

RESEARCH AND EDUCATION

Trueness and precision of 5 intraoral scanners for scanning edentulous and dentate complete-arch mandibular casts: A comparative in vitro study



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Digital workflows in dentistry rely on different techniques: from data acquisition of the oral cavity with intraoral scanners (IOSs), to computer-aided design (CAD) in dental modeling software, to the use of additive and subtractive manufacturing systems for manufacturing restorations in materials ranging from polymers to monolithic ceramics. To control or adapt to errors in this workflow, each process in the workflow should be carefully studied. The present study focused on the trueness and precision of 5 IOSs used on a dentate cast and an edentulous cast. ISO 5725-1¹ was used as a reference for describing the terms accuracy, trueness, and precision. Trueness is described as the closeness of agreement between the arithmetic mean of a measured subject and a known or true value. Precision is described as the closeness of agreement between test results. Test results that justify both trueness and precision are regarded as accurate. Precision is divided into 2 different groups: in the first group, the subject is tested in

ABSTRACT

Statement of problem. Limited information is available on the trueness and precision of intraoral scanners (IOSs) for scanning dentate and edentulous casts.

Purpose. The purpose of this in vitro study was to evaluate the trueness and precision of 5 different IOS devices for scanning a dentate and an edentulous cast in a standardized way for short arches and complete arches.

Material and methods. Five IOS devices were used to scan 2 computer metric measured casts using a coordinate measuring machine (CMM). Both were scanned 15 times. All scans were carried out by 1 experienced operator in a standardized way. One cast was edentulous, and 1 was dentate. Five cylindrical landmarks were added to each cast. These cylinders made the measurement of point-to-point distances possible, dividing the tests into cross-arch measurements and intercylindrical (short-arch) measurements. The Student *t* test, Mann-Whitney test, and Levene test for equality were used to calculate the difference between the edentulous and dentate scans for both cross-arch and intercylindrical measurements ($\alpha=.05$).

Results. For the cross-arch measurements on the edentulous scans, the trueness values ranged between 6 μm (Emerald P1-P2) and 193 μm (Omnicam P1-P5) and for the intercylindrical measurements, between 2 μm (Itero P4-P5) and -103 μm (CS 3600 P1-P2). For the dentate cast, the cross-arch trueness values ranged between 6 μm (CS 3600 P1-P2) and 150 μm (TRIOS 3 P1-P5) and for the intercylindrical measurements, between 4 μm (Itero P4-P5) and -56 μm (Emerald P4-P5).

Conclusions. Significant differences were found in scanning edentulous and dentate scans for short arches and complete arches. Trueness for complete-arch scans were <193 μm for edentulous scans and <150 μm for dentate scans. Trueness for short-arch scans were <103 μm for edentulous scans and <56 μm for dentate scans. (J Prosthet Dent 2019;122:129-36)

the same way by the same operator and measuring equipment under the same conditions. This first version of precision tests repeatability. In the second version of precision, the conditions change. Thus, this part tests reproducibility. The combination of trueness and precision describes the accuracy of the test subject.

Omnicam Sirona was provided by Dentsply Sirona, Itero Elements Unident, Planmeca Emerald by Planmeca, TRIOS 3 by 3Shape, and Carestream CS 3600 by Forstec Dental AB. The validation cast were manufactured by 3D TEC Sweden AB.

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Clinical Implications

Care should be taken with complete-arch scans because the precision is low for dentate scans and particularly low for edentulous scans. One observation from this *in vitro* study suggests that the tested intraoral scanner devices are reliable for digitizing short arches (16 to 22 mm) for both edentulous and dentate situations.

Several studies have shown that IOS devices have difficulty in scanning complete arches accurately,²⁻¹⁰ and this is even more problematic for edentulous areas.⁹ The main reason for enhanced errors on longer span scans could be the acquisition method found in most IOS devices. The scanners acquire images that are matched; a software process known as the best-fit algorithm stitches the images. To achieve a proper alignment, the scanned object needs a suitable geometry. If the scanned area has a simple geometry, the alignment of the images could cause errors. Typically, occlusal surfaces on molars and premolars present complex geometries with many anatomic details. Thus, these areas are easier to align compared with edentulous areas or the incisal edge of the mandibular anterior teeth.

As every overlapping image aligned with best-fit stitching could lead to an error, scanning longer spans would require more stitching and possibly lead to more errors.¹¹ To simplify the scanning of edentulous areas, landmarks can be added or objects with complicated geometries can be attached to the edentulous area to simplify the scanning procedure and improve the trueness of the virtual cast.¹² Several *in vitro* and *in vivo* studies have shown that prostheses made on shorter span scans could achieve trueness levels comparable with those of conventional impressions.¹³⁻¹⁷

The methods used to study the trueness and precision of IOS devices have varied, making comparison between studies difficult. Most of the studies used a master model that had been digitized either with a tactile coordinate measuring machine (CMM) or with an optical reference scanner to obtain reference data as a virtual 3-dimensional (3D) file or as raw data. The physical cast was then scanned by the test scanners to obtain virtual casts, which were later compared with the virtual master model, and the measurements were recorded. Some studies present color map data with threshold colors to visualize and measure differences between the 2 scans.

The present study used a different method: 5 cylinders were made as landmarks, making it possible to calculate only 5 points in the scan, instead of comparing thousands of points from the scan data. The cylinders were divided across 2 complete-arch mandibles; the first

cast was dentate and the second, edentulous. The purpose of this *in vitro* study was to measure the trueness and precision of the scanners for the 2 different arches; the null hypothesis was that no significant differences would be found within each IOS system for the 2 different arches.

MATERIAL AND METHODS

Two validation casts of a mandible were designed: one dentate and one edentulous. Each cast was supplied with 5 cylindrical landmarks. The casts were manufactured additively and measured with a coordinate measuring machine (CMM). From this step on, the casts were regarded as validation casts and were scanned using different IOSs; the virtual files from the scans were later measured, analyzed, and compared with the CMM data.

An intraoral scan of a complete-arch mandible was made with an IOS (TRIOS 3; 3Shape). The scan was exported as a standard tessellation language (STL) file and imported into CAD modeling software (Fusion 360 2017 v2.0.3800; Autodesk). In Fusion 360, 5 cylinders were designed and placed axially onto the occlusion (Fig. 1A, B). The locations of the cylinders were as follows: second molars, second premolars, and one was placed lingually to the anterior teeth (Fig. 1C). The same cylinders were used for the edentulous mandible, and the teeth were removed using mesh modeling software (Fig. 1D) (Autodesk Meshmixer 2017 v3.4.35; Autodesk).

Before manufacturing, the validation casts were hollowed and evaluated for errors using data preparation software (Materialise Magics v13; Materialise). The casts were produced additively (ConceptLaser M-lab 100W; GE Additive) and manufactured directly on the build plate without support structures, at a layer height set to 30 μm . Remanium-Star-CL (Co 60.5%, Cr 28%, W 9%, Si 15%) material powder was used. The casts were treated according to ConceptLaser recommendations for heat treatment after processing. The casts were not removed from the 90×90 mm build plate. Finally, the casts were airborne-particle abraded with 250- μm aluminum oxide until a nonreflective surface was achieved.

The validation casts were measured with CMM equipment (O-inspect, 153862; Zeiss) by authorized personnel at an ISO 13485:2016 validated institution (Elos Medtech). The CMM machine registered the diameter of each cylinder and the plane at the top of the cylinders. The intersection between cylinder and plane results in an intersecting point. Furthermore, the CMM device measured the distances between each intersecting point for cross-arch P1-P2, P1-P3, P1-P4, P1-P5 and intercylindrical measurements P1-P2, P2-P3, P3-P4, P4-P5 (Fig. 1A). The CMM measurements were regarded as true values (Supplemental Table 1).

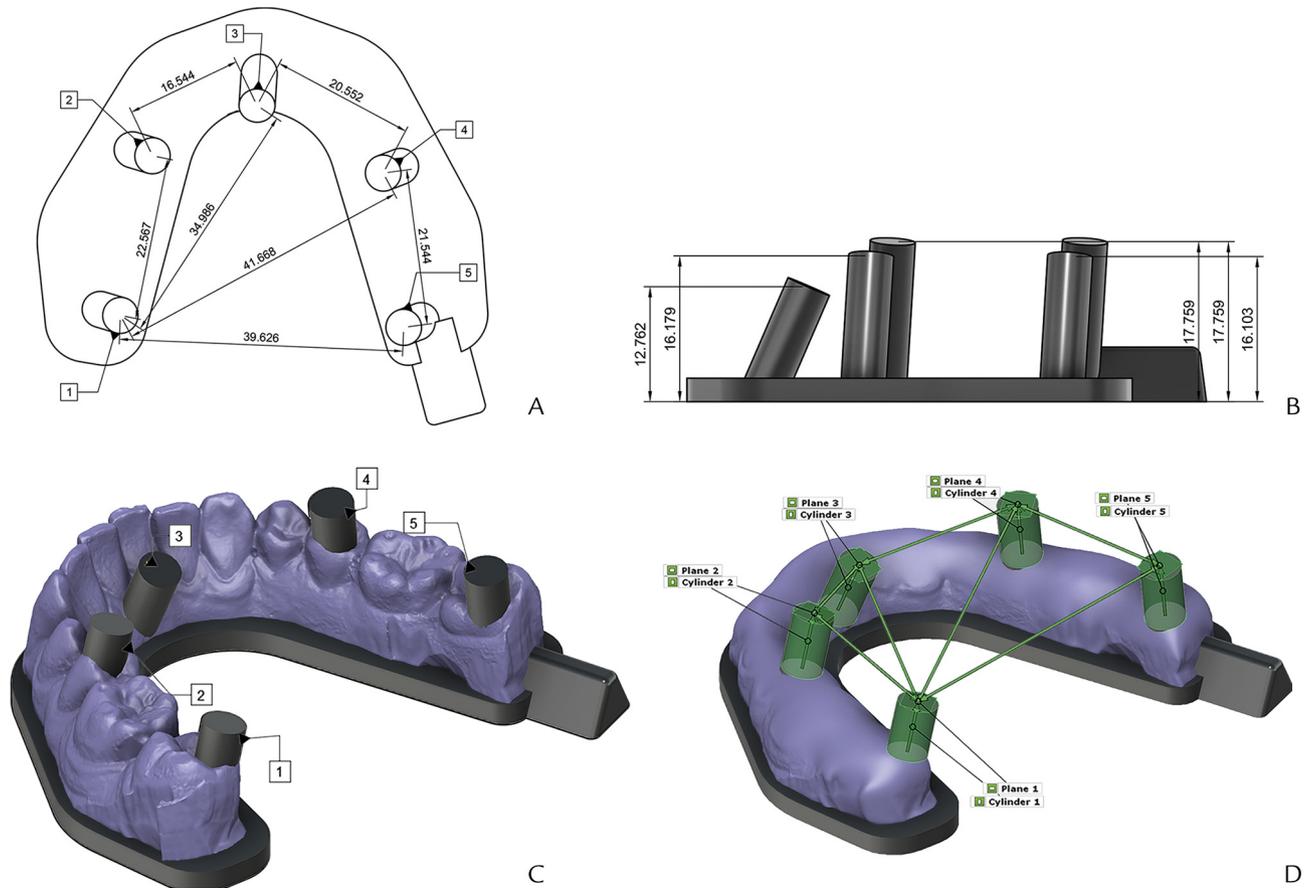


Figure 1. A, Occlusal view of CAD illustrating cylinder orientation. Dimensions from CMM measurements. B, Lateral view of CAD sketch illustrating cylinder design without cast. C, Profile view of assembled dentate CAD cast with cylinder abbreviations. D, Profile view of assembled edentulous CAD cast. Illustration of intersections between cylinders, planes, and intersecting points. CAD, computer-aided design; CMM, coordinate measuring machine.

Table 1. IOS-related specifications

IOS (Release)	Software	Acquisition	Device ID	Calibration	Case Selection	Scan Protocol	Export	Conditions	Notes
Omniscam Sirona (2012)	Sirona Connect 4.5.0.105736	Optical triangulation and confocal microscopy	Model 6371830 S/N 138016	Sirona ID 25782789	Acquisition No restoration	OLB	STL export on site	200 ANSI lumen ±50 lumen. 21 ±1 degree	High-resolution STL export
Itero Element (2015)	Itero Element 1.5.0.361	Parallel confocal microscopy	RTC2017 W10A076 REF 102611 S/N 34862	No calibration presented by manufacturer	iRecord No restoration	OLBW	STL export of site	200 ANSI lumen ±50 lumen. 21 ±1 degree	—
Planmeca Emerald (2017)	Planmeca Romexis 5.0.0.R	Multicolor laser scanning	REF 30006191 S/N 410405	No calibration (Only color calibration required)	No restoration	OLB	STL export on site	200 ANSI lumen ±50 lumen. 21 ±1 degree	Model mode scanning
Carestream CS 3600 (2016)	CS Imaging Software 7.0.3	Active speed 3D video	S/N FHNB0033	No calibration presented by manufacturer	Standard scanning	OWOLB	STL export on site	200 ANSI lumen ±50 lumen. 21 ±1 degree	To finish scan, all mandibular teeth selected
TRIOS 3 (2015)	TRIOS 2015-1 Design studio 1.4.7.4	Confocal microscopy	S/N 1WA1732S01015B	1AB1731TTA080B and 1KA1731188B (color)	Study model	OWOLB	STL export off site	200 ANSI lumen ±50 lumen. 21 ±1 degree	

ANSI, American National Standards Institute; B, buccal; IOS, intraoral scanner; L, lingual; O, occlusal; STL, standard tessellation language; W, wiggling (scanning in rocking manner).

Table 1 shows the scanners tested and provides information on the scan conditions, equipment, and software. Each system was used to scan each cast 15 times (n=15 for the dentate cast and n=15 for the

edentulous cast) by the same operator (M.B.). Although some difference was found between the scan protocols of the systems, all scans started at position 1 (Fig. 1C) and continued through positions 2, 3, 4, and 5. On

Table 2. Applied statistical methods

Intraoral scanning device	Statistical Analysis for Comparison of Each Cast (<i>P</i> <.05)							
	Cross-Arch				Intercylindrical			
	P1-P2	P1-P3	P1-P4	P1-P5	P1-P2	P2-P3	P3-P4	P4-P5
Omnica								
Mann-Whitney sig. 2× (1-tailed sig.)	.187	.187	.683	.021	.187	.137	.902	.026
Student <i>t</i> test sig. (2-tailed)	.688	.168	.972	.101	.688	.207	.664	.945
Levene test for equality of variances	.001	.001	.005	.002	.001	.046	.062	.009
CS 3600								
Mann-Whitney sig. 2× (1-tailed sig.)	<.001	<.001	.217	.016	<.001	.037	<.001	<.001
Student <i>t</i> test sig. (2-tailed)	<.001	<.001	.449	.031	<.001	.078	<.001	.002
Levene test for equality of variances	.001	<.001	.032	.011	.001	.007	.039	.027
Emerald								
Mann-Whitney sig. 2× (1-tailed sig.)	.081	.174	.838	.539	.081	.026	.067	.098
Student <i>t</i> test sig. (2-tailed)	.503	.245	.651	.453	.503	.012	.075	.125
Levene test for equality of variances	.009	.369	.876	.032	.009	<.001	.013	.004
Itero								
Mann-Whitney sig. 2× (1-tailed sig.)	.010	.089	.325	.775	.010	.106	.002	.902
Student <i>t</i> test sig. (2-tailed)	.023	.081	.636	.498	.023	.202	.001	.905
Levene test for equality of variances	.122	.225	.204	.760	.122	.902	.736	<.001
TRIOS 3								
Mann-Whitney sig. 2× (1-tailed sig.)	<.001	.029	.174	.001	<.001	.267	.217	<.001
Student <i>t</i> test sig. (2-tailed)	<.001	.022	.113	.001	<.001	.561	.196	<.001
Levene test for equality of variances	.007	.018	.885	.390	.007	.626	.173	.029

Significant difference (*P*<.05) shown in bold.

some occasions, a corrective scan was needed to achieve a watertight (that is, data without holes) scan file. Usually these corrections correlated with the cylinders. The validation casts were fixed; only the ISO device was moved during scanning; there was a 10-minute interval between each scan. Three-dimensional measuring data were used for the quality control software (Gom Inspect 2017 Hotfix 4 Rev v106794; Gom). All 150 intraoral scans were measured in the same way. Figure 1D illustrates the construction of the fitting cylinders, fitting planes, and the intersecting point between the constructed cylinders, planes, and the 2-point measurements between the intersecting points. The best Gaussian fit was used as the fitting algorithm for the cylinders and planes.

The measurement data were exported to statistical software (IBM SPSS Statistics, v25; IBM Corp) in which calculations for the mean, precision, trueness, the 2-tailed independent Student *t* test, and the Mann-Whitney test ($\alpha=.05$) were carried out.

RESULTS

The results and calculations were divided into 2 parts: in the first part, the calculations focused on the cross-arch measurements P1-P2, P1-P3, P1-P4, and P1-P5 for both the edentulous and dentate cast, where point 1 was used as the anchorage, or the starting point. In the second part, the calculations were conducted in the inter-cylindrical measurements P1-P2, P2-P3, P3-P4, and

P4-P5. The measurement P1-P2 is the same for both groups. Supplemental Table 1 presents the CMM data, the precision and trueness for both cross-arch, and inter-cylindrical measurements for both the edentulous cast and the dentate cast. The Mann-Whitney test and the Student *t* test showed conclusive data for all the statistical tests except for Omnicam P1-P5, P4-P5, and for CS 3600 P2-P3 (*P*<.05, Table 2).

For Omnicam, the cross-arch trueness data for Omnicam E ranged from 23 μm (P1-P2) to 193 μm (P1-P5), with precision levels from 22 μm (P1-P2) to 299 μm (P1-P5). The inter-cylindrical trueness data ranged from 16 μm (P4-P5) to 23 μm (P1-P2), with precision levels from 93 μm (P4-P5) to 22 μm (P1-P2). The cross-arch trueness data for Omnicam D ranged from 25 μm (P1-P2) to 67 μm (P1-P3), with precision levels from 6 μm (P1-P2) to 67 μm (P1-P5). The inter-cylindrical trueness data ranged from 14 μm (P4-P5) to 30 μm (P2-P3), with precision levels from 6 μm (P1-P2) to 16 μm (P2-P3 and P3-P4) (Supplemental Table 1, Figs. 2, 3).

For CS 3600, the cross-arch trueness data for CS 3600 E ranged from -103 μm (P1-P2) to 181 μm (P1-P5), with precision levels from 66 μm (P1-P2) to 247 μm (P1-P5). The inter-cylindrical trueness data ranged from -16 μm (P4-P5) to -103 μm (P1-P2), with precision levels from 42 μm (P2-P3) to 66 μm (P1-P2 and P3-P4). The cross-arch trueness data for CS 3600 D ranged from 6 μm (P1-P2) to 38 μm (P1-P4), with precision levels from 17 μm (P1-P2) to 82 μm (P1-P5). The inter-cylindrical trueness data ranged from 3 μm (P4-P5) to 33 μm (P3-P4),

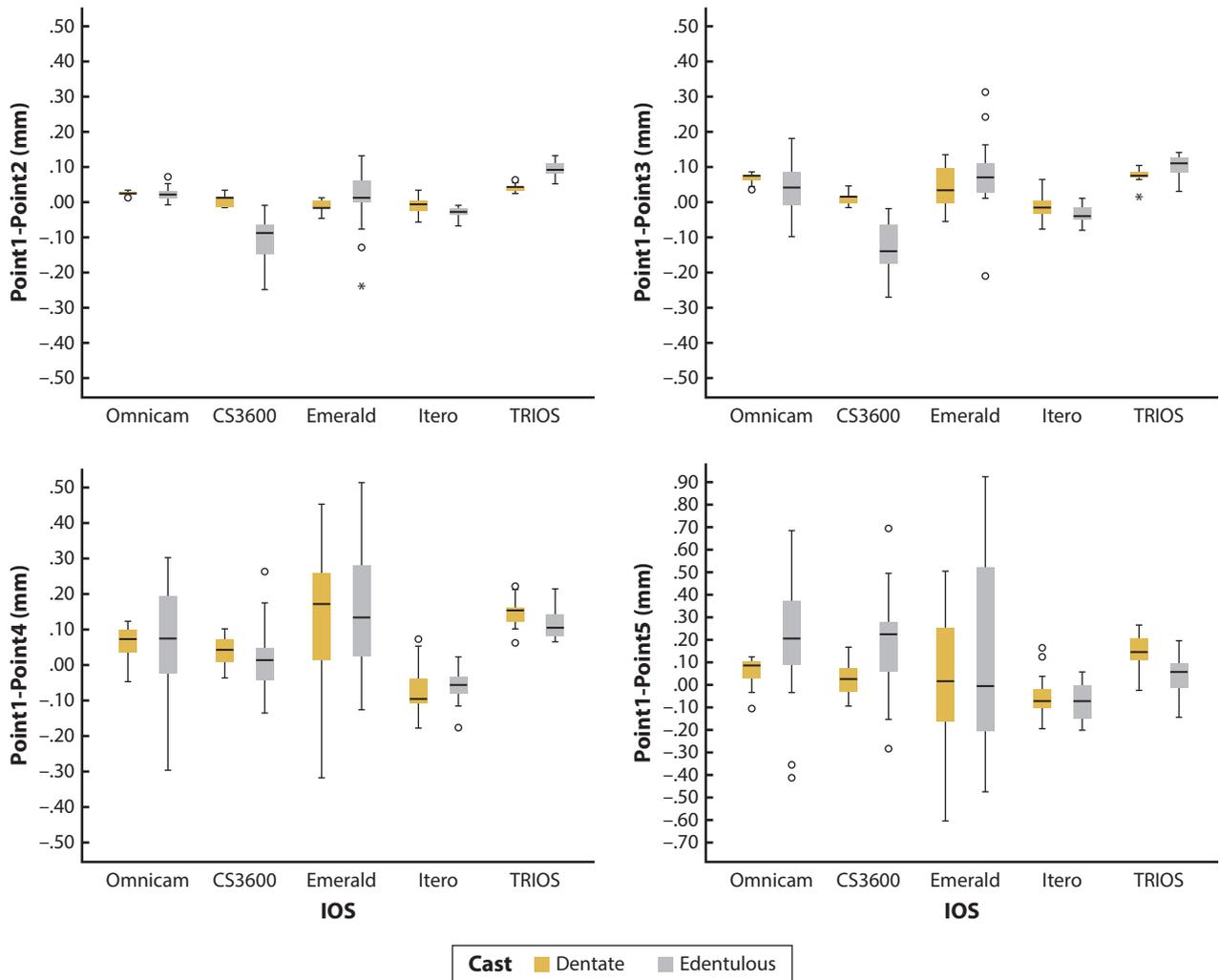


Figure 2. Cross-arch measurement deviations from CMM data (zero-line) for all IOS devices for each cast. CMM, coordinate measuring machine; IOS, intraoral scanner.

with precision levels from 16 μm (P2-P3) to 14 μm (P3-P4) (Supplemental Table 1, Figs. 2, 3).

For Emerald, the cross-arch trueness data for Emerald E ranged from 6 μm (P1-P2) to 163 μm (P1-P4), with precision levels from 96 μm (P1-P2) to 441 μm (P1-P5). The intercyindrical trueness data ranged from 6 μm (P1-P2) to -67 μm (P3-P4), with precision levels from 38 μm (P2-P3) to 97 μm (P3-P4). The cross-arch trueness data for Emerald D ranged from -11 μm (P1-P2) to 129 μm (P1-P4), with precision levels from 17 μm (P1-P2) to 311 μm (P1-P5). The intercyindrical trueness data ranged from -11 μm (P1-P2) to -56 μm (P4-P5), with precision levels from 17 μm (P1-P2) to 54 μm (P3-P4) (Supplemental Table 1, Figs. 2, 3).

For Itero, the cross-arch trueness data for Itero E ranged from -30 μm (P1-P2) to -81 μm (P1-P5), with precision values from 17 μm (P1-P2) to 85 μm (P1-P5). The intercyindrical trueness data ranged from 2 μm (P4-P5) to -30 μm (P1-P2), with precision values from 14 μm

(P2-P3) to 30 μm (P4-P5). The cross-arch trueness data for Itero D ranged from -11 μm (P1-P2) to -70 μm (P1-P4), with precision values from 25 μm (P1-P2) to 105 μm (P1-P5). The intercyindrical trueness data ranged from 4 μm (P4-P5) to 22 μm (P3-P4), with precision values from 10 μm (P4-P5) to 25 μm (P1-P2) (Supplemental Table 1, Figs. 2, 3).

For TRIOS 3, the cross-arch trueness data for TRIOS 3 E ranged from 117 μm (P1-P4) to 36 μm (P1-P5), with precision values from 23 μm (P1-P2) to 94 μm (P1-P5). The intercyindrical trueness data ranged from 31 μm (P2-P3) to 94 μm (P1-P2), with precision values from 19 μm (P4-P5) to 23 μm (P1-P2 and P3-P4). The cross-arch trueness data for TRIOS 3 D ranged from 150 μm (P1-P5) to 40 μm (P1-P2), with precision values from 12 μm (P1-P2) to 76 μm (P1-P5). The intercyindrical trueness data ranged from 34 μm (P2-P3) to 46 μm (P3-P4), with precision values from 10 μm (P4-P5) to 17 μm (P2-P3) (Supplemental Table 1, Figs. 2, 3).

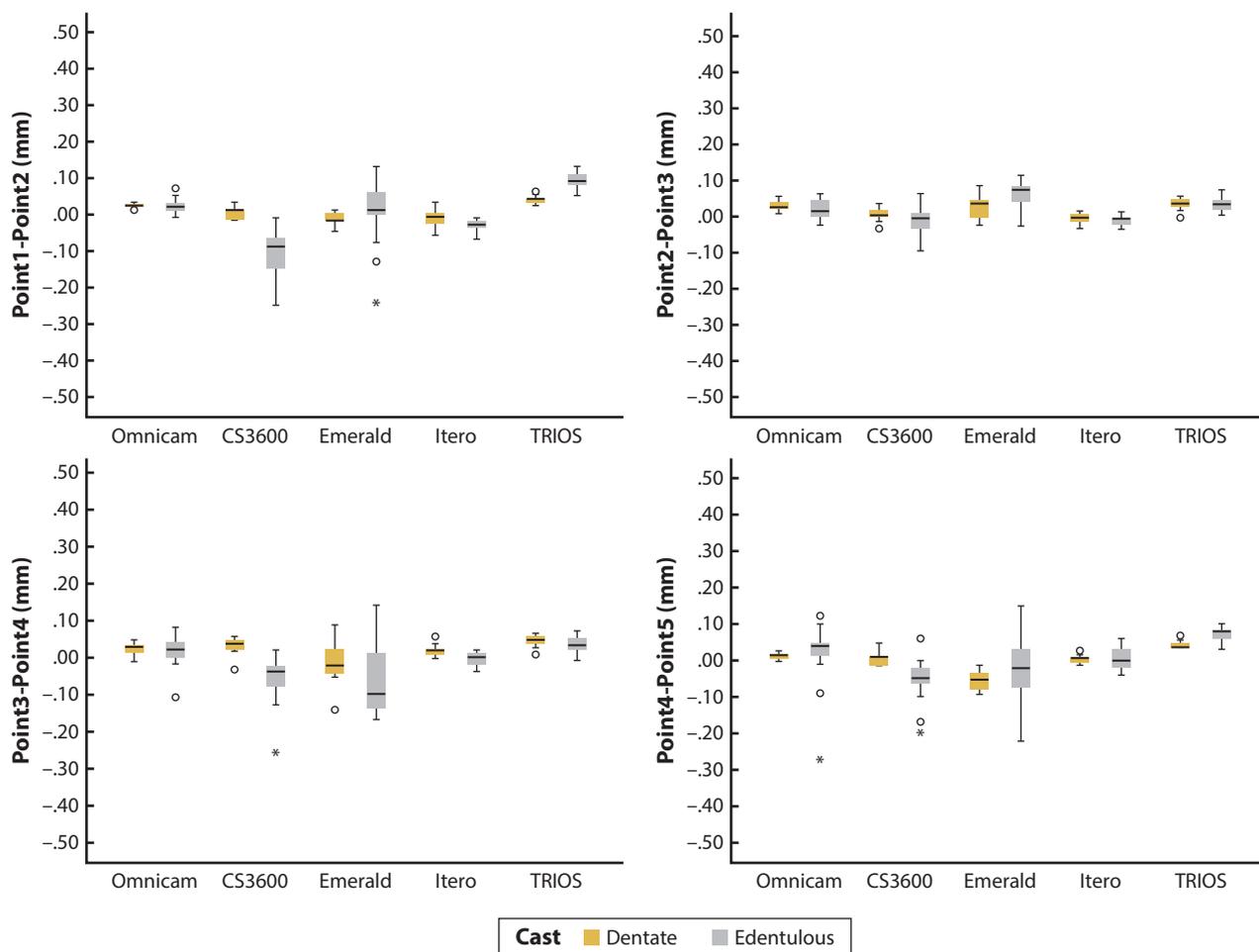


Figure 3. Intercylindrical measurement deviations from CMM data (zero-line) for IOS devices for each cast. CMM, coordinate measuring machine; IOS, intraoral scanner.

DISCUSSION

The null hypothesis that no significant differences would be found for the 2 different arches in each IOS system was partially rejected. For the cross-arch measurements, 3 of 4 measurements were statistically significant for TRIOS 3 and CS 3600 when the edentulous cast was compared with the dentate one. At the same time, the Emerald scanner showed no significant difference for the cross-arch measurement. For the intercyindrical measurements, CS 3600 showed overall significant differences, whereas differences for the other scanners only were partially significant. How many of the comparison studies used Itero Elements and how many used the older generation Itero is not clear. The Itero Elements scanner was launched in March 2015; for comparison purposes, studies before 2015 should be disregarded. The same problem arises for TRIOS and the Planmeca plan scan. 3Shape has released 3 generations of scanners, and the one used in this study was TRIOS 3 (2015, third generation), Planmeca released the Emerald scanner in late 2017, and, to the best of the authors' knowledge, no similar studies are available for comparison.

A method comparable with that of the present study was used in a study by Muallah al,¹⁸ where the authors measured the virtual files in a linear manner instead of superimposing 3D data. One of the linear measurements focused on the intermolar width of a maxillary master model; this measurement is similar to P1-P5 in the present study. The presented trueness results for TRIOS (version unreported) were 29.160 μm, with a precision of 52.872 μm; trueness for Itero (version unreported) was -47.030 μm, with a precision of 84.137 μm. The present study found trueness data for Itero D (P1-P5) at -56 μm, with a precision of 105 μm. Trueness for TRIOS D (P1-P5) was 150 μm, with a precision of 76 μm. Van der Meer et al⁶ used 3 cylinders on their master model that were measured using tactile CMM. Two of the cylinders replaced the first molars and 1 replaced a mandibular anterior tooth; the measurements conducted in that study were comparable with P1-P3 and P1-P5 in the present study. The study concluded that trueness for Itero (pre-2015 version) was 70.5 μm (P1-P3) with precision values of 56.3 μm, and 61.1 μm in trueness for P1-

P5 with precision values of 53.9 μm . These values could be compared with data from this article for trueness data at $-15\ \mu\text{m}$ (P1-P3) and $-56\ \mu\text{m}$ (P1-P5), with precision values of 37 μm (P1-P3) and 105 μm (P1-P5) for Itero D. Giménez *et al*¹¹ studied the Itero scanner (pre-2015 version) using a comparable master model with cylinders as geometric landmarks. They also used tactile CMM equipment to assess true values. Several factors were evaluated, one of them being comparable to the Itero E cross-arch data from the present study. They reported that error increased with the increase in stitching, starting from $-14.3\ \mu\text{m}$ (mean deviation) with an \pm standard deviation of 25.6 μm to $-32.0\ \mu\text{m}$ (mean deviation) with an \pm standard deviation of 216.1 μm in the last quadrant scanned. The clear effect of the stitching processes producing errors proportional to the scan distance, as noted in this study, has also been documented in other studies.¹⁹⁻²¹

Even though there are limitations to the comparison with other studies with regard to measuring methods, IOS versions, and the shape, size, and material of the validation casts, it is clear that complete-arch scans pose a challenge to the IOS devices with regard to trueness but even more with regard to precision. The findings suggest that the trueness and precision of intercylindrical distances on the dentate cast for all IOS devices were $<50\ \mu\text{m}$ (except Emerald D, P4-P5, $-56\ \mu\text{m}$), with precision data $\leq 35\ \mu\text{m}$ (except Emerald D, P3-P4, 54 μm). This suggests that the IOS devices are accurate for shorter arch acquisitions ranging from approximately 16 to 22 mm in length. In studying the cross-arch measurements, it is clear that the results are not as favorable for the dentate validation cast. The trueness for all IOS devices was $\leq 129\ \mu\text{m}$ (except TRIOS D, P1-P5, 150 μm) and the precision $\leq 105\ \mu\text{m}$ (except Emerald D, P1-P5, 311 μm), suggesting that the cross-arch measurement is less reliable than the intercylindrical measurement for the dentate cast. For the intercylindrical data on the edentulous validation cast, the IOS devices presented trueness values $\leq 94\ \mu\text{m}$ (except, CS 3600, P1-P2, $-103\ \mu\text{m}$) and precision values $\leq 97\ \mu\text{m}$. This indicates that the intercylindrical measurement on the dentate cast has almost twice the level of trueness and 3 times the level of precision when compared with the intercylindrical measurement on the edentulous cast. The trueness values for the cross-arch measurements on the edentulous cast were $\leq 193\ \mu\text{m}$ and the precision values, $\leq 299\ \mu\text{m}$ (except Emerald E, P1-P5, 441 μm). To validate whether these numbers are relevant for dentistry, a threshold value for different dental applications needs to be established. An accuracy level of $<150\ \mu\text{m}$ ¹ may be favorable for fixed tooth-supported prosthodontics. Ahrberg *et al*¹⁵ studied the digital workflow for ceramic restorations for single units and 3-unit fixed partial dentures in vivo, concluding that it was more accurate

than the conventional workflow. Their findings were supported by the data found in the present study, suggesting that the IOS devices are sufficiently accurate for shorter spans. Clinically acceptable tolerances for implant-supported, multiunit restorations should be between 50 and 90 μm .²² This study focused on the accuracy of IOS devices but did not compensate for the CAD of implant restorations or the manufacturing tolerances of selected manufacturing equipment, factors that will add dimensional changes to the definitive restoration. If 50 to 90 μm were used as a threshold, only short-arch spans would be suitable for scanning implants.

To calculate the fit of implant restorations, accuracy measurements of the total digital workflow are needed for IOS, CAD, and computer-assisted manufacturing. As the oral situation is affected by factors that could not be included in the present study design, one can only speculate that saliva, light conditions, soft and hard tissue reflections, humidity, intermittent acquisition, and movement of the soft tissue and tongue would affect the outcome of a similar study in vivo. Furthermore, an edentulous condition without implants would not have 5 cylinders aiding in the acquisition process. Therefore, in vivo studies with a similar approach are needed.

CONCLUSIONS

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

1. Complete-arch scanning had low precision, suggesting that the intraoral scanning devices are less reliable for complete-arch scans, especially for edentulous patients.
2. All scanners presented better accuracy compared with the complete-arch measurements when distances of approximately 16 to 22 mm were measured.

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Noteworthy Abstracts of the Current Literature

Effectiveness of pre-silanization in improving bond performance of universal adhesives or self-adhesive resin cements to silica-based ceramics: Chemical and in vitro evidences

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Objectives. To examine effectiveness of pre-silanization in improving bond performance of multipurpose products such as universal adhesives or self-adhesive resin cements to silica-based ceramics.

Methods. The present study investigated reactions between silanol groups of γ -methacryloxypropyltrimethoxysilane (γ -MPS) and silica, dehydration self-condensation of γ -MPS, and condensation polymerization between γ -MPS and 10-methacryloxydecyl dihydrogen phosphate (10-MDP) by using thermodynamic calculations. Shear bond strength (SBS) tests were used to evaluate the influence of pre-silanization on resin bonding when a silane-containing universal adhesive, a silane-unknown universal adhesive, or two self-adhesives in cements were applied for bonding lithium disilicate to resin. In addition, reactions between silane and lithium disilicate were analyzed using X-ray photoelectric spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR).

Results. Acquired thermodynamic data indicated formation of siloxane between γ -MPS and silica. However, self-condensation of γ -MPS and reaction between γ -MPS and 10-MDP consumed the silanol. Pre-silanization enhanced SBS for self-adhesive resin cements or universal adhesives when applied for bonding silica-based ceramics. Thermocycling and aging decreased SBS in most groups. XPS and FTIR supported formation of siloxane between the employed silane coupling agent and two universal adhesives and lithium disilicate.

Significance. Pre-silanization is beneficial in further enhancing bond performance of universal adhesives or self-adhesive resin cements to silica-based ceramics.

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Supplemental Table 1. Calculated data from IOS devices for both casts

Units (mm)	Edentulous					Dentate					
	Measurement	N	CMM	Mean	Precision	Trueness	N	CMM	Mean	Precision	Trueness
Omnica											
Cross-arch											
Point 1-point 2	15	22.618	22.641	0.022	0.023	15	22.567	22.592	0.006	0.025	
Point 1-point 3	15	35.020	35.061	0.070	0.042	15	34.986	35.053	0.015	0.067	
Point 1-point 4	15	41.687	41.747	0.174	0.061	15	41.668	41.727	0.050	0.059	
Point 1-point 5	15	39.566	39.759	0.299	0.193	15	39.626	39.685	0.067	0.059	
Intercylindrical											
Point 1-point 2	15	22.618	22.641	0.022	0.023	15	22.567	22.592	0.006	0.025	
Point 2-point 3	15	16.536	16.556	0.028	0.020	15	16.544	16.575	0.016	0.030	
Point 3-point 4	15	20.568	20.585	0.044	0.017	15	20.552	20.575	0.016	0.023	
Point 4-point 5	15	21.591	21.607	0.093	0.016	15	21.544	21.558	0.009	0.014	
CS 3600											
Cross-arch											
Point 1-point 2	15	22.618	22.515	0.066	-0.103	15	22.567	22.573	0.017	0.006	
Point 1-point 3	15	35.020	34.895	0.074	-0.125	15	34.986	34.995	0.018	0.009	
Point 1-point 4	15	41.687	41.702	0.111	0.015	15	41.668	41.706	0.044	0.038	
Point 1-point 5	15	39.566	39.747	0.247	0.181	15	39.626	39.653	0.082	0.027	
Intercylindrical											
Point 1-point 2	15	22.618	22.515	0.066	-0.103	15	22.567	22.573	0.017	0.006	
Point 2-point 3	15	16.536	16.520	0.042	-0.016	15	16.544	16.550	0.016	0.006	
Point 3-point 4	15	20.568	20.508	0.066	-0.060	15	20.552	20.585	0.024	0.033	
Point 4-point 5	15	21.591	21.537	0.061	-0.054	15	21.544	21.547	0.018	0.003	
Emerald											
Cross-arch											
Point 1-point 2	15	22.618	22.624	0.096	0.006	15	22.567	22.556	0.017	-0.011	
Point 1-point 3	15	35.020	35.099	0.115	0.079	15	34.986	35.025	0.061	0.039	
Point 1-point 4	15	41.687	41.849	0.199	0.163	15	41.668	41.797	0.197	0.129	
Point 1-point 5	15	39.566	39.711	0.441	0.145	15	39.626	39.665	0.311	0.039	
Intercylindrical											
Point 1-point 2	15	22.618	22.624	0.096	0.006	15	22.567	22.556	0.017	-0.011	
Point 2-point 3	15	16.536	16.598	0.038	0.062	15	16.544	16.570	0.035	0.026	
Point 3-point 4	15	20.568	20.501	0.097	-0.067	15	20.552	20.539	0.054	-0.013	
Point 4-point 5	15	21.591	21.574	0.093	-0.017	15	21.544	21.487	0.027	-0.056	
Itero											
Cross-arch											
Point 1-point 2	15	22.618	22.588	0.017	-0.030	15	22.567	22.556	0.025	-0.011	
Point 1-point 3	15	35.020	34.985	0.025	-0.035	15	34.986	34.971	0.037	-0.015	
Point 1-point 4	15	41.687	41.628	0.053	-0.059	15	41.668	41.598	0.072	-0.070	
Point 1-point 5	15	39.566	39.485	0.085	-0.081	15	39.626	39.569	0.105	-0.056	
Intercylindrical											
Point 1-point 2	15	22.618	22.588	0.017	-0.030	15	22.567	22.556	0.025	-0.011	
Point 2-point 3	15	16.536	16.525	0.014	-0.011	15	16.544	16.539	0.014	-0.005	
Point 3-point 4	15	20.568	20.566	0.017	-0.002	15	20.552	20.573	0.018	0.022	
Point 4-point 5	15	21.591	21.593	0.030	0.002	15	21.544	21.547	0.010	0.004	
TRIOS 3											
Cross-arch											
Point 1-point 2	15	22.618	22.712	0.023	0.094	15	22.567	22.607	0.012	0.040	
Point 1-point 3	15	35.020	35.120	0.033	0.100	15	34.986	35.061	0.021	0.075	
Point 1-point 4	15	41.687	41.803	0.045	0.117	15	41.668	41.811	0.046	0.143	
Point 1-point 5	15	39.566	39.602	0.094	0.036	15	39.626	39.776	0.076	0.150	

(continued on next page)

Supplemental Table 1. (Continued) Calculated data from IOS devices for both casts

Units (mm)	Edentulous					Dentate					
	Measurement	N	CMM	Mean	Precision	Trueness	N	CMM	Mean	Precision	Trueness
Intercylindrical											
Point 1-point 2	15	22.618	22.712	0.023	0.094	15	22.567	22.607	0.012	0.040	
Point 2-point 3	15	16.536	16.567	0.020	0.031	15	16.544	16.579	0.017	0.034	
Point 3-point 4	15	20.568	20.605	0.023	0.037	15	20.552	20.598	0.015	0.046	
Point 4-point 5	15	21.591	21.662	0.019	0.071	15	21.544	21.587	0.010	0.044	

CMM, coordinate measuring machine; IOS, intraoral scanner.