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CLINICAL RESEARCH

Effect of a calibration aid and the intraoral scanner on the registration of a partially edentulous maxilla: An in vitro study

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ABSTRACT

Statement of problem. Precise data are a prerequisite for accurately fitting restorations. Therefore, intraoral scanners have to be reliable. Data on differences between the same model of intraoral scanning systems are lacking.

Purpose. This in vitro study evaluated differences in the scanning accuracy of a partially edentulous maxilla between combinations of new intraoral scanners of a single model from the same manufacturer (Primescan; Dentsply Sirona) and several calibration aids.

Material and methods. The in vitro reference model simulated a maxilla with 6 prepared teeth for a complete arch fixed partial denture. Five precision ceramic balls were used to detect dimensional deviation between the reference model and the scan. Distances were divided into 4 categories, from short distances between 2 neighboring precision balls to the cross-arch distance with the scan path comprising all 5 balls. For each combination of 4 new intraoral scanners and their respective calibration aids, 12 model registrations were generated. The data were statistically analyzed using ANOVA (α=.05).

Results. Distance deviations increased with increasing scan path length and were significantly affected by the covariates "scanner" ($P\leq.023$) and, for 3 of 4 distance categories, the "calibration aid" (short, medium, and long distances: $P\leq.013$). For short and medium distances, acceptable scanning results were achieved for all test groups. The largest deviation was 539 µm for the cross-arch distance.

Conclusions. Scanning accuracy depends on the scanner and the calibration aid used, in particular, for spans exceeding a single quadrant. (J Prosthet Dent 2025;133:560-567)

Intraoral scanners have become popular in dental practice as an efficient and applicable alternative to conventional impression making.[1–3] A prerequisite for accurately fitting fixed restorations is precise representation of the individual tooth and, for fixed partial dentures, the correct spatial positioning of the abutment teeth in relation to each other. The local scanning accuracy of contemporary scanning systems is sufficient to fabricate any type of single-tooth restoration.[4,5] However, the global scanning accuracy depends directly on the scan path length or the volume of the scan, the number and distribution of the abutment teeth, and the number and size of edentulous ridge sections.[6–13]

The scanning system should be calibrated for optimal results.[14] Calibration should be done before first use, after it has been transported, after it has been stored in an unheated or non-airconditioned room, if the temperature changes by more than 15 °C since the last calibration or operation, and if errors occurred during the scanning process. Recalibration of the scanning system is generally recommended least once a month and is typically performed with the calibration aid supplied with the intraoral scanner.

Theoretically, scanning systems that use identical hardware and software programs should have comparable accuracy. However, because of tolerances in the manufacture of scan heads and calibration aids, their

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Clinical Implications

Digital scanning is currently only sufficiently accurate for restorations of up to 1 quadrant to ensure fixed partial dentures with an acceptable fit.

scanning accuracy may differ. Whether scans captured with different intraoral scanners of a certain type or the combination of intraoral scanners and calibration aids give model data with comparable and clinically sufficient accuracy has not been determined.

The aim of the present study was to determine whether combinations of several new calibration aids and intraoral scanners of the same model and from the same manufacturer affected the scanning accuracy of complete arch scans of a partially edentulous maxillary model. The null hypotheses were that scanning accuracy would not be influenced by the individual intraoral scanner, the individual calibration aid, or by a combination of these.

MATERIAL AND METHODS

A partially edentulous test model was designed and produced according to the International Organization for Standardization (ISO) 20896 standard.[15] The model simulated a patient treated with a jaw-spanning fixed dental prosthesis (FDP) with the following abutment teeth prepared for complete crowns: central incisors, canines, and first molars (Fig. 1). The second molars were intact. The teeth were made from a cobalt chromium alloy core (Colado CAD CoCr4; Ivoclar AG) to which a polymethyl methacrylate crown (SR Vivodent CAD Multi; Ivoclar AG) in the corresponding shape had been adhesively attached (PANAVIA 21; Kuraray GmbH). All teeth were welded to a cobalt chromium alloy base (Colado CAD CoCr4; Ivoclar AG), which represented the maxilla. Five precision ceramic balls (Optische Kalibrierkugel TOPIC white; Saphirwerk AG) with nominal diameters of 5.9711 to 5.9714 mm, an equatorial roundness deviation of <0.5 µm, and mounted on a metal pin were welded to the metal base. They were placed buccally to each of the second molars, the canines, and the proximal contact of the central incisors at the level of the margin. The balls defined reference points in the reference, and scan data and were used primarily to detect and measure dimensional changes between the test model, serving as the reference, and the intraoral scans of the model. Finally, the metal base was covered with a stereolithographically produced gingival mask (FREEPRINT gingiva; Detax GmbH Co KG).

Figure 1. Occlusal view of reference model.

To determine the exact spatial position of the precision balls and their respective center points, 3 repetitive measurements were made with a coordinate measuring machine (MarVision 222; Mahr GmbH) with an accuracy of 1 to 2 µm, resulting in point clouds consisting of 200 measuring points per precision ball. Each precision ball had a calibration certificate that stated the nominal diameter with an accuracy of 0.1 µm. The ball centers were defined by minimizing the sum of all squared errors for any sphere with the given nominal radius and the variable center point. The 5 center points were numbered P_1 next to the right second molar, P_2 next to the left second molar, P_3 next to the central incisors, P_4 next to the right canine, and P_5 next to the left canine. A global coordinate system was defined with P_1 as the origin. The direction of the x-axis was represented by P_1P_2, and the x-y plane by P_1, P_2, and P_3, with the y axis oriented in the anterior direction. Between the 3 measurements, the x, y, and z coordinates of the respective ball centers deviated less than 1 µm from each other in the global coordinate system. The mean values of the precision ball center coordinates defined the reference situation.

By connecting each 2 precision ball centers, 10 distances were defined (Table 1). The distances were divided into 4 categories depending on the number of precision balls between the respective measuring points along the dental arch: short distance (SDI; consisting of distances 3, 7, 8, and 9) with no precision ball; medium distance (MDI; consisting of distances 2, 5, and 10) with 1 precision ball; long distance (LDI; consisting of distances 4 and 6) with 2 precision balls, and cross-arch

Table 1. Distances between center points of 5 ceramic precision balls in reference model

Distance	Distance Number	Distance Category	Length (mm)
P_1P_2	1	CADI	71.210
P_1P_3	2	MDI	57.387
P_1P_4	3	SDI	38.267
P_1P_5	4	LDI	67.914
P_2P_3	5	MDI	60.018
P_2P_4	6	LDI	70.209
P_2P_5	7	SDI	40.081
P_3P_4	8	SDI	24.343
P_3P_5	9	SDI	25.054
P_4P_5	10	MDI	45.443

CADI, cross-arch distance; LDI, long distance; MDI, medium distance; SDI, short distance

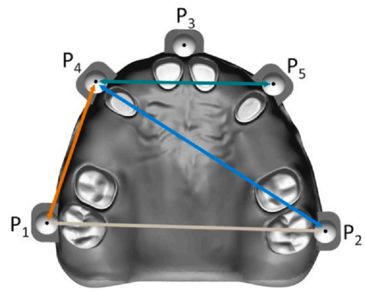

Figure 2. Three-dimensional view of reference model with ball centers P_1–P_5. Example distances displayed for short distances (no precision ball between two precision balls; *orange*), medium distances (following dental arch 1 precision ball between 2 precision balls; *turquoise*), long distances (following dental arch 2 precision balls between 2 precision balls; *blue*) and cross-arch distance (following dental arch 3 precision balls between 2 precision balls; *gray*).

Figure 3. Reference model inserted in phantom head.

distance (CADI; consisting of distance 1) with 3 precision balls along the scan path between the 2 precision balls defining the measured distance (Table 1, Fig. 2). In addition, 11 angles were evaluated: 10 angles were each defined by 3 precision ball centers and the opening angle between the orientations of the start segment $\overrightarrow{P_4P_1}$, and the end segment $\overrightarrow{P_5P_2}$ was determined by 4 precision ball centers.

The test model was inserted in a phantom head (PK-1 TSE; frasaco GmbH) fixed onto a dental chair in a windowless room with artificial ceiling lighting to simulate clinical conditions (Fig. 3). Digital scans were performed with 4 new intraoral scanners of the same model and from the same manufacturer (Primescan with software program Sirona Connect v5.2. and the following hardware settings:

Figure 4. Three-dimensional view of intraoral scan.

CPU: 3.20 GHz, RAM: 32.0 GB, graphics card: NVIDIA GeForce RTX 3060; Dentsply Sirona) after calibration with 4 calibration aids (CAs). Each scanner was calibrated with each CA, and 12 complete arch scans were made per combination, resulting in a total of 192 intraoral scans. The room temperature was 24.8 ±0.4 °C, and the relative humidity was 24.2 ±7.5% for all scans. All scans were performed by a calibrated investigator with experience in scanning (S.B.) and according to the manufacturer's recommended scanning strategy.

The scans were postprocessed by using the scanner's software program and exported in standard tessellation language (STL) file format for further evaluation (Fig. 4). For standardization reasons during the evaluation, the scans were first aligned with the reference data set via the teeth with a commercially available CAD software program (Geomagic Design X; 3D systems) using a best fit algorithm (Fig. 5). Second, scan surfaces were trimmed with predefined cutting surfaces such that only precision ball sections relevant for evaluation remained (Fig. 6). Individual precision ball surfaces were exported in separate STL files. Then, an automized evaluation (Matlab version R2022a; MathWorks) was executed to determine the 5 precision ball centers (P1′ to P5′, numbered as those in the reference model) by means of optimization and to calculate the angular and distance deviations between the scan and the reference. Mathematical details of the optimization procedure used to determine the precision ball centers can be found in a previous publication.[7] Box plots were created for each category to visualize the distance deviations, with the

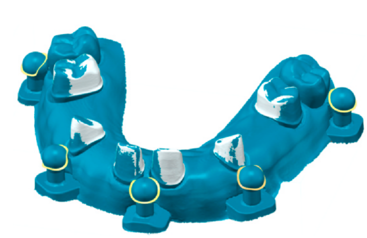

Figure 5. Alignment of individual intraoral scan (*turquoise*) with teeth of reference data set (*white*) to enable standardized trimming.

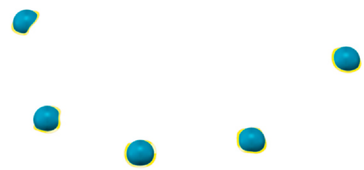

Figure 6. With predefined cutting surfaces (*yellow*) trimmed scan surface resulting in precision ball sections only relevant for evaluation (*turquoise*).

different scanners plotted on the x-axis and the calibration aids distinguished with colors.

Separate linear models were fitted to the deviations found for each distance category and for each angle. These models included the factors scanner (PS1–PS4) and calibration aid (CA1–CA4) as covariates and the deviation between measured and reference values as the dependent variable. To account for the different effects of the calibration aid on each scanner, an interaction term was also included.

A type III ANOVA was performed for each angle and for each distance category to examine the significance of each effect. Contrasts for each factor were reported together with the standard error using conditional estimated marginal means, also known as conditional least-square means. In the case of multiple comparisons, *P*-values were adjusted by using the Tukey method, with the mean difference between 2 levels of each factor calculated while the other factor remained fixed. Differences between the different scanners and between the different calibration aids were determined at a 5% significance level. The data were assumed to be normally distributed, which was checked by using the Shapiro-Wilk test and graphical inspection of the QQ-Plots. All analyses were performed using an open source software program (R, version 4.2.2; R Foundation for Statistical Computing).

RESULTS

The absolute distance deviations for the 4 distance categories and all combinations of scanner and calibration aid are shown in Figure 7. Irrespective of scanner and calibration aid, the distance deviation and the scatter of measured values increased with the scan path length (that is, with increasing distance category) (Table 2). The respective mean deviations for SDI and MDI were a maximum of 34.8 µm and 63.6 µm, and the maximum deviation did not exceed 160 µm. Differences in mean value between the test groups for SDI did not exceed 20 µm (Table 1). The respective mean and maximum distance errors increased to 105.4 µm and 298.4 µm for category 3 and to 181.8 µm and 539.2 µm for CADI. In

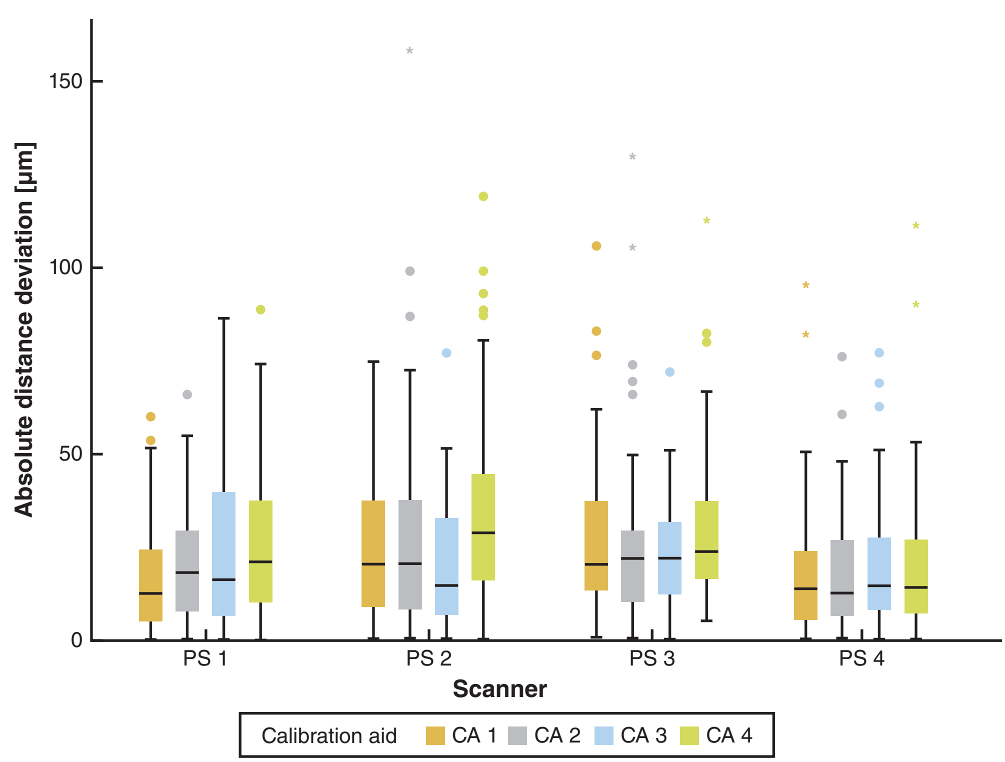

Figure 7. Absolute deviations for all calibration aids (CA) and all scanners (PS = Primescan) displayed for distances of category “short distances”.

Table 2. Absolute distance deviations between reference model and intraoral scans for all categories

PS	CA	Category	Distance Deviation (μm)					
			N	Min	Median	Max	Mean	SD
1	1	SDI	48	0.1	12.6	59.7	16.7	14.9
		MDI	36	0.1	13.2	58.5	20.3	16.4
		LDI	24	0	34.2	96.8	33.3	29.2
		CA	12	51.8	90.9	169.5	100.5	43.5
	2	SDI	48	0.1	18.3	66.0	20.5	15.0
		MDI	36	2.7	23.6	89.8	27.7	22.2
		LDI	24	4.8	44.8	187.4	53.2	40.2
		CA	12	8.9	92.4	331.7	109.4	87.7
	3	SDI	48	0.3	16.2	86.4	25.1	24.1
		MDI	36	0.1	31.8	96.8	38.9	29.8
		LDI	24	0.9	56.9	147.7	64.1	46.6
		CA	12	15.7	85.9	230.2	102.7	72.2
	4	SDI	48	0	21.0	88.7	26.6	21.2
		MDI	36	0.9	20.6	92.4	30.2	27.2
		LDI	24	1.6	45.6	114.2	45.2	31.5
		CA	12	12.2	52.0	149.1	71.7	46.9
2	1	SDI	48	0.1	20.4	74.8	25.4	20.8
		MDI	36	0.1	21.8	94.6	27.5	24.0
		LDI	24	3.5	38.8	157.6	51.0	38.6
		CA	12	0.6	79.1	311.8	83.9	87.7
	2	SDI	48	0.6	20.6	158.2	29.3	30.6
		MDI	36	11.5	37.9	132.6	49.0	29.7
		LDI	24	0.4	77.6	187.9	77.8	45.9
		CA	12	51.3	91.3	284.2	130.8	83.8
	3	SDI	48	0.2	14.8	77.2	19.6	16.7
		MDI	36	0.2	20.4	82.2	28.8	25.8
		LDI	24	0.3	56.8	151.4	64.0	42.8
		CA	12	40.7	159.9	332.3	150.2	99.2
	4	SDI	48	0.1	28.9	119.3	34.8	27.6
		MDI	36	4.6	63.7	152.2	63.6	40.8
		LDI	24	7.2	102.7	298.4	105.4	80.6
		CA	12	10.0	157.8	539.2	181.8	153.2
3	1	SDI	48	0.8	20.4	105.8	28.1	22.7
		MDI	36	1.0	29.8	122.8	39.3	30.9
		LDI	24	2.8	36.7	180.8	55.1	49.1
		CA	12	3.4	65.0	339.5	87.8	108.7
	2	SDI	48	0.6	22.0	130.0	26.4	25.6
		MDI	36	1.1	29.8	124.1	35.2	30.0
		LDI	24	0.4	44.6	163.8	55.9	42.8
		CA	12	30.0	92.2	297.9	116.3	85.1
	3	SDI	48	0.4	22.0	71.8	22.7	14.4
		MDI	36	0.3	32.7	85.3	35.6	24.4
		LDI	24	3.4	42.0	162.2	52.5	43.2
		CA	12	6.9	72.3	228.4	87.0	72.9
	4	SDI	48	5.2	23.8	112.8	30.2	22.2
		MDI	36	2.8	37.4	138.3	47.2	32.6
		LDI	24	10.9	68.0	181.0	69.0	45.8
		CA	12	6.8	99.9	221.9	106.8	69.9
4	1	SDI	48	0.2	13.8	95.4	18.0	19.2
		MDI	36	2.1	22.0	66.1	24.0	16.6
		LDI	24	0.3	17.1	87.2	27.5	28.1
		CA	12	3.1	67.3	186.0	68.8	49.8
	2	SDI	48	0.5	12.7	76.1	18.2	16.4
		MDI	36	3.6	26.0	88.7	30.4	21.9
		LDI	24	1.5	45.6	133.3	52.3	36.3
		CA	12	13.1	72.5	296.1	99.5	87.3
	3	SDI	48	0.5	14.7	77.2	20.4	18.2
		MDI	36	0.8	24.6	69.1	27.4	18.8
		LDI	24	1.6	33.3	90.9	37.9	27.3
		CA	12	9.3	48.9	191.8	71.5	64.9
	4	SDI	48	0.1	14.1	111.3	21.0	21.5
		MDI	36	1.2	18.3	96.4	26.6	22.7
		LDI	24	3.0	50.1	114.9	50.4	33.0
		CADI	12	18.2	80.5	269.5	105.2	79.9

CA, calibration aid; CADI, cross-arch distance; LDI, long distance; Max, maximum; MDI, medium distance; Min, minimum; PS, Primescan; SD, standard deviation; SDI, short distance.

addition, the scanning accuracies were different, irrespective of the distance category, between the intraoral scanners and between one scanner in combination with different calibration aids.

Type III ANOVA analyses showed that the distance deviations were significantly affected by the covariates scanner ($P \leq .023$) and calibration aid (SDI, MDI, and LDI: $P \leq .013$). The interaction term between the scanner and

Table 3. Results of ANOVA Type III analyses for distance categories

Distance Category	Variable	*P*
SDI	PS	<.001
	CA	.013
	PS:CA	.176
MDI	PS	<.001
	CA	<.001
	PS:CA	<.001
LDI	PS	<.001
	CA	<.001
	PS:CA	.057
CADI	PS	.023
	CA	.261
	PS:CA	.480

CA, calibration aid; CADI, cross-arch distance; LDI, long distance; Max, maximum; MDI, medium distance; Min, minimum; PS, Primescan; SDI, short distance.

the calibration aid had no significant effect (P>.05) except for the distance deviations of MDI (P<.001) (Table 3).

For all evaluated angles, the mean deviations given by 3 ball centers ranged between 0.03 degrees and 0.21 degrees. The maximum angular deviation never exceeded 0.59 degrees. Deviations were largest in the opening angle. The mean absolute deviations for the opening angle ranged between 0.10 degrees and 0.21 degrees. Type III ANOVA analyses showed that the deviations in the opening angle were significantly affected by the covariate scanner (P<.001) and not by the covariate calibration aid or the interaction term.

Multiple comparisons showed that, for distance categories 2 and 3, calibration aids CA1 and CA3 performed significantly better than CA4 (Figs. 8, 9). No systematic behavior could be extracted from the other significant pairwise test results.

DISCUSSION

The null hypotheses that no difference in scanning accuracy would be found among the 4 intraoral scanners, among the 4 calibration aids, and for all combinations of these were rejected. A model of a partially edentulous maxilla with 6 remaining prepared teeth to accommodate a complete arch fixed partial denture was evaluated, representing typical prosthodontic treatment. However, the interrupted dental arch with edentulous ridge sections creates problems for intraoral scanning systems, as these sections[11,12] and the number and distribution of the remaining teeth reduce the scanning accuracy.[7,12]

The results showed that the size and spread of distance deviations depended on the respective distance category given by the respective scan path length, consistent with previous studies.[7,10,16,17] Horizontal and vertical distance deviations have been previously reported to be linearly dependent on the scan path length.[6,8]

Distance deviations were found to be dependent on the scanner and the calibration aid used. Identical scanning systems from the same manufacturer can provide different scanning results, and the calibration aid supplied by the

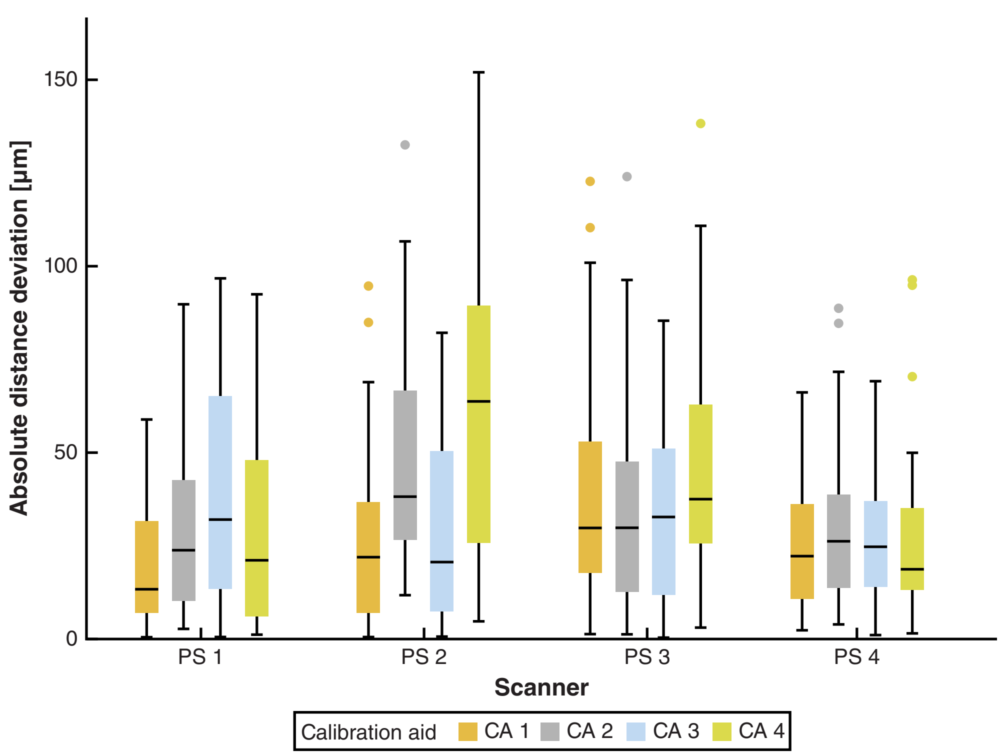

Figure 8. Absolute deviations for all calibration aids (CA) and all scanners (PS = Primescan) displayed for distances of category "medium distances".

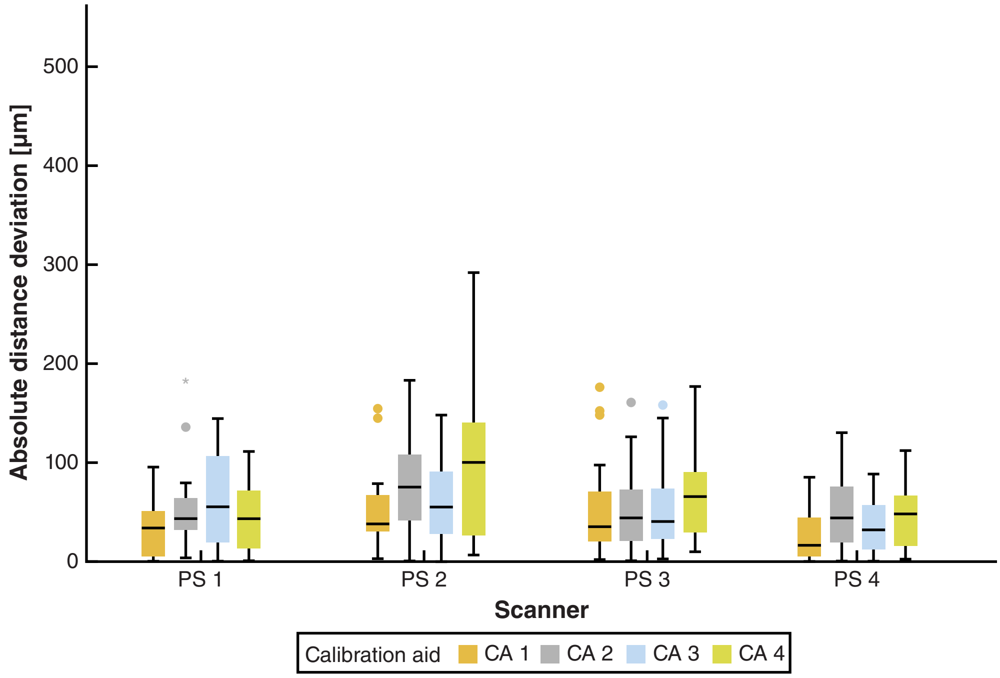

Figure 9. Absolute deviations for all calibration aids (CA) and all scanners (PS = Primescan) displayed for distances of category "long distances".

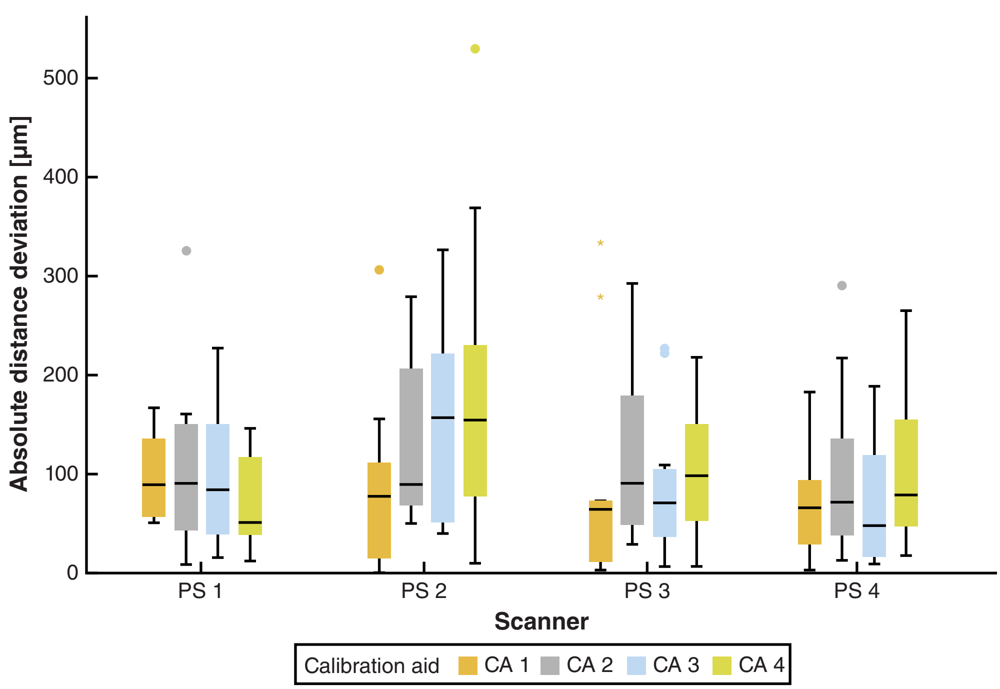

Figure 10. Absolute deviations for all calibration aids (CA) and all scanners (PS = Primescan) displayed for distances of category "cross-arch distance".

manufacturer does not necessarily give the best possible scanning results. Because the differences were rather small (mean error <64 µm, maximum error <160 µm) for scans up to a quadrant, and only became apparent for scans exceeding a quadrant, current scanners should only be used for half a jaw or less when providing fixed prostheses. This also implies that investigations into the scanning accuracy of complete arches must be interpreted critically, as the data originate from variable combinations of scanner and calibration aid.

To enable the clinical use of intraoral scanners in complete arch scans, either the manufacturer needs to enhance the standardization of all scanners or dentists need calibrated complete arch reference models to determine whether their intraoral scanner–calibration aid combination provides accurate results even for longer scan path lengths.

The scanners tested in this study were new. Intraoral scanners can be exposed to vibration or shock due to transport, mishandling, or accidents, which may change their performance over time. These changes cannot be identified by the dentist using the intraoral scanner but rather only after observing a deterioration in the fit of similar restorations. A test model with which to regularly check the scanner performance would be beneficial.

Limitations of this study included that only 1 scanning system was used, so the results cannot be extrapolated to other scanning systems and can only serve as an example. However, because of tolerances in the manufacturing process of scan heads and calibration aids, the trends observed may also apply to scanners from other manufacturers. Another limitation was the in vitro design with only 1 partially edentulous situation, so the results cannot be fully extrapolated to other partially edentulous jaws with fewer and more unevenly distributed teeth. Further studies should be carried out with scanning systems from different manufacturers in other models of partially edentulous jaws with unevenly distributed teeth, and these results should be verified clinically. The sample size (n=12) of this explorative study allowed mean groups differences to be identified with a power >.80 as long as the group standard deviations were below 80% of difference in group mean values. With large standard deviations of 2 to 3 times the difference in group mean value, which was often the case with the data, a sample size of n=64 to 143/group would have been necessary to identify more significant differences in accuracy with pairwise post hoc testing.

CONCLUSIONS

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

1. Scanning accuracy depended on the scanner and the calibration aid used.
2. Acceptable scanning results were achieved regardless of the combination of scanner and calibration aid if the scan path was restricted to 1 quadrant.

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