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RESEARCH AND EDUCATION

Accuracy of three digital scanning methods for complete-arch tooth preparation: An in vitro comparison

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ABSTRACT

Statement of problem. The accuracy of digital scanning for complete dental arch and implant-supported complete-arch restorations has been reported. However, research addressing the accuracy of digital scanning methods for complete-arch tooth preparation is lacking.

Purpose. The purpose of this in vitro study was to compare the accuracy of intraoral scanning, impression scanning, and cast scanning for complete-arch preparation.

Material and methods. Maxillary and mandibular jaw typodonts with 28 teeth prepared for complete crowns were used as reference casts and digitized as reference data sets with a desktop scanner. Three digital scanning methods were applied. First, the reference casts were each scanned 10 times with an intraoral scanner to generate the intraoral scanning group data sets. Second, the reference casts were each captured 10 times by using polyvinyl siloxane impression material, and the impressions were scanned with a desktop scanner to generate the impression scanning group data sets. Third, the impressions obtained in the impression scanning group were used to make gypsum casts which were then digitized with a desktop scanner to generate the cast scanning group data sets. Accuracy was determined by trueness and precision. Three-dimensional deviations of the prepared arches and anterior and posterior segments were measured from root mean square values and depicted on color-difference maps. Differences among test groups were analyzed by using a 1-way ANOVA and the post hoc Bonferroni test for normally distributed data or the Kruskal-Wallis test with Bonferroni correction for non-normally distributed data (α=.05).

Results. The trueness of the maxillary arch was significantly higher in the impression scanning group than in the cast scanning and intraoral scanning groups (P<.05), but no significant differences were found among the 3 groups of the mandibular arch (P>.05). The precision of both arches was significantly higher in the impression scanning and intraoral scanning groups than in the cast scanning group (P<.05). Color maps showed horizontal symmetrical displacement in the intraoral scanning group relative to the reference data sets and within-group unilateral distal-end distortion. Irregular arch deformations were noted in the impression scanning group, and buccal and occlusal expansion occurred in the anterior-posterior direction in the cast scanning group. Pooled data for anterior teeth indicated that the trueness was lowest in the intraoral scanning group; however, that for the maxillary anterior teeth did not differ, while that for the mandibular anterior teeth differed significantly among groups (P<.05). For the posterior teeth, deviation was the lowest in the impression scanning group, and significant differences were noted in both arches among the 3 groups (P<.05).

Conclusions. Of the methods tested, impression scanning was the most accurate for the creation of a digital cast of a complete prepared arch. (J Prosthet Dent 2022;128:1001-8)

Digital workflow and computer-aided design and computer-aided manufacturing (CAD-CAM) have become integral to prosthodontics. With an increasing number of imaging devices enabling digital data acquisition intraorally and from impressions and casts extraorally, digitized dental casts have become a major trend in the workflow.[1,2] Currently, direct intraoral scanning (IOS) with an intraoral scanner and indirect

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Clinical Implications

In the digital workflow for occlusal rehabilitation of the complete dentition, cast accuracy is essential. Extraoral impression scanning of complete-arch tooth preparation with a desktop laboratory scanner was more accurate than intraoral scanning or cast scanning.

extraoral scanning (EOS) of conventional impressions or gypsum casts with a desktop scanner are the 2 major techniques used to generate digital 3-dimensional (3D) casts.[3-5] These methods are indicated for 1- to 5-unit crowns or fixed partial dentures (FPDs), complete-arch prostheses, removable prostheses, and extensive implant-supported prostheses.[6-9]

Traditionally, definitive casts are fabricated from gypsum poured into elastomeric impressions of prepared teeth. However, the resultant casts have dimensions that are larger than the actual teeth.[10,11] EOS of the impression itself may avoid the time-consuming fabrication of casts or sectioned casts, eliminating laboratory steps and additional sources of error.[12] Furthermore, IOS circumvents the need to make an impression and create a gypsum cast.

A fully digital workflow is contingent on an accurate digital cast of the complete arch, particularly in complex situations, such as complete-arch rehabilitation. The utility of IOS and EOS for this purpose remains undetermined.[13] Studies have evaluated the accuracy of digital casts generated from direct and indirect digitization of the complete arch.[14-17] However, the studies have been contradictory because of confounding factors such as diverse scanning systems,[18] methodologies,[19] scanning strategies,[20] and data interpretation methods.[21] Previous studies have been predominantly conducted in vitro on completely dentate models or complete arches with 1 to 5 prepared teeth,[22] and deviations between the generated cast and reference cast on long span scans have been reported to differ significantly from the data obtained on a single tooth or a quadrant.[23] Studies regarding the accuracy of digitization methods for complete-arch preparation are sparse.[24,25] For prepared teeth, the curvatures and undercuts of the natural anatomy of the teeth are eliminated, making data acquisition using IOS and EOS systems straightforward.[26,27] However, it is unclear how this may affect the accuracy of different digital scanning methods. It is essential to determine the accuracy of this initial step in the transfer of the complete prepared arch to a digital cast.

This in vitro study aimed to evaluate and compare the accuracy of 3 digital scanning methods for the maxillary and mandibular complete-arch preparation in terms of trueness and precision. The null hypothesis was that the accuracy would not significantly differ among the 3 methods for recording prepared maxillary and mandibular complete arches, for both the anterior and posterior segments.

MATERIAL AND METHODS

Maxillary and mandibular jaw typodonts (Basic study models; KaVo Dental) with an anatomic dentition (except for the third molars) were used. The remaining teeth were bonded in fixed positions to avoid any movement and prepared manually for ceramic crowns[28] with diamond rotary instruments (Dia-Burs; Mani) under a dental microscope (EyeZoom; Orascoptic) (Fig. 1). Thereafter, the typodonts were used as reference casts and were digitized with a laboratory scanner (D2000; 3Shape A/S) adjusted for high-resolution scanning (5 μm). Reliability was determined by repeated scanning. Each arch was digitized 5 times to create virtual reference cast data sets (group REF, n=5/arch).

The sample size of 3 digital scanning methods (n=10) was based on a large effect size, Type I error at α=.05 and Type II error at β=.80. Direct scans of the reference casts were acquired with the IOS device (TRIOS 3 color; 3Shape A/S) with specific high-resolution scanning mode and complete-arch scanning sequence to generate the IOS group data sets (n=10/arch).[23,29,30] Impressions of the reference casts were acquired with a polyvinyl siloxane material (Honigum-Light and Honigum-Heavy; DMG) and the 2-step technique at room temperature of 20 ±2 °C and a relative humidity of 40% ±3%. Excess material was trimmed with a scalpel to expose the margins of the preparations. The impressions were scanned by using a desktop scanner (D2000; 3Shape A/S) to generate the impression scanning (IS) group data sets (n=10/arch). Type IV dental stone (Royal Rock; Pemaco) was vacuum mixed (Retomix Mini; Reitel) for 1 minute and poured into the impressions obtained in the IS group after 8 hours of storage. The casts were stored for 24 hours and then scanned with the desktop scanner (D2000; 3Shape A/S) to generate the cast scanning (CS) group data sets (n=10/arch).

A total of 60 test data sets and 10 reference data sets were saved as standard tessellation language (STL) files and imported into a 3D scanning software program (Geomagic studio 2015; 3D systems). Reference casts were first n-point aligned and then finely registered with one other by using the iterative closest point algorithm. The prepared teeth were isolated from the reference cast by curves along the marginal line and designated as the underlying reference standard data set, and the test data sets were applied to the reference for geometric alignment. Thereafter, the "trim with curve" order was applied to test data sets such that all prepared teeth were

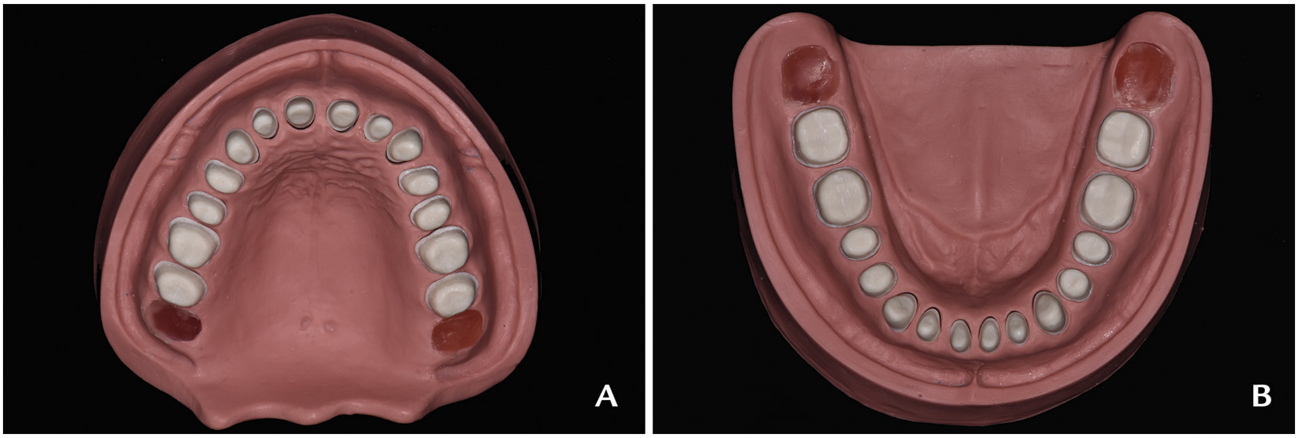

Figure 1. Preparation design of teeth on maxillary and mandibular typodonts. A, Maxillary reference cast. B, Mandibular reference cast.

Table 1. Mean root mean squared trueness values (μm) of 3 digital scanning methods tested on complete-arch tooth preparation

	Intraoral Scanning		Impression Scanning		Cast Scanning		Statistics	
Arch	Trueness	95% CI	Trueness	95% CI	Trueness	95% CI	*P*	*F* Value
Maxillary arch	52.6 ±7.6[b]	(47.1-58.1)	38.7 ±4.9[a]	(35.2-42.2)	48.8 ±5.5[b]	(44.9-52.8)	<.001	13.693
Mandibular arch	45.4 ±10.3[b]	(38.1-52.8)	38.9 ±8.3[b]	(33.0-44.8)	43.7 ±3.5[b]	(41.0-46.4)	.180	1.827

CI, confidence interval. Different letters indicate statistically significant differences (*P*<.05).

Table 2. Median root mean squared precision values (μm) of 3 digital scanning methods tested on complete-arch tooth preparation

	Intraoral Scanning		Impression Scanning		Cast Scanning		Statistics	
Arch	Precision	95% CI	Precision	95% CI	Precision	95% CI	*P*	*F* Value
Maxillary arch	30.4 (20.1)[a]	(30.1-38.1)	30.3 (14.8)[a]	(28.3-34.9)	40.6 (14.1)[b]	(38.9-43.6)	<.001	24.865
Mandibular arch	27.1 (21.7)[a]	(27.5-38.5)	30.3 (14.8)[a]	(28.3-34.9)	40.7 (13.3)[b]	(37.2-42.5)	<.001	20.276

CI, confidence interval. Different letters indicate statistically significant differences (*P*<.05).

isolated for accuracy comparison. The prepared teeth were cut to either the anterior or posterior segment for respective accuracy analysis. The 3D accuracy was measured in terms of trueness, which describes the discrepancy between the measurement values of the reference and test casts, and precision, which describes the discrepancy among the test casts.[31] The reference data sets were superimposed to validate the manufacturer's data of the reference scanner. Trueness was calculated by overlapping test data with the reference data (n=10), and precision was calculated by overlapping test data within each group (n=45). Paired data sets were imported into a metrology software program (Geomagic Control X64; 3D systems) for 3D comparison. Root mean squared values were used for quantitative analysis. Color maps were generated for qualitative representation with an overall range of ±120 μm and a tolerance range (green) of ±40 μm.

A statistical software program (IBM SPSS Statistics, v24.0; IBM Corp) was used for statistical analyses. Normality of data distribution was tested using the Shapiro-Wilk test. Descriptive statistics, mean ±standard deviation or median and interquartile range, and 95% confidence intervals were calculated for all paired groups. Differences among test groups were analyzed by using a 1-way ANOVA and the post hoc Bonferroni test for normally distributed data or the Kruskal-Wallis test with the Bonferroni correction for non-normally distributed data. All tests were 2-sided (α=.05).

RESULTS

The repeatability of the reference scanner did not significantly differ among the reference scans. The mean deviation of the maxillary reference cast was 9.9 ±0.4 μm and that of the mandibular reference cast was 10.0 ±0.4 μm.

The trueness of the maxillary complete prepared arch significantly differed among the 3 groups (*P*<.001). The degree of deviation was significantly lower in the IS group than in the CS (*P*=.003) and IOS (*P*<.001) groups. For the mandibular complete prepared arch, no significant difference of trueness was found among the 3 groups (*P*=.180) (Table 1). The precision of both complete prepared arches significantly differed among the 3 groups (*P*<.001). 3D deviation was significantly larger in the CS group than in the IS and IOS groups (*P*<.001) (Table 2).

Table 3. Mean/median root mean squared trueness values (μm) of 3 digital scanning methods tested on prepared anterior and posterior teeth

		Intraoral Scanning		Impression Scanning		Cast Scanning		Statistics	
Arch	**Segment**	**Trueness**	**95% CI**	**Trueness**	**95% CI**	**Trueness**	**95% CI**	***P***	***F* Value**
Maxillary	Anterior teeth	40.6 (3.10)[a]*	(38.5-41.5)	42.8 (13.6)[a]*	(35.8-47.2)	45.9 (24.8)[a]*	(36.9-55.4)	.160	1.554
	Posterior teeth	56.4 ±7.9[a]	(50.7-62.0)	36.2 ±6.8[b]	(31.3-41.1)	45.8 ±5.5[c]	(41.8-49.7)	<.001	21.977
Mandibular	Anterior teeth	29.0 (2.1)[b]*	(28.2-30.2)	36.9 (10.5)[a]*	(38.3-54.4)	40.4 (6.9)[a]*	(38.6-45.2)	<.001	20.020
	Posterior teeth	46.3 ±13.2[b]	(36.9-55.8)	34.5 ±9.3[a]	(27.9-41.2)	43.3 ±10.6[b]	(35.8-50.9)	.015	4.930

CI, coincidence interval. Different letters indicate statistically significant differences (*P*<.05). *Not normally distributed.

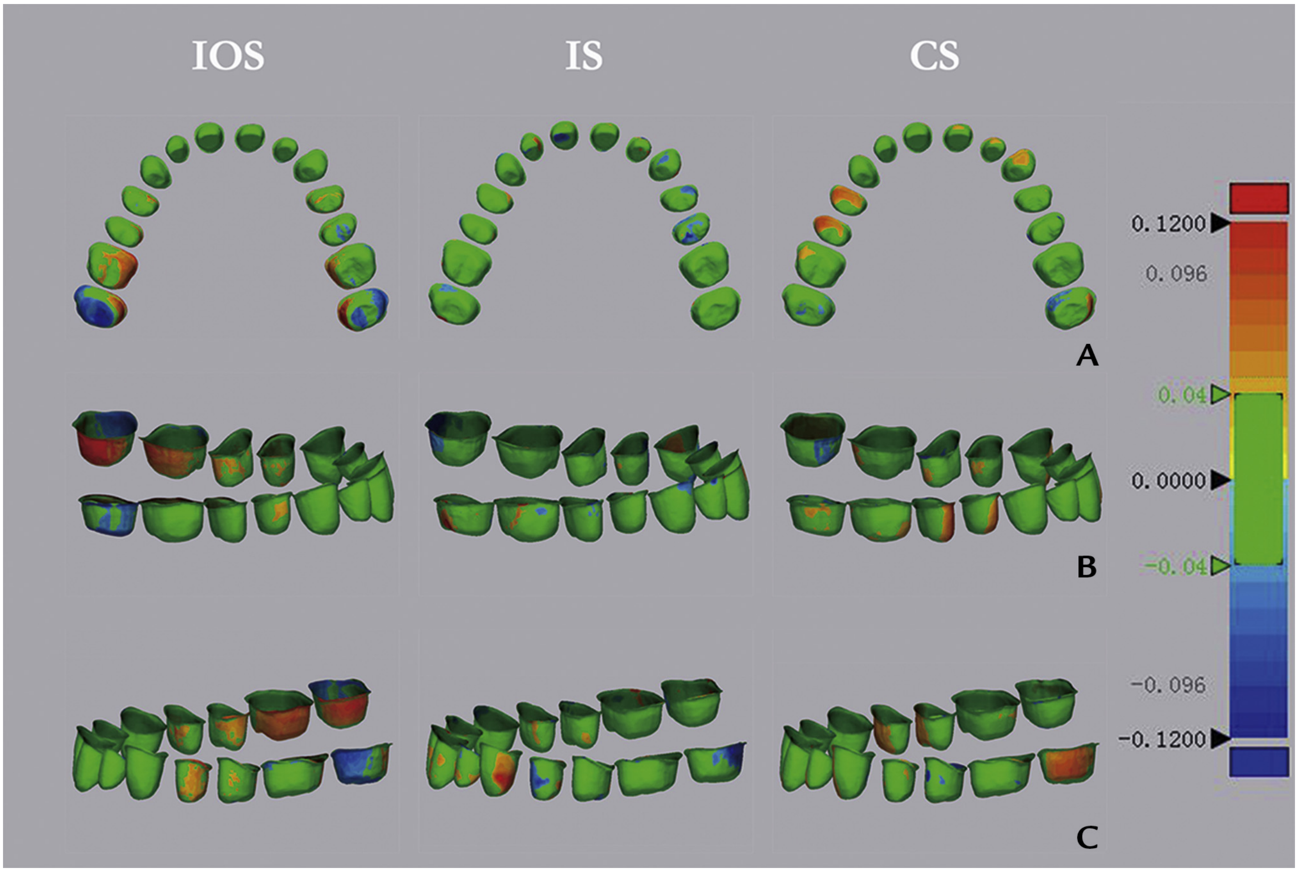

Figure 2. Color-coded map of deviations between maxillary reference and test casts. Colors indicate deviations from -120 μm (*blue*) to +120 μm (*red*), representing contraction and expansion. A, Occlusal view. B, Right lateral view. C, Left lateral view. CS, cast scanning; IOS, intraoral scanning; IS, impression scanning.

For the maxillary anterior teeth, the trueness did not significantly differ among the 3 groups (*P*=.160). For the mandibular anterior teeth, the trueness was significantly higher in the IOS group than in the IS (*P*<.001) and CS (*P*=.002) groups, and no significant difference was found between the IS and CS groups (*P*=1.000). For maxillary posterior teeth, the trueness was significantly lower in the IOS group than in the IS (*P*<.001) and CS (*P*=.005) groups, and a significant difference was found between the IS and CS groups (*P*=.012). For mandibular posterior teeth, the trueness was significantly higher in the IS group than in the IOS (*P*<.001) and CS (*P*=.005) groups, while no significant difference was found between the IOS and CS groups (*P*=1.000) (Table 3).

Color maps of the surface matching differences between the reference cast and test groups are shown in Figures 2, 3. In the IOS group, systematic distortions were observed. Palatal displacement was detected in the maxillary arch and buccal displacement in the mandibular arch. In the IS group, a highly homogenous distance pattern was observed in both arches, along with irregular deformations on the second molar of the mandibular arch and on inclined surfaces of the maxillary arch. In the CS group, increasing bilateral deviation toward the buccal side and irregular deformations on the occlusal surfaces were observed in both arches.

Color maps of the surface matching differences between test casts are shown in Figures 4, 5. In the IOS

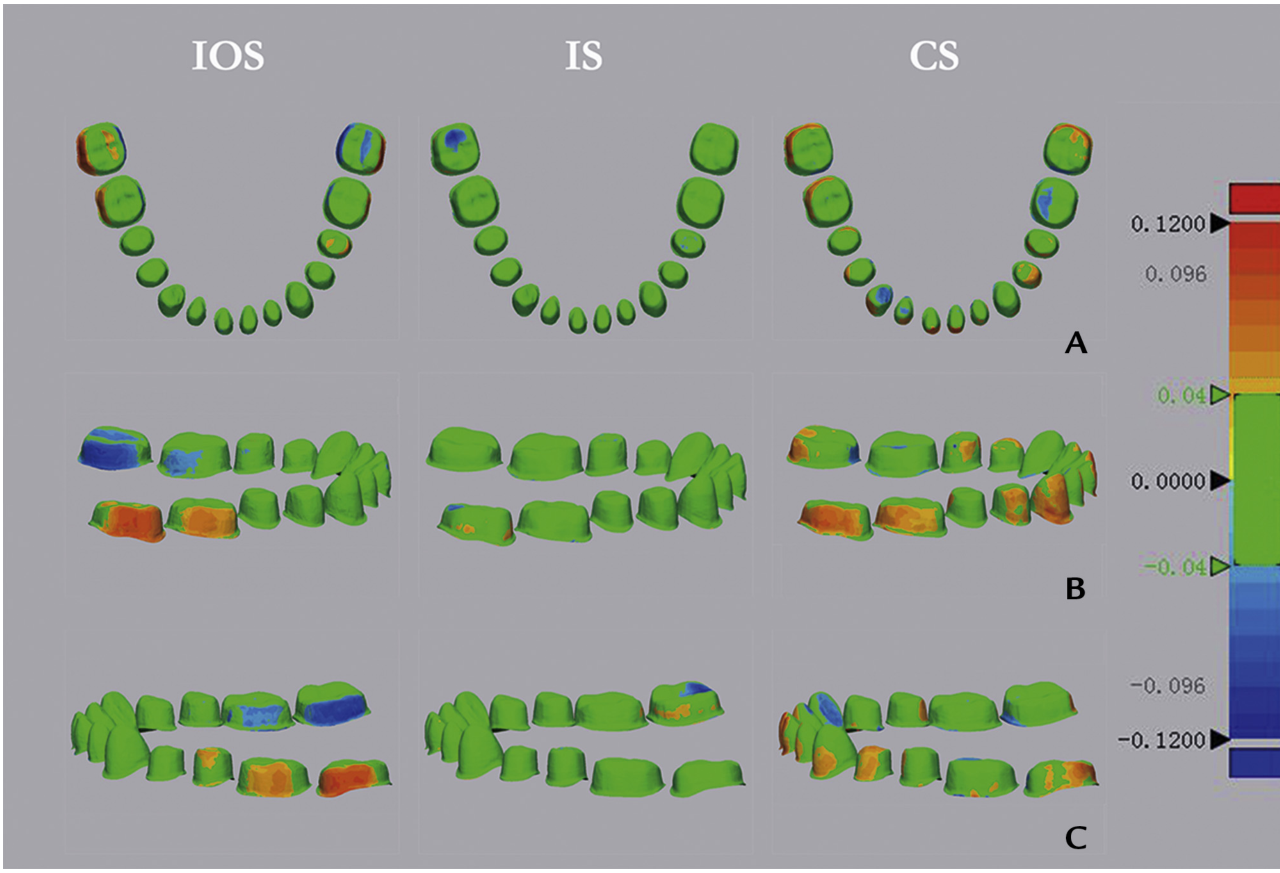

Figure 3. Color-coded map of deviations between mandibular reference and test casts. Colors indicate deviation from -120 μm (*blue*) to +120 μm (*red*), representing contraction and expansion. A, Occlusal view. B, Right lateral view. C, Left lateral view. CS, cast scanning; IOS, intraoral scanning; IS, impression scanning.

group, distortion was observed on one side at the distal end of the arches. In the IS group, there were irregular deformations on the occlusal and buccal surfaces. In the CS group, irregular deformations on the occlusal and incisal surfaces and marginal area were observed.

DISCUSSION

This in vitro study assessed the accuracy of 3 digital scanning methods for complete-arch tooth preparation. IS was significantly more accurate for complete-arch preparation, as compared with IOS or CS. In addition, IOS was significantly more accurate for the mandibular anterior teeth, and IS was significantly more accurate for the posterior teeth of both arches. Therefore, the null hypothesis was partially rejected.

The trueness of the IS group was the best among the 3 digital scanning methods. The IOS uses a wand with the transmission of a light source from the end of a small head and an image stitching mechanism, which can decrease the accuracy of long-span scanning.[21,32] Some accuracy is lost when pouring the impression to make a gypsum cast. For arch segments, the IS group exhibited the lowest deviation in the posterior segment, and the IOS group exhibited the highest accuracy in the anterior segment. Root mean squared values indicated that the shorter span and reduced curvature of the mandibular anterior teeth resulted in higher trueness.[23] However, for the complete arch, particularly for the posterior segment, the performance of IOS was inferior to that of IS or CS. The systematic horizontal deviation of the distal end might be related to incorrect software stitching processes and a summation of matching errors of the captured data during processing. Deviations greater than 120 μm across the posterior teeth may lead to poorly fitting restorations. The trueness results indicated that IS might be a sensible approach to making accurate digital casts and avoiding the disadvantages of IOS or CS.

For precision, IOS and IS were both better than CS. The median value of the 3 scanning methods differed no more than 15 μm, but the IOS group exhibited a larger deviation, which was consistent with the color map. Precision in the anterior segment was about 30 μm with a

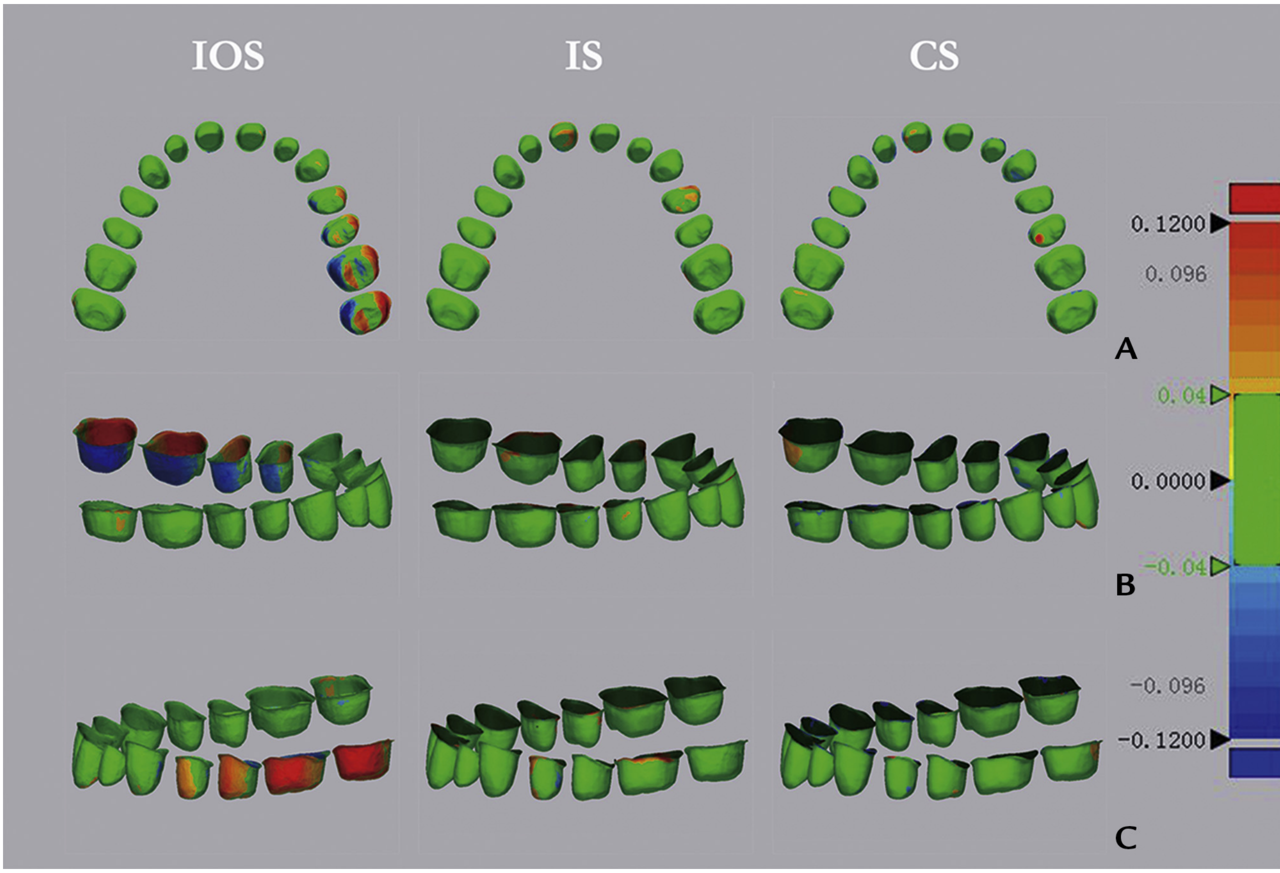

Figure 4. Color-coded map of deviations between maxillary test casts. Colors indicate deviations from -120 µm (*blue*) to +120 µm (*red*), representing contraction and expansion. A, Occlusal view. B, Right lateral view. C, Left lateral view. CS, cast scanning; IOS, intraoral scanning; IS, impression scanning.

maximum difference of 144 µm in the distal posterior region. Additionally, unilateral distal distortion of the maxillary and mandibular IOS test casts was denoted in the color map, which may be related to the selection of the superimposition areas during the best fit alignment. However, the low precision in the CS group may be related to the setting expansion of the Type IV dental stone, which was greater than the polymerization shrinkage of the impression material and led to increased dimensions.[33] Digital cast production is susceptible to minor surface flaws while making the impression or pouring the gypsum cast. Cast distortion may increase during scanning if irregularities are present on the surface. The postprocessing of STL data with the desktop scanner may overestimate errors because of surface irregularities.[34] This explains the positive or negative deviation of the marginal area and irregular deformations in the CS group on the color map.

The results were consistent with those of previous studies reporting that impression scans in combination with high-precision impression materials result in the most accurate data.[11,12] However, dimensional changes of impression materials with thermal contraction from mouth to room temperature have been estimated to be about 40 µm,[35] which might affect the impression scanning accuracy if in vitro studies are performed at room temperature. In the present study, the IOS devices were equipped with an up-to-date scanning unit and software, and the scanning was made extraorally without the influences of the intraoral environment. Therefore, the accuracy of IOS was close to that of EOS for the mandibular complete prepared arch and anterior segments. Recent studies have also demonstrated that the trueness of IOS was comparable with that EOS for complete arches.[14-16] Actual digital devices would presumably further minimize transfer errors between the intraoral environment and the digital cast, with the improvement of equipment hardware and software programs.[36]

Limitations of this study included that the experimental conditions differed from the clinical environment. Furthermore, when evaluating the restoration fit in complex complete dentition rehabilitation, all contributing factors, such as the CAD design, CAM milling process, and restoration seating, must be considered. Whether the accuracy of a digital cast can be translated to

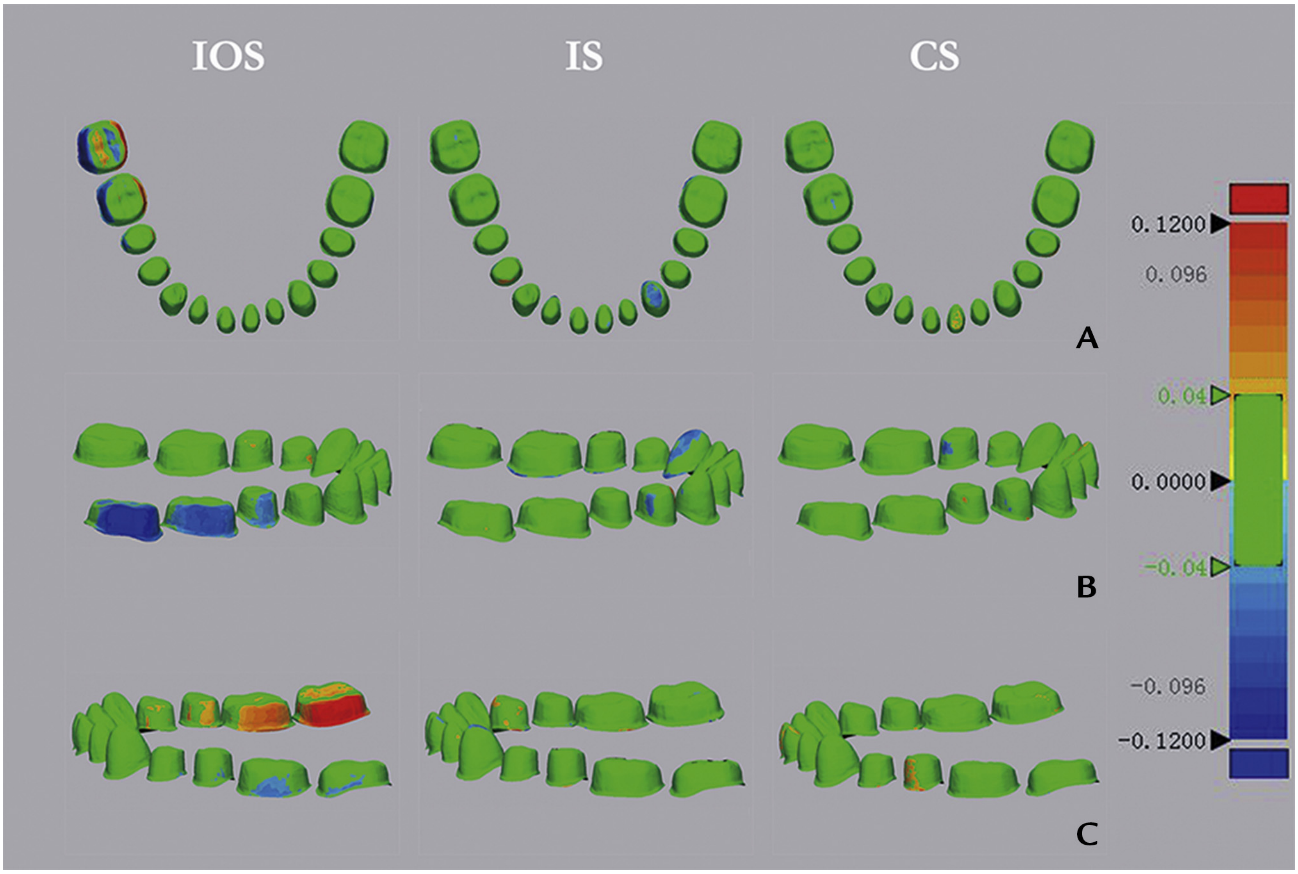

Figure 5. Color-coded map of deviations between mandibular test casts. Colors indicate deviations from -120 μm (*blue*) to +120 μm (*red*), representing contraction and expansion. A, Occlusal view. B, Right lateral view. C, Left lateral view. CS, cast scanning; IOS, intraoral scanning; IS, impression scanning.

a definitive restoration fit over the complete manufacturing workflow is a subject of ongoing research.

CONCLUSIONS

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

1. Digital casts fabricated using IS were more accurate than those fabricated using IOS or CS for complete-arch tooth preparations.
2. IOS exhibited higher accuracy for the prepared anterior teeth but showed higher local deviations in the posterior teeth than did IS and CS. IS exhibited higher accuracy for the posterior segments.
3. In spite of the expanding implementation of IS devices, indirect digitization of conventional impressions or casts represents a reliable source for accurate data acquisition for complete-arch preparation.

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