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

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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 ¹³. 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 ⁸⁻¹⁰. Quick and easy digital impressions offer convenience to both patients and dentists, and are a core technology for dental CAD/CAM systems⁵⁻⁷.

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 prosthesis⁹. Intraoral scanner performance is evaluated by measuring the accuracy and precision of the scanned image⁸⁻¹⁰. 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 models¹⁰⁻¹⁷. 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 introduced¹⁹, 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.

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MATERIALS AND METHODS

Fabrication of models
In this study, 70% reduced inlay and 4-unit bridge models described in ISO 12836 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.

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, 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.

The trueness of each scanned images were calculated by equation (1):
\[ \text{Trueness} = \left| \frac{d_R - d_M}{d_R} \right| \]

\[ d_R \] 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):

$$\text{Precision} = \frac{|d_A - d_M|}{d_M}$$  \hspace{1cm} (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:\(^{(3)}\)

$$\Delta d_M = \frac{|d_R - d_M|}{d_R}$$  \hspace{1cm} (3)

- $\Delta d_M$: 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

$$\Delta S(d_M) = \frac{|S(d_M)|}{d_R}$$  \hspace{1cm} (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 ($\alpha=0.05$).

### 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

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### 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     | 21.209   | 7.025    |

| 4-unit bridge model | Length (µm) | Height (µm) | Angle (°) |
|---------------------|-------------|-------------|-----------|
|                     | 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±61.09| 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    |           |
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 |
| 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, 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 imaging22), accordion fringe interferometry, optical coherence tomography,
and active wavefront sampling technologies\textsuperscript{9}. 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\textsuperscript{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.\textsuperscript{25} and Naidu and Freer\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.

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**CONFLICTS OF INTEREST**

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