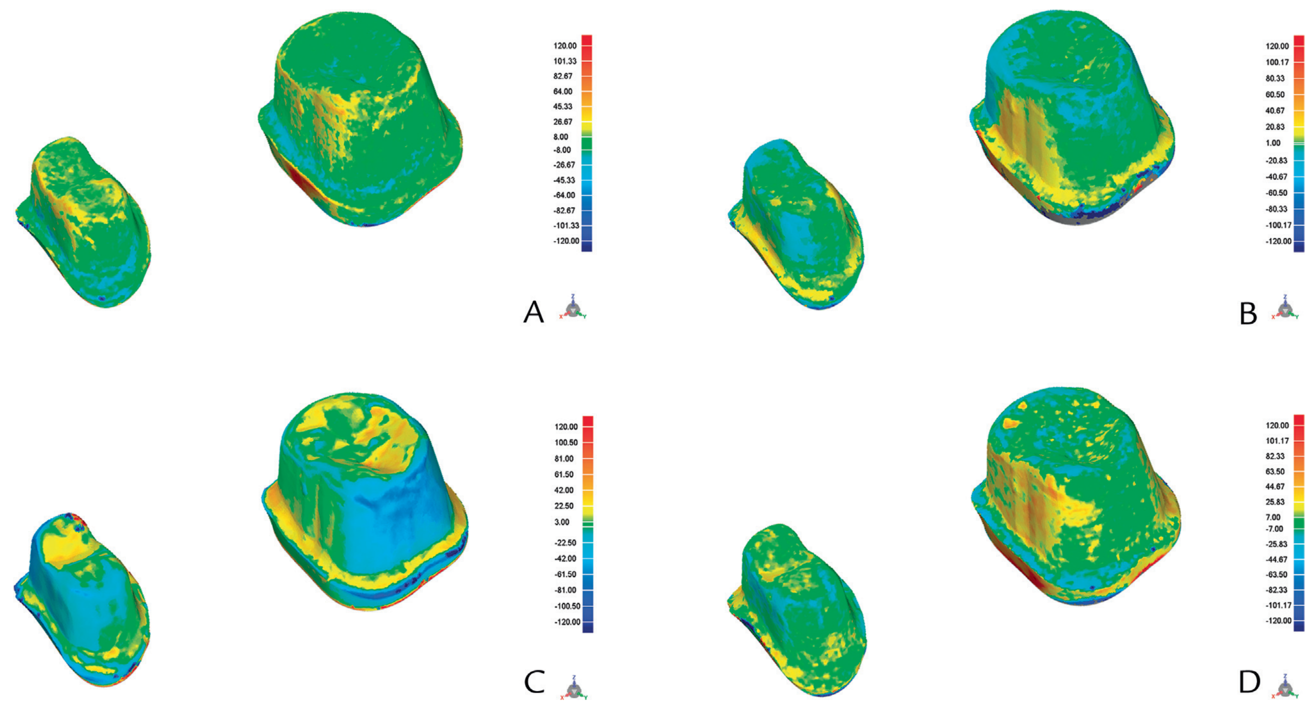

Figure 8. Color-coded map of deviations between CRM and test models in arrangement FDP (Geomagic Control software). Color indicates from -120 µm (*blue*) to + 120 µm (*red*), representing contraction (*blue*) and expansion (*red*). A, TRIOS. B, iTero. C, Omnicam. D, True Definition. CRM, CAD reference model.

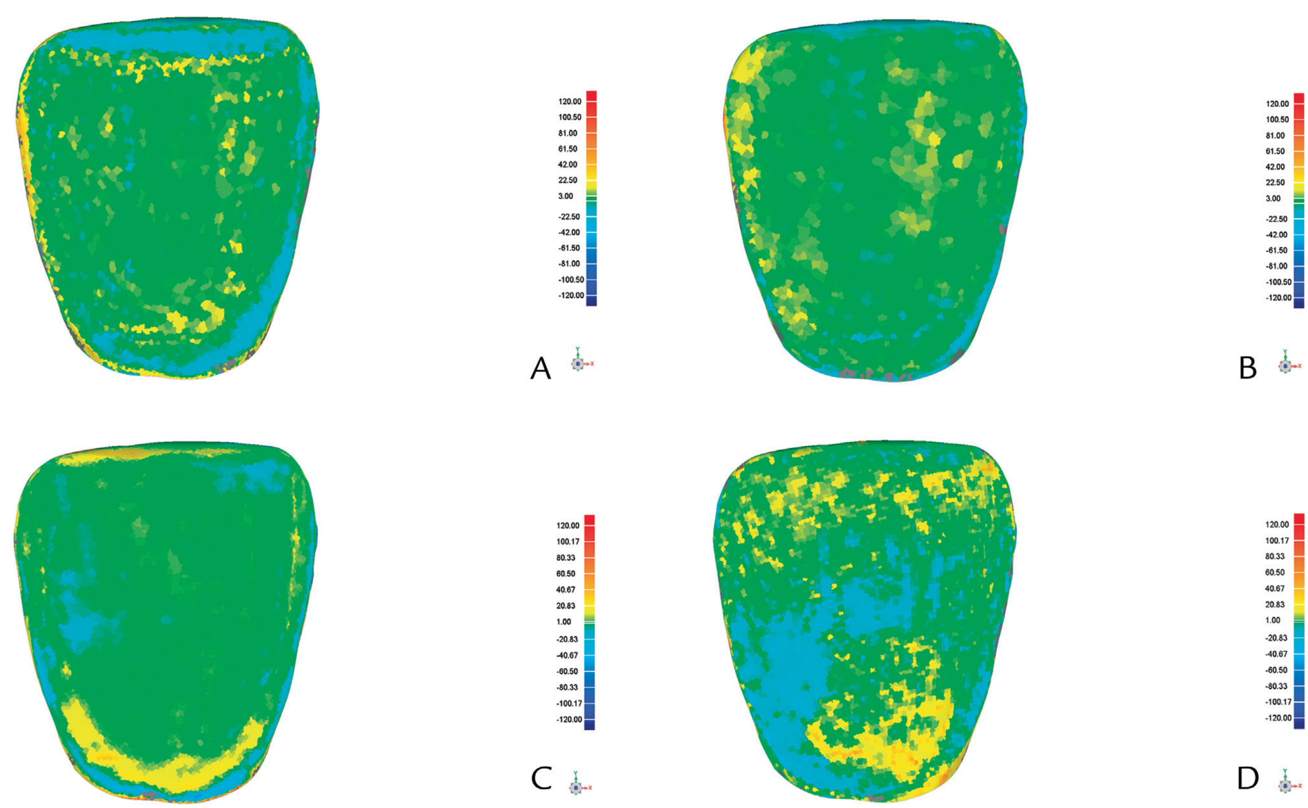

Figure 9. Color-coded map of deviations between CRM and test models in arrangement CI (Geomagic Control software). Color indicates from -120 µm (*blue*) to + 120 µm (*red*), representing contraction (*blue*) and expansion (*red*). A, TRIOS. B, iTero. C, Omnicam. D, True Definition. CRM, CAD reference model.

Table 2. Unprocessed trueness data (μm) used for statistical analysis of digital scanning systems tested on complete dental arch and digitally isolated tooth preparations

Digital Scanning Systems	Arrangement	Mean ±SD	Minimum	Maximum
TRIOS	CDA	55.3 ±8.7	10.0	70.1
	SM	8.6 ±0.8	7.6	11.1
	FM	9.7 ±1.1	4.4	12.3
	FP	12.0 ±1.1	9.8	14.7
	FDP	23.5 ±1.6	20.6	27.3
	CI	11.1 ±1.5	8.7	15.1
iTero	CDA	94.5 ±20.7	64.6	157.1
	SM	11.9 ±1.5	9.4	15.1
	FM	11.2 ±1.6	8.4	15.5
	FP	14.5 ±4.1	6.7	34.3
	FDP	31.7 ±4.5	26.3	54.8
	CI	12.7 ±4.8	8.7	37.9
Omnicam	CDA	98.3 ±14.0	74.7	127.7
	SM	22.9 ±5.2	14.4	34.7
	FM	20.6 ±3.0	16.4	27.9
	FP	18.4 ±4.0	4.7	30.1
	FDP	36.4 ±6.0	8.9	43.2
	CI	13.0 ±3.0	8.8	21.2
True Definition	CDA	32.1 ±13.7	19.1	69.1
	SM	11.9 ±1.9	8.6	19.4
	FM	12.7 ±2.3	9.1	18.0
	FP	12.1 ±2.5	8.7	19.0
	FDP	23.2 ±2.7	18.2	31.3
	CI	9.4 ±3.4	6.8	26.8

CDA, complete dental arch; CI, veneer preparation on right maxillary central incisor; FDP, fixed dental prosthesis; FM, right maxillary first molar complete crown abutment; FP, first premolar complete crown abutment; SM, right maxillary second molar onlay preparation.

Table 3. Unprocessed precision data (μm) used for statistical analysis of digital scanning systems tested on complete dental arch and digitally isolated tooth preparations

Digital Scanning Systems	Arrangement	Mean ±SD	Minimum	Maximum
TRIOS	CDA	194.5 ±11.7	167.2	218.6
	SM	14.0 ±3.1	11.2	25.0
	FM	15.1 ±2.2	5.3	20.4
	FP	19.2 ±2.4	14.4	24.3
	FDP	63.7 ±7.0	53.3	80.2
	CI	16.2 ±2.3	12.6	21.1
iTero	CDA	246.8 ±45.0	157.1	391.7
	SM	21.3 ±3.4	16.2	29.9
	FM	18.4 ±3.5	12.7	25.9
	FP	26.8 ±7.7	16.6	63.1
	FDP	85.9 ±13.1	73.0	151.2
	CI	25.2 ±12.9	12.9	78.3
Omnicam	CDA	261.8 ±32.6	191.2	327.4
	SM	43.4 ±12.8	10.1	71.0
	FM	33.2 ±8.4	19.6	57.6
	FP	31.8 ±6.7	22.6	54.4
	FDP	93.0 ±8.0	78.6	114.7
	CI	23.7 ±8.3	13.5	44.4
True Definition	CDA	98.8 ±40.4	56.6	209.9
	SM	18.4 ±3.3	10.1	29.6
	FM	18.6 ±2.7	12.8	24.9
	FP	19.1 ±4.0	14.3	33.3
	FDP	61.1 ±7.6	47.4	90.4
	CI	13.7 ±6.0	9.9	43.9

CDA, complete dental arch; CI, veneer preparation on right maxillary central incisor; FDP, fixed dental prosthesis; FM, right maxillary first molar complete crown abutment; FP, first premolar complete crown abutment; SM, right maxillary second molar onlay preparation.

precision and the significant post hoc comparisons of the digital scanning systems tested are presented in Table 4.

DISCUSSION

The null hypothesis that no significant difference would be found in the accuracy of the digital scans on a CDA and on a single tooth in each digital scanning system was rejected. Additionally, differences regarding trueness and precision were found among the 4 investigated digital scanning systems for CDA and single tooth scans.

The study focused on analyzing the CDA and digitally isolated tooth preparations in the first step of the manufacturing process to establish their accuracy, other errors in the digital workflow, for example, the sintering parameters of the restoration material, the individual skills and experience of the clinician, and whether the scanning strategy increases the discrepancy. This study used a reference data set generated from an industrial scanner and a best-fit alignment for the evaluation and interpretation of spatial divergences between data sets.

This study calculated the trueness by the mean of the positive (expansion) and negative (contraction) deviations of the data set generated by the superimposition of the CRM and the experimental scans disregarding the algebraic sign. The standard deviation of this superimposition was used to calculate the precision; therefore, the overall trueness (mean value) and the overall precision (standard deviation) were dependent on each other. The test data sets were each superimposed with the reference data set to obtain simultaneous values for trueness and precision from one single alignment process. This helped better estimate the overall performance of the single scan.[31] Digitally isolated tooth preparations may have reduced the number of possible errors that could result from the superposition of large data sets of CDA scans. All the digital scanning systems tested had satisfactory accuracy for single teeth; however, in CDA scans, only the True Definition showed accuracy that was within the clinically accepted limits (120 μm).

The master model was placed inside a black methacrylate box to maintain a controlled environment, avoid light reflections, and simulate the oral cavity. To minimize the risk of interoperator influence, 1 experienced investigator (P.M-S.) performed the scans. Despite modeling several variables, this study did not replicate the actual clinical situation and had limitations. Further

Table 4. Accuracy (µm) in terms of trueness and precision and significant post hoc comparisons of digital scanning systems tested on complete dental arch and digitally isolated tooth preparations

	Arrangement											
	CDA		SM		FM		FP		FDP		CI	
Digital Scanning Systems	Trueness	Precision	Trueness	Precision	Trueness	Precision	Trueness	Precision	Trueness	Precision	Trueness	Precision
TRIOS	55.3[b]	194.5[b]	8.6[a]	14.0[a]	9.7[a]	15.1[a]	12.0	19.2	23.5	63.7	11.1[b]	16.2[b]
iTero	94.5[b]	246.8[b]	11.9[b]	21.3[b]	11.2[b]	18.4[b]	14.5[b]	26.8[b]	31.7[b]	85.9[b]	12.7[b]	25.2[b]
Omnicam	98.3[b]	261.8[b]	22.9[b]	43.4[b]	20.6[b]	33.2[b]	18.4[b]	31.8[b]	36.4[b]	93.0[b]	13.0[b]	23.7[b]
True Definition	32.1[a]	98.8[a]	11.9[b]	18.4[b]	12.7[b]	18.6[b]	12.1	19.1[a]	23.2[a]	61.1[a]	9.4[a]	13.7[a]

CDA, complete dental arch; CI, veneer preparation on right maxillary central incisor; FDP, fixed dental prosthesis; FM, right maxillary first molar complete crown abutment; FP, first premolar complete crown abutment; SM, right maxillary second molar onlay preparation. [a]Scanner with best accuracy within each preparation. [b]Scanner with statistically significant differences within each preparation according to Tamhane T2 test (α=.05).

studies should be carried out to determine whether the saliva or soft tissue present clinically will affect the accuracy of the scans.

The True Definition had the best accuracy for CDA scans and was found to be significantly different (P<.05) from the other scanners. The Omnicam scanner had the higher deviations in CDA scans, which can be explained by the architecture of the digital files. All scanners (except the Omnicam) evaluated in this study had an open architecture, which meant that the acquired digital files could be transferred with an open connection directly to the analysis software. This connection avoided the error in converting to the STL file format, estimated at up to 20 to 40 µm[38,39] and explained the values of the Omnicam scanner in the present study. Recently, the Omnicam scanner has enabled direct export to STL, which might improve its accuracy. Although a direct comparison with previous studies is difficult because of variations in study design, the results of this study are consistent with reported values for the accuracy of intraoral impressions systems.[4,6,34,36,40-42] The True Definition scanner has been reported to be the most precise scanner for CDA scans, and its error values did not exceed 59 µm; in contrast, the Omnicam scanner reached values of 133 µm and had the same problem with the conversion of the digital files. Recent improvements in the devices may be the primary reason for the more accurate data sets found in the present study.

Few studies have evaluated the accuracy of digital scanning systems using the scan technology of the intraoral scanner as a variable.[20,37] The iTero had a larger standard deviation than the other 3 scanners with 20.7 µm in trueness and 45.0 µm in precision. This may be because the video scanning method provides better scan technology than the single-image capture.[20] However, the Omnicam scanner, having a video scanning method system, had the lowest accuracy for CDA scans. Recent studies found that the algorithm of the software processes the scans captured by the scanner, and to reduce the file size, reduces the total number of the point clouds.[31] The Omnicam had the best resolution with 79 points/mm^2 in CDA scans, and a relationship between this resolution and its precision has been reported.[38] This algorithm could affect its accuracy by reducing the total number of triangles that can place a higher triangle density in areas of curvature and a lower density in flatter areas. The accuracy of any scanner is a combination of the quality of the point cloud generated by the hardware and of the software algorithms.[43]

The TRIOS had the best accuracy for the SM, FM, and FP scans, while the True Definition had the best precision for the FP scans. These findings are consistent with those of a recent study[37] that reported the TRIOS to be the most precise scanner for complete crown abutments with an error below 6.9 µm for trueness and 4.5 µm for precision. Better accuracy was obtained by reducing the number of compared points during the 3D comparison.

The True Definition scanner had the best accuracy for FDP and CI scans. Guth at al[31] found the True Definition to be the most accurate scanner, despite testing with a reflective titanium model. The titanium reflective surface was coated with powder. The True Definition scanner has been reported to have the highest accuracy for FDP scans,[1,23-25] findings consistent with those of the present study, although powdering reduced the accuracy. Despite the central incisor location and the use of a short span, the mean deviations were similar to those found in distal and long-span scans.

Future studies should investigate the location of the tooth scanned, and a standardized method should be developed to evaluate and compare multiple digital scanning systems and evaluate the performance under in vivo conditions. The results of this article should be interpreted with caution, and conclusions can only be drawn for the scanning scenario used.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The accuracy of digital scanning systems differed according to the span scan.
2. In terms of trueness and precision, the True Definition scanner had the best accuracy for long-span scans of the CDA, followed by the TRIOS scanner.

3. In terms of trueness and precision, the True Definition and the TRIOS scanner had the best accuracy for a single tooth scan.
4. All values of accuracy were in a clinically acceptable range.

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