Dental Materials Journal 2017; 36(1): 27–34

Evaluation of the accuracy and precision of four intraoral scanners with 70% reduced inlay and four-unit bridge models of international standard

Soo-Hyuk UHM[1]*, Jae-Hong KIM[2]*, Heng Bo JIANG[1], Chang-Woo WOO[3], Minho CHANG[4], Kyoung-Nam KIM[1], Ji-Myung BAE[5] and Seunghan OH[5]

[1] *Department and Research Institute of Dental Biomaterials and Bioengineering, College of Dentistry, Yonsei University, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea*
[2] *Department of Dental Technology, School of Medical and Public Health, Kyungdong University, 815 Gyeonhwon-ro, Wonju, Gangwondo 24695, Republic of Korea*
[3] *Central Dental Laboratory, Dental Hospital of Yonsei University, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea*
[4] *School of Mechanical Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea*
[5] *Department of Dental Biomaterials and the Institute of Biomaterials and Implant, College of Dentistry, Wonkwang University, 460 Iksan-Daero, Iksan, Jeonbuk 54538, Republic of Korea*
Corresponding author, Seunghan OH; E-mail: shoh@wku.ac.kr

The aims of this study were to evaluate the feasibility of 70% reduced inlay and 4-unit bridge models of International Standard (ISO 12836) assessing the accuracy of laboratory scanners to measure the accuracy of intraoral scanner. Four intraoral scanners (CS3500, Trios, Omnicam, and Bluecam) and one laboratory scanner (Ceramill MAP400) were used in this study. The height, depth, length, and angle of the models were measured from thirty scanned stereolithography (STL) images. There were no statistically significant mean deviations in distance accuracy and precision values of scanned images, except the angulation values of the inlay and 4-unit bridge models. The relative errors of inlay model and 4-unit bridge models quantifying the accuracy and precision of obtained mean deviations were less than 0.023 and 0.021, respectively. Thus, inlay and 4-unit bridge models suggested by this study is expected to be feasible tools for testing intraoral scanners.

Keywords: Trueness (Accuracy), Precision, Intraoral scanner, Laboratory scanner, International Standard

INTRODUCTION

The recent introduction of digital dentistry based on industrial computer-aided design and computer-aided manufacturing (CAD/CAM) systems promises to produce prostheses more easily and quickly than conventional methods, and is also able to mass-produce various types of prostheses[1,2]. In particular, development of intraoral scanners has changed the paradigm of impression procedures from impression materials and gypsum-based indirect impression techniques to digital dentistry based chair-side impression techniques[3-5]. Quick and easy digital impressions offer convenience to both patients and dentists, and are a core technology for dental CAD/CAM systems[6,7].

Digital impression systems are generally composed of a three-dimensional intraoral scanner recording the image of the object and CAD software that uses the scanned image to design the prosthesis[8]. Intraoral scanner performance is evaluated by measuring the accuracy and precision of the scanned image[6,9]. Evaluation of the precision and accuracy of oral scanners allows development of methods to reduce impression error in dental clinics and increase the fabrication success rates of customized prostheses.

Most previous studies have estimated the accuracy and precision of intraoral scanners using various shaped objects such as customized inlay cavity models, natural tooth-shaped models, and full-arch dentiform models[10-17]. However, the precision and accuracy measurement of the oral scanner differs between each researcher because of differences in scanning models; thus, the interpretations of the measured precision and accuracy have been variously expressed. It is therefore necessary to develop a standard model to evaluate the precision and accuracy of oral scanners under standard conditions. The International Standards Organization has published standards for assessing the accuracy and precision of laboratory scanners (ISO 12836)[18], but intraoral scanners are not currently included. Moreover, although the American standard of testing the accuracy and precision of dental scanner enacted by American Dental Association (ADA) was recently introduced[19], its validation by various researchers is ongoing.

The objectives of the present study were to (1) prepare inlay and 4-unit bridge models for intraoral scanners based on the standard models suggested by ISO 12836, (2) test the accuracy and precision of intraoral scanners using these prepared models, and (3) evaluate the feasibility of the new standard models for testing the accuracy and precision of intraoral scanners.

*Authors who contributed equally to this work.
Color figures can be viewed in the online issue, which is available at J-STAGE.
Received Feb 15, 2016: Accepted Aug 2, 2016
doi:10.4012/dmj.2016-064 JOI JST.JSTAGE/dmj/2016-064

MATERIALS AND METHODS

Fabrication of models

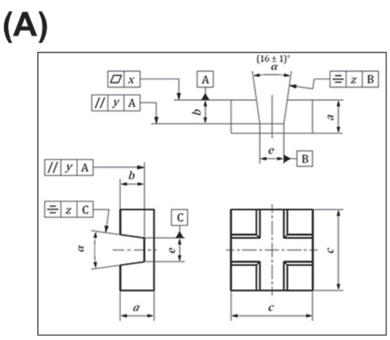
In this study, 70% reduced inlay and 4-unit bridge models described in ISO 12836[18] were prepared in order to assess the accuracy and precision of intraoral scanners. Stainless-steel material-based models were fabricated using computer numerical controlled (CNC) milling. The models were sand-blasted with 50 µm alumina powders in order to minimize light reflection. Figure 1 illustrates the schematic diagrams of the inlay and 4-unit bridge models used in this study.

Dental 3D scanners

Four intraoral scanners; CS3500 (Carestream Dental LLC, USA), Trios (3shape, Denmark), Bluecam (Sirona Dental Systems, USA), and Omnicam (Sirona Dental Systems) were tested in this study. One laboratory scanner (Ceramill MAP400, Amann Girrbach, Germany) was used as a control. A coordinate measurement machine (CMM: Hexagon Manufacturing Intelligence, USA; precision=1 µm) was used to measure the true values of the inlay and 4-unit bridge models.

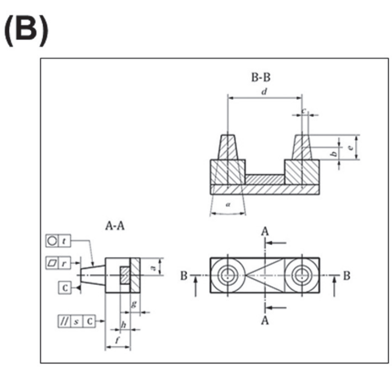
Model scanning and data acquisition

As described in ISO 12836, the depth and angle of the 70% reduced inlay model and the length, height, and angle of 4-unit bridge model were measured to assess the accuracy and precision of intraoral scanners.



Key index of figure 1(A)

a (4.90 ± 0.35) mm;
b (3.50 ± 0.35) mm;
c (11.20 ± 0.70) mm;
e (3.50 ± 0,35) mm;
α (16 ± 1)°.



Key index of figure 1(B)

a (3.50 ± 0.35) mm;
b e/2;
c (1,8 ± 0,1) mm;
d (21 ± 0.7) mm;
e (7 ± 0.35) mm;
f (7 ± 0.35) mm;
g (2.8 ± 0.35) mm;
h (2.8 ± 0.35) mm;
α (16 ± 1)°.

Fig. 1 Schematic diagrams of (A) inlay and (B) 4-unit bridge models modified by ISO 12836 standard models (70% reduction).

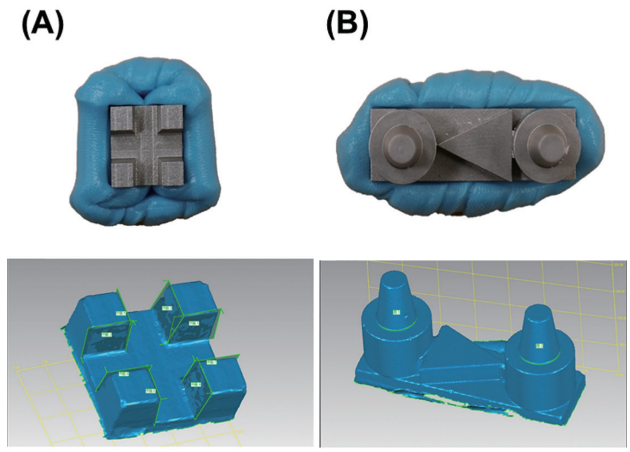


Fig. 2 Real image and STL format images of (A) inlay and (B) 4-unit bridge models with rubber impression indicator.

Data acquisition was performed by repeatability measurement, which is conducted by one trained operator and same measuring conditions, in order to remove inter-operator interference. Thirty scans per model were collected to minimize un-wanted distance and angulation errors in the scanned images. Rubber impression materials were attached to the bottom of the models as indicators in order to provide non-symmetrical shape to the scanning model and improve the scanning ability of intraoral scanner, because symmetrical object is supposed to reduce the image recording ability of intraoral scanner (See Fig. 2).

The measured raw data were converted to stereolithography (STL) CAD software files in the open architecture software for the intraoral scanners. As shown Fig. 2, the converted STL files were imported to 3D measurement software (Geomagic Studio 2015, 3D systems engineering, USA). As explained in annexes A and B of ISO 12836[18], the depth and angle of the inlay and the length, height, and angle of 4-unit bridge models were measured (See Fig. 1). The Omnicam and Bluecam do not use open architecture software, so raw data obtained from these systems were converted to STL format using dedicated software from Sirona Company.

Calculation of accuracy (trueness) and precision

The overall absolute mean deviations between datasets from the reference and experimental scanners (trueness) and deviations between datasets within the same scanner (precision) were calculated in order to show distance and angulation errors of measured values[9].

The trueness of each scanned images were calculated by equation (1);

$$\text{Trueness}=|(d_R-d_M)| \quad (1)$$

d_R: The standard reference value for the distance (depth, height, length) and angle of the model

d_M: Measured value for the distance (depth, height, length) and angle of the model

The precision of each scanned images were calculated by equation (2);

$$\text{Precision}=|(d_A-d_M)| \quad (2)$$

d_A: Average of the measured value for the distance (depth, height, length) and angle of the model

d_M: Measured value for the distance (depth, height, length) and angle of the model

The boxplots of the trueness and precision of each experimental group were plotted by thirty trueness and precision values of scanned images. In addition, the relative errors were calculated from the absolute mean deviations in order to quantify trueness and precision[19].

$$\Delta d_M=|(d_R-d_M)/d_R| \quad (3)$$

Δd_M: Relative error of trueness

d_R: The standard reference value for the distance (depth, height, length) and angle of the model

d_M: Measured value for the distance (depth, height, length) and angle of the model

$$\Delta S(d_M)=|S(d_M)/d_R| \quad (4)$$

$\Delta S(d_M)$: Relative error of precision

$S(d_M)$: Standard deviation of the measured value for the distance (depth, height, length) and angle of the model

d_R: The standard reference value for the distance (depth, height, length) and angle of the model

Statistical analysis

To analyze absolute discrepancies, all data from absolute mean trueness and precision calculations were analyzed using one-way analysis of variation (ANOVA) in IBM SPSS Statistics for Windows, Version 22.0 (IBM, USA) and *post-hoc* Scheffe's test (α=0.05).

RESULTS

Trueness and precision of the inlay models

The absolute mean trueness and precision values of the inlay and 4-unit bridge models are listed in Table 1. Figure 3 shows boxplots of the absolute mean trueness and precision values of the depth and angle of the inlay model. In terms of depth errors of the inlay model, the CS3500 (trueness: 40.77±28.53 µm) and Trios (precision: 30.97±26.23 µm) showed the highest accuracy and precision, respectively. There was no significant difference between absolute mean trueness values obtained from all intraoral scanners (p>0.05), but the absolute mean precision values of the Trios were significantly lower than those of the Bluecam (p<0.05). The angulation errors of the inlay model revealed the highest angulation accuracy and precision observed in the Omnicam (trueness: 0.20±0.14 degree; precision: 0.17±0.13 degree). The absolute mean angulation trueness values did not differ significantly among all

Table 1 Mean trueness/precision values±standard deviation (SD)

	Inlay model			
	Depth (µm)		Angle (°)	
	Trueness	Precision	Trueness	Precision
CS3500	40.77±28.53	36.03±15.24	0.28±0.16	0.27±0.17
Trios	51.90±34.85	30.97±26.23	0.27±0.20	0.18±0.14
Omnicam	70.23±52.01	53.03±56.48	0.20±0.14	0.17±0.13
Bluecam	71.80±61.09	60.53±41.20	0.30±0.19	0.30±0.19
MAP400 (Lab)	7.63±5.01	5.30±3.82	0.07±0.05	0.05±0.05
True value	3.460		16.076	

	4-unit bridge model					
	Length (µm)		Height (µm)		Angle (°)	
	Trueness	Precision	Trueness	Precision	Trueness	Precision
CS3500	154.23±95.03	77.10±61.55	64.73±45.82	55.60±39.34	0.32±0.21	0.29±0.17
Trios	129.83±103.42	112.20±92.36	56.13±40.70	46.87±34.14	0.16±0.11	0.16±0.11
Omnicam	118.20±61.06	100.87±74.23	65.97±59.68	60.83±43.22	0.19±0.13	0.18±0.12
Bluecam	166.27±135.54	136.53±123.34	74.80±49.15	72.87±45.37	0.31±0.17	0.13±0.10
MAP400 (Lab)	55.63±14.32	12.10±7.34	29.23±2.24	1.77±1.36	0.23±0.18	0.23±0.18
True value	21.209		7.025		15.919	

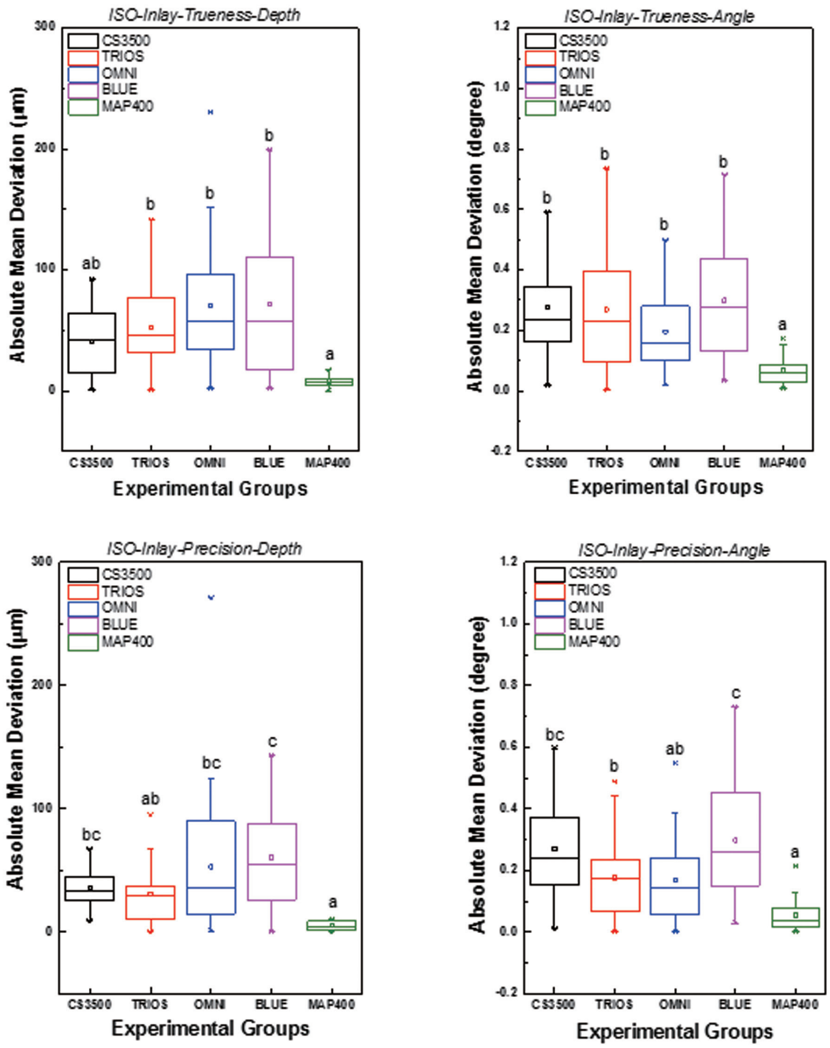


Fig. 3 Boxplots of absolute mean trueness (comparison of intraoral scanner datasets to the reference scanner datasets) and precision (comparison of intraoral scanner datasets within a single device) values (μm) of the depth and angle of inlay model. *Different alphabetical letters mean that there is significant statistical difference between data.

intraoral scanners ($p>0.05$). However, the absolute mean angulation precision values of the Omnicam scanner were significantly lower than those of the Bluecam scanners ($p<0.05$). Comparison of intraoral scanners with laboratory scanner revealed significantly lower absolute mean depth trueness values in the MAP400 (7.63±5.01 μm) compared to those of the Trios, Omnicam, and Bluecam scanners. The absolute mean depth precision value of the MAP400 (5.30±3.82 μm) was significantly lower than those of the CS3500, Omnicam, and Bluecam scanners. The absolute mean angulation trueness value of the MAP400 (0.07±0.05 degree) was significantly lower than those of the other intraoral scanners, and its absolute mean angulation precision (0.05±0.05 degree) was significantly lower than those of the CS3500, Trios, and Bluecam scanners.

Trueness and precision of 4-unit bridge models

Figure 4 shows the boxplots of the absolute mean trueness and precision values of the length, height, and angles of 4-unit bridge models. The highest length accuracy and precision were observed in the Omnicam (trueness: 118.20±61.06 μm) and CS3500 (precision: 77.10±61.55 μm) scanners, respectively. The Trios scanner showed the highest height accuracy (56.13±40.70 μm) and precision (46.87±34.14 μm) among all intraoral scanners. However, the length and height errors did not differ significantly among the intraoral scanners ($p>0.05$). The angulation errors of the 4-unit bridge models showed the highest angulation accuracy

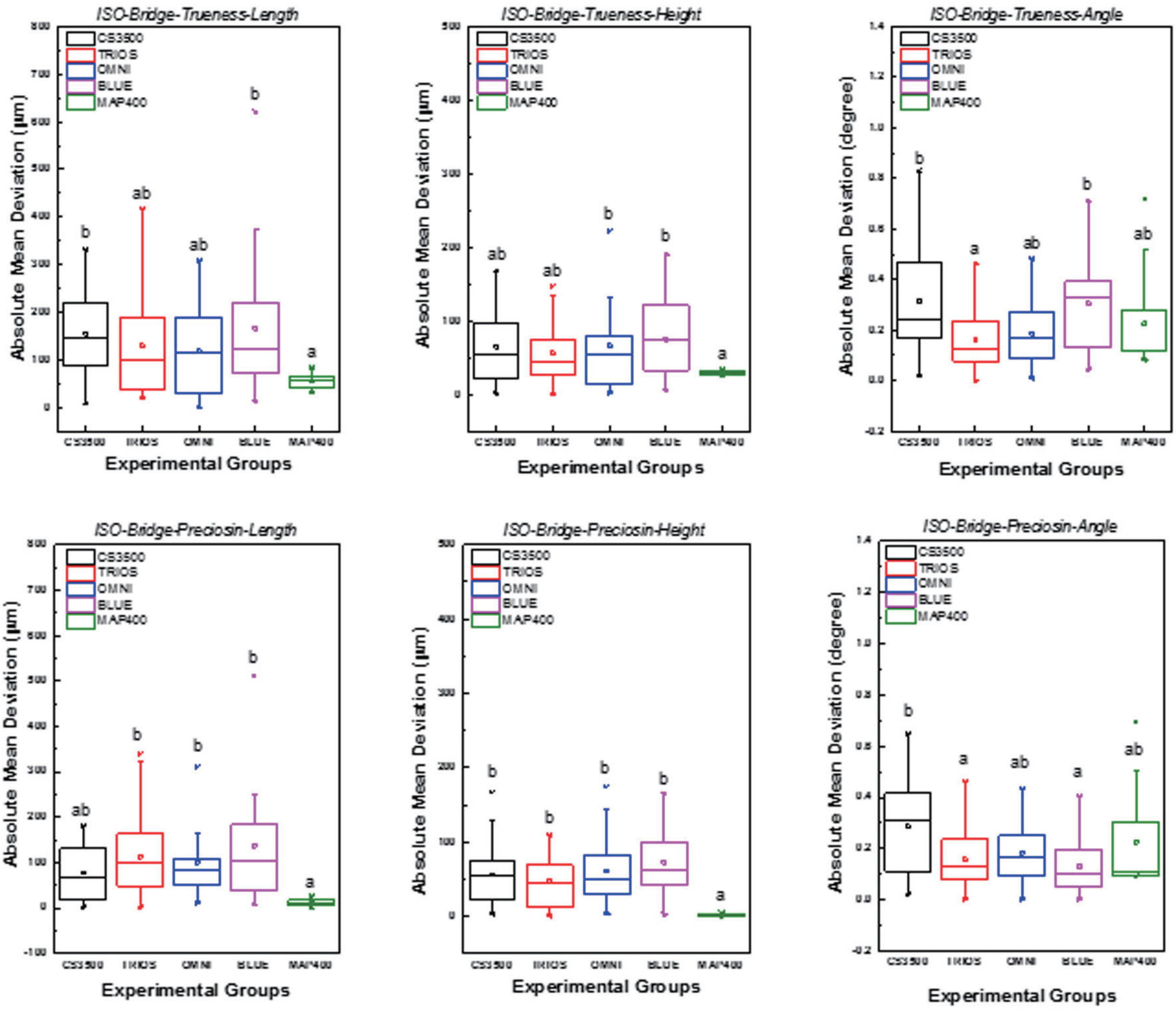


Fig. 4 Boxplots of absolute mean trueness (comparison of intraoral scanner datasets to the reference scanner datasets) and precision (comparison of intraoral scanner datasets within a single device) values (μm) of the length, height and angle of 4-unit bridge model.
*Different alphabetical letters mean that there is significant statistical difference between data.

and precision in the Trios (trueness: 0.16±0.11 degree) and Bluecam (precision: 0.13±0.10 degree) scanners, respectively. The absolute mean angulation trueness values of the Trios was significantly lower those of the CS3500 and Bluecam scanners, and the absolute mean angulation precision values of the Trios and Bluecam scanners were significantly lower than those of the CS3500, respectively (p<0.05).

Comparison between the intraoral scanners and laboratory scanner revealed that the absolute mean length trueness values of the MAP400 (55.63±14.32 μm) were significantly lower than those of the CS3500 and Bluecam scanners, and the absolute mean length precision value of the MAP400 (12.10±7.34 μm) was significantly lower than those of the Trios, Omnicam, and Bluecam scanners. In terms of the height errors between the four intraoral scanners and the laboratory scanner, the absolute mean trueness values of the MAP400 (29.23±2.24 μm) was significantly lower than those of the Omnicam and Bluecam scanners, and the absolute mean precision values of the MAP400 (1.77±1.36 μm) was significantly lower than those of all other intraoral scanners (p<0.05). With regard to angulation errors between intraoral and laboratory scanners, there were no significant differences between the MAP400 (trueness and precision: 0.23±0.18 degree) and the intraoral scanners (p>0.05).

Relative errors of inlay and 4-unit bridge models

Table 2 shows the relative errors of the inlay and 4-unit bridge models used to quantify the trueness and precision. The relative errors of inlay model and

Table 2 Relative errors of the trueness and precision of inlay and 4-unit bridge model

	Inlay model			
	Depth (µm)		Angle (°)	
	Trueness	Precision	Trueness	Precision
CS3500	0.009	0.011	0.002	0.020
Trios	0.014	0.012	0.015	0.014
Omnicam	0.012	0.023	0.007	0.013
Bluecam	0.017	0.021	0.001	0.022
MAP400 (Lab)	0.002	0.002	0.003	0.005

	4-unit bridge model					
	Length (µm)		Height (µm)		Angle (°)	
	Trueness	Precision	Trueness	Precision	Trueness	Precision
CS3500	0.007	0.005	0.006	0.010	0.011	0.021
Trios	0.004	0.007	0.005	0.008	0.000	0.012
Omnicam	0.004	0.006	0.007	0.011	0.003	0.014
Bluecam	0.005	0.009	0.004	0.012	0.019	0.011
MAP400 (Lab)	0.003	0.001	0.004	0.000	0.002	0.018

4-unit bridge models were less than 0.023 and 0.021, respectively. Especially, precision relative errors of inlay models were comparatively higher than trueness relative errors of inlay models. The trend when comparing the relative errors of accuracy and precision between scanners was similar to that of comparing the absolute mean deviation of accuracy and precision between scanners.

DISCUSSION

In this study, the accuracy and precision values for various intraoral scanners were calculated *via* datasets measured using 70% reduced inlay and 4-unit bridge models. Scanning of the original size of the inlay and 4-unit bridge ISO models was not possible due to limitations of the operation view of the intraoral scanners. The size of the operation view was not enough large to cover the entire inlay and 4-unit bridge models. Also, the size of the inlay and 4-unit bridge models described in ISO 12836 are intended test laboratory scanners rather than intraoral scanners, and are somewhat larger than that of natural tooth and real 4-unit bridges used in dental practice. We prepared miniature (60, 70, 80, and 90% reduction) inlay and 4-unit bridge models. From the results of the pilot test (data not shown), 70% reduced miniatures of the two models were similar to the size of real prostheses used in dental practice and were suitable for evaluating the accuracy and precision of intraoral scanners.

Laboratory scanner (axis scan based system) and intraoral scanner (subject scan based system) have different scanning operation mechanism with regard to image recording and acquisition. Because the intraoral scanner acquire the images by accumulating the scanned images and memorizing the scanning pathway of the object at the same time, the scanning performance of intraoral scanner depends on the geometric structure of the object. Especially, the uniformity of object is possible to lessen the image recording ability of intraoral scanner. Thus, rubber impression materials were attached to the bottom of the two models as an indicators in order to enhance the readability of the object.

In general, repeatability and reproducibility commonly used to assess accuracy and precision. Repeatability measurements involve measuring the object with the same operator and measuring conditions, while reproducibility measurements measuring the object under different experimental conditions. As explained in a previous study[9,20], it is possible for inter-operator technical aspects to affect the final accuracy and precision of the datasets. To minimize the un-wanted influence from reproducibility measurements, a single trained operator scanned the inlay and 4-unit bridge models. In addition, intraoral scanners typically utilize two image recording types (real-time video rendering *vs.* a point-and-click stitching) and various image acquisition techniques such as a light stripe projection (triangulation)[21], a confocal laser imaging[22], accordion fringe interferometry, optical coherence tomography, and active wavefront sampling technologies[8]. This study used two confocal laser imaging technique-based rendering-type (Trios and Omnicam) and two triangulation technique-based stitch-type scanners (CS3500 and Bluecam) to evaluate the accuracy and precision of 70% reduced inlay and 4-unit bridge models. In general, the various image recording and acquisition systems is also possible to affect the measurement of the accuracy and precision of custom made artificial tooth models which have unique contour and curvature.

In previous studies, natural tooth-shaped models manually prepared by the researcher or full-arch dentiforms were used to test the accuracy and precision of intraoral scanners[6,9,14,20,23,24]. Alongside the development of various types of intraoral scanners, multiple studies have been conducted on their accuracy. Wiranto *et al.*[25] and Naidu and Freer[26] reported that tooth widths measured from digital models obtained in clinic using intraoral scanners did not differ significantly from measurements made from plaster models. Grünheid *et al.*[27] assessed the accuracy of an intraoral scanner by superimposing digital models made from intraoral scans and those made by scanning plaster models. Another study by Hayashi *et al.*[28] compared digital models obtained by scanning dental casts with an intraoral scanner and a laser-based dental scanner and reported that accurate digital models can be created using the intraoral scanner. Further, Flügge *et al.*[16] compared the reproducibility of digital models obtained by directly scanning the oral cavity with an intraoral scanner and those obtained by scanning stone cast models.

The main function of intraoral scanners is to scan the tooth structure precisely and accurately, so it is reasonable to compare the accuracy performance of intraoral scanners using tooth-shaped models. However, as explained above, the image recording and acquisition technologies of intraoral scanners differ, making it difficult to compare their accuracy and precision using manually fabricated tooth and full-arch dentiform models. In addition, technical differences between operators used to scan tooth and dentiform models may affect the final accuracy and precision values. Thus, the purpose of this study was to develop the optimal scanning model for intraoral scanner, which minimize any external variables caused by intraoral scanner operation type and resemble inlay and 4-unit bridge prostheses used in dental practice.

In terms of the quantification of the trueness and precision values, most studies have adopted absolute mean deviation to compare the trueness and precision of scanned images. Comparing distance errors is one of applicable methods in order to compare the trueness and precision of scanned images, but it is difficult to quantify the trueness and precision values of scanning models. Therefore, the quantification of measured values plays an important role in evaluating the comparison of the trueness and precision between different types of models, intraoral scanners, and researches.

In this study, a repeatability measurement procedure was used to remove inter-operator interference, and 30 scans per model were performed in order to minimize un-wanted distance and angulation errors in the scanned images. From all results of absolute mean deviation values of the trueness and precision measurement (Figs. 3 and 4), there were no statistically significant deviations in most horizontal distance, vertical distance, and angulation errors of the scanned images between intraoral scanners, even though significant differences were observed in angulation values of the inlay and 4-unit bridge models. The statistically significant difference of angulation values may be originated from the measurement method of scanned images in 3D measurement software. In this study, we could obtain the angle of scanned images *via* automated calculation procedure in software. The automatically calculated angulation values seems to be one of variables showing significant difference between intraoral scanners.

The relative errors of inlay model and 4-unit bridge models were less than 0.023 and 0.021, respectively. The ADA standards call for the minimum relative error of trueness and precision of dental scanners of less than 0.01 (ADA inlay and crown models). We used ISO 12836-based scanning models, which are more complicated than the ADA inlay and crown models, so it is possible that higher relative errors are obtained from inlay and 4-unit bridge models compared to the minimum requirement of ADA standard models. Moreover, we obtained similar trueness and precision relative errors for both inlay and 4-unit bridge models.

Thus, within the limitation of this study, the results indicate that inlay and 4-unit bridge models are expected to simplify the inlay cavity and 4-unit bridge prosthesis, complement the limitation of customized natural tooth models and full arch dentiform, and offer universal scanning to all intraoral scanners.

CONCLUSION

In summary, there were no statistically significant mean deviations in accuracy and precision distance values of the inlay and 4-unit bridge models tested in this study, although significant differences were observed in angulation values of the inlay and 4-unit bridge models. The relative errors of inlay model and 4-unit bridge models were less than 0.023 and 0.021, respectively. Thus, inlay and 4-unit bridge models suggested by this study may be feasible tools for testing intraoral scanners.

ACKNOWLEDGMENTS

This research was supported by a grant (15172MFDS394) from Ministry of Food and Drug Safety in 2015.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

REFERENCES

1) Kim JH, Lee J. A semantic network analysis of technological innovation in dentistry: a case of CAD/CAM. Asian J Technol Inno 2015; 23: 40-57.
2) Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations - Current systems and future possibilities. J Am Dent Assoc 2006; 137: 1289-1296.
3) Fasbinder DJ. The CEREC system 25 years of chairside CAD/CAM dentistry. J Am Dent Assoc 2010; 141: 3S-4S.
4) Kim TY, Shin MH, Chang R, Kim YJ. Development of image-space telecentric lens for intra-oral 3D scanner. J Opt Soc Korea 2015; 19: 303-310.
5) Silva JSAE, Erdelt K, Edelhoff D, Araujo E, Stimmelmayr M, Vieira LCC, Güth JF. Marginal and internal fit of four-unit zirconia fixed dental prostheses based on digital and conventional impression techniques. Clin Oral Investig 2014; 18: 515-523.
6) van der Meer WJ, Andriessen FS, Wismeijer D, Ren YJ. Application of intra-oral dental scanners in the digital workflow of implantology. Plos One 2012; 7(8): e43312.
7) Patel N. Integrating three-dimensional digital technologies for comprehensive implant dentistry. J Am Dent Assoc 2010; 141: 20s-24s.
8) Logozzo S, Zanetti EM, Franceschini G, Kilpela A, Makynen A. Recent advances in dental optics —Part I: 3D intraoral scanners for restorative dentistry. Opt Laser Eng 2014; 54: 203-221.
9) Patzelt SBM, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 2014; 18: 1687-1694.
10) Andriessen FS, Riikens DR, van der Meer WJ, Wismeijer DW. Applicability and accuracy of an intraoral scanner for scanning multiple implants in edentulous mandibles: A pilot study. J Prosthet Dent 2014; 111: 186-194.
11) Lin X, Chen T, Liu J, Jiang T, Yu D, Shen SG. Point-based superimposition of a digital dental model on to a three-dimensional computed tomographic skull: an accuracy study in vitro. Br J Oral Maxillofac Surg 2015; 53: 28-33.
12) Park TJ, Lee SH, Lee KS. A method for mandibular dental arch superimposition using 3D cone beam CT and orthodontic 3D digital model. Korean J Orthod 2012; 42: 169-181.
13) Patzelt SBM, Bishti S, Stampf S, Att W. Accuracy of computer-aided design/computer-aided manufacturing-generated dental casts based on intraoral scanner data. J Am Dent Assoc 2014; 145: 1133-1140.
14) Yang X, Lv P, Liu YH, Si WJ, Feng HL. Accuracy of digital impressions and fitness of single crowns based on digital impressions. Materials 2015; 8: 3945-3957.
15) Nedelcu RG, Persson ASK. Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-Dimensional analysis. J Prosthet Dent 2014; 112: 1461-1471.
16) Flügge TV, Schlager S, Nelson K, Nahles S, Metzger MC. Precision of intraoral digital dental impressions with iTero and extraoral digitization with the iTero and a model scanner. Am J Orthod Dentofacial 2013; 144: 471-478.
17) Akyalcin S, Cozad BE, English JD, Colville CD, Laman S. Diagnostic accuracy of impression-free digital models. Am J Orthod Dentofacial Orthop 2013; 144: 916-922.
18) International Standard (ISO) 12836 - Dentistry —Digitizing devices for CAD/CAM systems for indirect dental restorations— Test methods for assessing accuracy (2nd Ed.). International Organization for Standardization, Geneva, Switzerland 2015.
19) ADA/ANSI Standard No. 132-Scanning Accuracy of Dental Chairside and Laboratory CAD/CAM System. American Dental Association, Chicago, USA 2015.
20) Hack GD, Patzelt SBM. Evaluation of the accuracy of six intraoral scanning devices: an in-vitro investigation. ADA PPR 2015; 10: 1-5.
21) Schenk O. The new acquisition unit Cerec AC. Int J Comput Dent 2009; 12: 41-46.
22) Kachalia PR, Geissberger MJ. Dentistry a la carte: in-office CAD/CAM technology. J Calif Dent Assoc 2010; 38: 323-330.
23) Kim JH, Kim KB, Kim WC, Kim JH, Kim HY. Accuracy and precision of polyurethane dental arch models fabricated using a three-dimensional subtractive rapid prototyping method with an intraoral scanning technique. Korean J Orthod 2014; 44: 69-76.
24) Nie Q, Lin JX. Comparison of intermaxillary tooth size discrepancies among different malocclusion groups. Am J Orthod Dentofacial Orthop 1999; 116: 539-544.
25) Wiranto MG, Engelbrecht WP, Tutein Nolthenius HE, van der Meer WJ, Ren Y. Validity, reliability, and reproducibility of linear measurements on digital models obtained from intraoral and cone-beam computed tomography scans of alginate impressions. Am J Orthod Dentofacial Orthop 2013; 143: 140-147.
26) Naidu D, Freer TJ. Validity, reliability, and reproducibility of the iOC intraoral scanner: A comparison of tooth widths and Bolton ratios. Am J Orthod Dentofacial Orthop 2013; 144: 304-310.
27) Grünheid T, McCarthy SD, Larson BE. Clinical use of a direct chairside oral scanner: An assessment of accuracy, time, and patient acceptance. Am J Orthod Dentofacial Orthop 2014; 146: 673-682.
28) Hayashi K, Sachdeva AUC, Saitoh S, Lee SP, Kubota T, Mizoguchi I. Assessment of the accuracy and reliability of new 3-dimensional scanning devices. Am J Orthod Dentofacial Orthop 2013; 144: 619-625.