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Original article

Evaluation of the trueness and precision of eight extraoral laboratory scanners with a complete-arch model: a three-dimensional analysis

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ABSTRACT

Purpose: The purpose of this study was to evaluate the trueness and precision of eight different extraoral laboratory scanners using three-dimensional (3D) analysis method.
Method: An arch-shaped master model was designed with a computer software (Rapidform XOR2) and manufactured with a 3D printer (Projet 3510 MP). Then the master model was digitized with an industrial 3D scanner (ATOS Core 200). With each scanner master model was scanned ten times and stereolithography (.stl) data were imported into 3D analysis software (Geomagic Control). Accuracy was determined with evaluating trueness and precision.
Results: Trueness of the scanners were 27.5 μm for 7 series; 30.9 μm for D640; 26.8 μm for D710; 33.3 μm for Activity 102; 32.4 μm for Tizian Smart-Scan; 21.6 μm for NeWay; 26.1 μm for inEOS X5 and 17,47 μm for D2000. 28.2 μm for laser; 32.9 μm for white light and 21.7 μm for blue light scanners. Significant differences were found between scanners ($p < .001$), ($p < .001$). Precision of the scanners were 30.1 μm for 7 series; 31.7 μm for D640; 26.3 μm for D710; 22.7 μm for Activity 102; 25.1 μm for Tizian Smart-Scan; 15.7 μm for NeWay; 26.1 μm for inEOS X5; 16.6 μm for D2000. 29.2 μm for laser; 24.4 μm for white light and 19.2 μm for blue light scanners. Significant differences were found between scanners ($p < .001$), ($p = .027$).
Conclusions: The systems that had the best combination of trueness and precision for complete-arch scanning were D2000 and NeWay. Scanners using blue-light showed more accurate results than the white-light and laser scanners.

1. Introduction

Computer-aided design/computer aided manufacturing (CAD/CAM) was introduced in dentistry in 1980's [1–3]. Since then it has continued to be used more extensively than the conventional casting process for the production of dental infrastructures due to the constant development of technology [2]. Digital workflow eliminates impression procedure, disinfection, impression packaging and shipping, definitive cast fabrication and articulation when compared to conventional methods [4,5]. Because of the standardized manufacturing process, the CAD/CAM systems produce high-quality restorations [6]. Digital workflow has 3 main steps: direct or indirect data acquisition, the design of the restoration and manufacturing process [2,7,8]. In the data acquisition process, two types of scanners are used; intraoral and extraoral. Intraoral scanners are used for chairside digitizing of patients' arches and extraoral laboratory scanners are used for indirect digitization of definitive casts [6,9]. Digital intraoral scanning is gaining popularity in dentistry due to the high patient acceptance, reduced distortion of impression materials, simplifying fabrication procedure and decrease in costs [10]. However, digital intraoral scanning has also disadvantages, such as limitations of scanning technologies and devices, distortion of captured images, the difference in the operator's skill, movement of the patient, restricted space in the oral cavity and high price of machines [11–13]. Thus, the required time for digital impressions was 27% more than conventional impressions [14] and in many clinical conditions, the accuracy of intraoral scanners has not been proven yet [5,10,15]. According to some authors, extraoral scanning has a higher precision than intraoral scanning [15,16]. On the other hand, conventional impressions and stone casts are still used in the fabrication of prosthetic restorations. Stone casts are scanned by extraoral scanners and obtained data are used in many CAD/CAM systems and restorations made from this process show excellent long-term results [8,17]. According to some studies, extraoral scanners showed acceptable accuracy [5,18].

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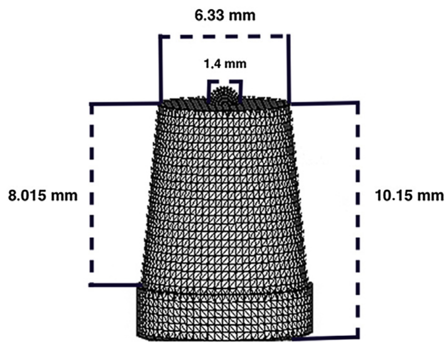

Fig. 1. Dimensions of the abutments on the arch.

Accuracy consists of two parameters; trueness and precision [2,19]. Trueness is the deviation of the scanned object from its actual dimensions [2,15]. Precision is the deviation between repeated scans [19]. A high trueness describes how close to the original dimensions of the measured object and high precision defines predictability of the measurement. As a consequence, the fit of the restorations depends on the trueness and precision of the dental scanners [2]. Some studies have compared the fitting of fixed restorations fabricated with different scanning systems [8,17,20–22]. However, very few studies evaluate the accuracy of full-arch scans using different extraoral scanning systems [2,13,14]. Every step of CAD/CAM process has a potential source of error and each procedure in any CAD/CAM workflow can affect overall performance [6,23]. Therefore, the aim of this study was to evaluate the accuracy, in terms of trueness and precision of eight different extraoral scanners. The null hypothesis was that no statistically significant differences exist between the scanners.

2. Materials and methods

An arch-shaped master model mimicking the mandibular arch, 14 mm in height and 16 mm in width, was designed with a computer software (RapidForm XOR2; 3D Systems Inc, Rock Hill, SC, USA). Five abutments with a 6° total angle of convergence and 1 mm flat circumferential shoulder finish lines, resembling prepared teeth (right mandibular first molar, right mandibular canine, central incisor, left mandibular first molar, and left mandibular canine) with a 10,15 mm height were placed on the arch. Hemispherical landmarks (1,4 mm diameter) were added in the middle of the occlusal surfaces of the 5 abutments and used as reference points to allow measurements (Fig. 1). The digital file was saved in stereolithography format (.stl). The master model was manufactured with a proffesional three-dimensional (3D) printer (Projet 3510 MP, 3D Systems) using multi-jet-modelling printing technology. Resolution (xyz) of the 3D printer was 375 × 375 × 790 DPI. VisiJet PS200, VisiJet PearlStone material was used with a layer thickness of 32 μm.

2.1. Scanning procedure

An industrial structured blue light-emitting diode (LED) 3D scanner (ATOS Core 200 5M, GOM GmbH, Braunschweig, Germany), was selected as the reference scanner (RS). RS uses two cameras combine with the projector to capture three views of an object in a single measurement process. This requires fewer scans and delivers higher quality data. RS was calibrated and tested according to VDI/VDIE 2634 Part 3 (VDI e.V.; Düsseldorf, Germany), displaying maximum deviations: 0,002 mm probing error form (Sigma), 0,004 mm probing error (size), 0,007 mm sphere spacing error and 0,008 mm length measurement error.

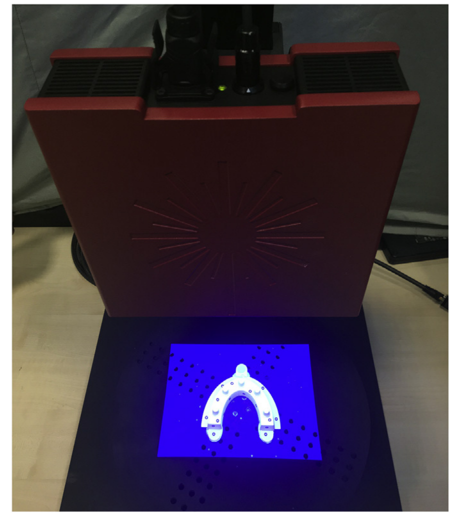

Fig. 2. Scanning process of the master model.

Before the study, RS was calibrated with a calibration panel (GOM Type/SN CP40/200/100846). Then, the master model was digitized ten times with the RS (Fig. 2). Ten scan data of the master model was merged with computer software and one file was created as the digital master model (DMM). The models and light source properties of eight extraoral scanners that were used in tests are as listed in Table 1. With each extraoral scanner the master model was scanned according to the manufacturer's instructions. Ten scan data of each scanner were exported and saved in. stl file format.

2.2. 3D analysis

3D analysis software (Geomagic Control, 3D Systems) superimposed laboratory scan data (LSD) over the DMM, using the best-fit alignment method and the same method was used for each LSD. A sample size of 15,000 points with a tolerance of 0,001 mm was used in the 3D analysis. In the 3D analysis software reports, the best-fit aligment results indicated by root mean square (RMS), average maximum and minimum values and standard deviation (SD) of each scan was saved. Color-coded maps were used to show the differences spread over the master model surface. The settings of the distribution of deviations were at nominal ±10 μm and critical ±150 μm (Fig. 3). In the color-coded maps, yellow-to-red fields indicated LSD were larger than DMM; and light blue-to-dark blue fields indicated LSD were smaller than DMM. Graphical pass-fail presentation of deviations was also given (Fig. 4). Pass value shows (green fields) deviations, which remain between 0 and 30 μm and fail value shows (red fields) deviations higher than 100 μm.

2.3. Statistical analysis

The statistical analysis was achieved with a significance level of 95% using a statistical software (SPSS v20 for Macintosh; IBM Corp., Chicago, IL, USA). Levene's test was used for determining

Table 1. Characteristics ofextraoral laboratory scanners

Scanner model	Manufacturer	Light source	Camera/ color	Triangle count
7 Series	Dental Wings, Montréal, Canada	Blue laser	3 cameras/ one color	100.297
D640	3Shape, Copenhagen, Denmark	Red laser	2 cameras	84.516
D710	3Shape	Red laser	2 cameras	91.953
Activity 102	Smart Optics, Bochum, Germany	White light	One camera	1.613.626
Tizian Smart-Scan	Schütz Dental, Rosbach, Germany	White light	One camera	737.670
NeWay	Open Technologies, Rezzato, Italy	Blue LED	2 cameras/ two color	185.882
InEOS X5	Sirona Dental Systems, Bensheim, Germany	Blue LED	One camera	522.991
D2000	3Shape	Blue LED	4 cameras/ four color	389.564

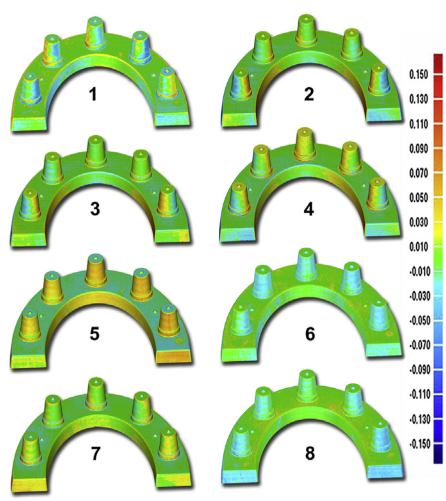

Fig. 3. Superimposition of LSDs onto DMM. Yellow through red indicates LSD is larger than DMM; light blue through dark blue indicates LSD is smaller than DMM; green surface shows difference ±10 µm between LSD and DMM. (1) 7 Series, (2) D640, (3) D710, (4) Activity 102, (5) Tizian Smart-scan, (6) NeWay, (7) inEOS X5, (8) D2000.

homogenity of variances. Kolmogorov–Smirnov with Lillefors adjustment test was conducted for testing normality. If the variances normally distributed Welch's test was used to evaluate between-group differences (α = .05 for all tests) and Tamhane test was used for multiple comparisons. When homogenity and normality assumption was not met, Kruskal-Wallis non-parametric test was used to evaluate between-group differences (α = .05 for all tests). In addition, Dunn test was conducted for pairwise comparisons.

3. Results

3.1. Trueness

According to Kolmogorov–Smirnov test with Lilliefors Significance correction (p = .200) variances were found normally distributed. Therefore, Welch's test was used to analyze RMS

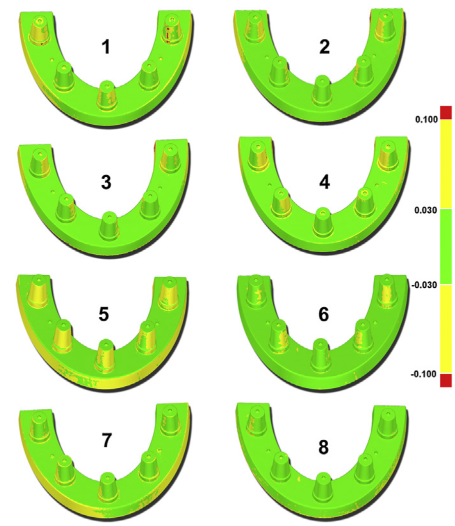

Fig. 4. Graphical presentation of deviation distribution and pass-fail scale. The deviation range is color-coded from −30 to +30 µm. Red surface shows differences higher than 100 µm. Yellow fields represent deviations between ±30 and ±100 µm. (1) 7 Series, (2) D640, (3) D710, (4) Activity 102, (5) Tizian Smart-scan, (6) NeWay, (7) inEOS X5, (8) D2000.

Table 2. Trueness values (µm) for all test groups

	Mean	Std. deviation	Minimum	Maximum
7 Series	27.5	2.63	25.3	32.4
D640	30.9	1.16	29.5	32.5
D710	26.8	1.75	24.6	30.3
Activity 102	33.3	6.99	23.8	47.2
Tizian Smart-Scan	32.4	3.07	25.2	35.9
NeWay	21.6	3.10	16.7	25.1
InEOS X5	26.1	2.63	22.0	30.9
D2000	17.4	1.25	16.2	19.6

values and statistically significant differences were found between the tested scanners. (F [7, 30.353] = 90.511, $p < .001$). D2000 (17.4 µm) and NeWay (21.6 µm) scanners showed lowest RMS values (Table 2) but the difference between them was statistically not significant (p = .056). Tamhane test was used for multiple comparisons. (Table 6). RMS value of D2000 scanner was statistically significantly lower than other tested scanners. Trueness values for scanners with different scanning technologies were given in Table 3. Welch's test was used and statistically significant differences were found between the scanners with different scanning technologies (F [2, 41.934] = 45.832, $p < .001$). Scanners using blue LED light showed statistically significant differences ($p < .001$, $p < .001$) from scanners using white light and laser (Table 7).

3.2. Precision

According to Kolmogorov–Smirnov test with Lilliefors Significance correction (p = .023) variances were not normally distributed. Therefore, Kruskal–Wallis non-parametric test was used to analyse RMS values and statistically significant differences were found between the tested scanners. ($p < .001$). Dunn test was used for multiple comparisons. NeWay (15.7 µm) and D2000 (16.6 µm)

Table 3. Trueness values (μm) for scanners with different scanning technologies

	Mean	Std. deviation	Minimum	Maximum
Laser	28.2	2.46	24.6	32.5
White light	32.9	4.05	23.8	41.5
Blue light	21.7	4.28	16.2	30.9

Table 4. Precision values (μm) for all test groups

	Mean	Std. deviation	Minimum	Maximum
7 Series	30.1	1.58	27.8	33.1
D640	31.7	1.27	30.3	35.0
D710	26.3	1.54	24.6	29.5
Activity 102	22.7	1.73	20.6	26.0
Tizian Smart-Scan	25.1	1.89	21.7	27.9
NeWay	15.7	1.23	14.1	17.8
InEOS X5	26.1	1.94	22.3	30.1
D2000	16.6	3.08	13.9	21.3

(Table 4) scanners showed the highest precision but the difference between them was statistically not significant ($p = .992$). The precision values of D2000 was statistically significant than other tested scanners except Activity 102 ($p = .082$) (Table 6). Significant decrease in precision was found in accordance with the other scanners: 7 Series (30.1 μm, $p < .001$), D640 (31.7 μm, $p < .001$), D710 (26.3 μm, $p = .001$), Activity 102 (22.7 μm, $p = .082$), Tizian Smart-Scan (25.1 μm, $p = .004$) and inEOS X5 (26.1 μm, $p < .001$). Precision values of scanners analyzed with Kolmogorov–Smirnov test with Lilliefors Significance correction ($p = .004$) and found normality assumption was not met. Therefore, Kruskal–Wallis non-parametric test was used to analyze precision values and statistically significant differences were found between the scanners using different light sources. ($p < .001$). According to the scanning technology (Table 5), scanners using blue LED light showed statistically significant differences ($p = .027$, $p < .001$) from scanners using white light and laser (Table 7).

4. Discussion

According to the results of the present study, different extraoral scanners showed significant differences in terms of trueness and precision. Therefore, the null hypothesis of the study was rejected.

In previous digitizing system analyses, mean positive or mean negative deviations [24], absolute values [20], different surface areas, deviation percentages [15] and RMS values [5,11,25] were used for trueness. Also, SD values were used when evaluating precision [19,26]. In the present study, RMS values were used to evaluate trueness because in the quantitative inspection if the positive and negative deviations show an equal distribution, total deviation values will be close to zero [5,20,27]. In addition, qualitative inspection on color-coded maps was a necessity to evaluate the distribution of deviations [27].

Some studies showed that the accuracy decreases when the scanned area increases [20,25]. When scanning larger areas, multiple images are merged and this may lead to progressive distortion and higher inaccuracy [15]. González de Villaumbrosia et al. [6] used a single master die and evaluate trueness and precision of six extraoral scanners. They reported that trueness values varied between 29 μm to 46 μm and precision values varied between 37.5 μm to 50.6 μm. Mandelli et al. [5] used a single titanium abutment and test seven extraoral scanners. Their trueness values were changed between 7.7 μm to 31.1 μm and precision was between 4 μm to 19.5 μm. According to Hayashi et al. [28] trueness of two optical scanners were found 50–55 μm when complete arch casts were used.

Table 5. Precision values (μm) for scanners with different scanning technologies

	Mean	Std. deviation	Minimum	Maximum
Laser	29.2	2.64	24.6	35.0
White light	24.4	2.27	20.6	28.0
Blue light	19.2	5.17	13.9	30.1

Renne et al. [13] used a full-arch model and found trueness and precision of an extraoral scanner 43.6 μm and 69.2 μm, respectively. Vandeweghe et al. [2] tested four laboratory scanners and scanned a full arch acrylic resin model and their mean trueness values varied between 37 μm to 58 μm and mean precision values varied between 3 μm to 69 μm. As can be seen from the studies mentioned above, single abutments can be digitized with a higher accuracy compared to a complete dental arch. However, arch-shaped master models would be more relevant to clinical conditions and full arch definitive casts were also used for complete arch scanning in the fabrication of the fixed restorations.

Internal and marginal fit of the restoration is an important factor for the long-term success because misfit can compromise abutment teeth and periodontal tissues [29–32]. Some studies showed clinically acceptable marginal fit values below 100 μm [2,33–35]. This means that the accuracy of the tested scanners must be within this range or even below [2]. In the present study trueness values were ranged between 17.4 and 33.3 μm. The precision values were ranged between 15.7 and 31.7 μm. Comparing our results with other studies is challenging because reference scanners, tested scanners, master models, 3D analysis software and methodology used in these studies were varying.

Different types of laboratory scanners available in the dental market such as; white-light scanners, the laser scanners, and blue-light scanners. Structured white light scanners project a pattern in the 2-dimensional mode and have good scanning speed. However, repeatability is lacking and in narrow and deeper areas errors can be occurred frequently. Laser scanners use a line pattern, however, they have slow scanning speed and low initial scanning repeatability. Structured blue light scanners, have greater scanning repeatability and produce fewer errors [36]. Their blue LEDs have a shorter wavelength and this lead to a higher precision [20,37]. The present study compared the accuracy of the structured blue-light scanners with that of the structured white-light scanners and laser scanners. The blue-light scanners exhibited more accurate results than the white-light scanners and laser scanners. For this reason, devices using blue-light for digitizing might be an important requisite for extraoral scanning [36]. The accuracy of scanners was statistically different but it is challenging to explain the source of the deviations because the scanners use different light sources, scan technologies, and algorithms.

On the other hand, digitized data consist of triangles that are generated by the algorithms of the scanner software [38]. However, according to Nedelcu et al. [21] and Mandelli et al. [5], there is no linear correlation between scanner accuracy and triangle count. In our study, NeWay and D2000 were most accurate machines and had an average of 185.882 and 389,564 triangles, respectively. On contrary, Activity 102 was the least accurate device and had an average of 1.613.626 triangles. These results are in accordance with previous studies [5,21].

As a result, device hardware and algorithms of software, scanning technology [5], shape [6] and size of the master model [20,25] has a significant impact on the accuracy of an extraoral scanner.

This study has several limitations. As known in the clinical conditions, patients' dental arches are encountered in various sizes and shapes. Therefore, a single type of master model cannot be entirely simulated the clinical conditions. Most of the master models

Table 6. Statistical outcome of the comparison between the different scanners

		Precision								
Trueness		7 Series	D640	D710	Activity 102	Tizian Smart-Scan	NeWay	InEOS X5	D2000	Precision
	7 Series		.516	.052	<.001	.013	<.001	.059	<.001	
	D640	.073		.010	<.001	.002	<.001	.011	<.001	
	D710	1000	<.001		.089	.580	.001	.958	.001	
	Activity 102	.581	1.000	.383		.252	.083	.080	.082	
	Tizian Smart-Scan	.037	.997	.006	1000		.004	.544	.004	
	NeWay	.007	<.001	.010	.010	<.001		<.001	.992	
	InEOS X5	1000	.005	1.000	.254	.003	.069		<.001	
	D2000	<.001	<.001	<.001	.001	<.001	.056	<.001		
Trueness										

Table 7. Statistical outcome of the comparison between different scanning technologies

	Precision				
Trueness		Laser	White light	Blue light	Precision
	Laser		<.001	<.001	
	White light	<.001		.027	
	Blue light	<.001	<.001		
Trueness					

in studies had different geometries. These different geometries also could affect the accuracy. Using full-arch master models with different width and shapes for future studies may make it possible to achieve more consistent and precise information. Also, the scanning speed of complete-arch model is an important factor for comparing the scanners. According to Renne et al. there is a strong correlation exist between accuracy and time [13]. For this reason, speed factor might be included into further researches.

5. Conclusion

Within the limitations of this study, with regard to trueness and precision of evaluated scanners for a complete-arch model, D2000 (17.47 μm–16.62 μm) and NeWay (21.62 μm–15.7 μm) were significantly more accurate than other scanners. Different scanning technologies (laser, white light, blue light) were also used as a parameter of this study. It can be concluded that scanners that use blue light technology (21.7 μm–19.2 μm) were more accurate than scanners using laser (28.2 μm–29.2 μm) and white light (32.9 μm–24.4 μm). Further studies needed to evaluate accuracy of new devices with additional paramaters like scanning speed, and different master model geometry.

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