INTRODUCTION

The use of dental digital technology has been increasing in the last few decades. In particular, computer-aided design and manufacturing (CAD/CAM) systems, technology originally introduced by Duret and Termoz in the 1970s 

1), has been widely accepted by the prosthodontic and restorative dentistry field. The first digital intraoral scanner was introduced by Mörmann and Brandestini in the 1980s, and was further developed as a powerful tool for Chairside Economical Restoration of Esthetic Ceramics (CEREC)2,3).

Digital three-dimensional (3D) models are created by scanning impression and plaster models using desktop scanners, or otherwise by cone-beam computed tomography. These methods have been widely accepted in clinical orthodontics, and are advantageous due to the compact storage space, their potential to expand applications for treatment planning, and their easy customization4-5). The use of commercial intraoral scanners to capture information on dental arches has increased in recent years, and is an attractive method for orthodontist. Not only are there a variety of applications for digital information that is generated, but the technology does not require conventional dental impression to be taken6-10). However, the use of intraoral scanners does have some drawbacks, such as the high price of the equipment and the long chair-time required for scanning11). The dimensional accuracy of digital models generated by intraoral scanning compared to desk-top scanning of conventional impressions has been investigated7,8,10). Most studies report that intraoral scanners are highly accurate6-8), and that distance measurements taken from digital images and plaster-cast models do not differ significantly6,12).

The establishment of a reliable reference is an important consideration when investigating the accuracy and precision of digital models, and is a process that must be considered carefully. Many studies that investigate the accuracy of digital models employ reference measurements taken by hand, typically using a caliper13), which carries a risk of inaccuracy.

This study aims to compare the accuracy of digital models generated by desktop-scanning of conventional impression/plaster models versus intraoral scanning. Eight ceramic spheres were attached to the buccal molar regions of dental epoxy models, and reference linear-distance measurement were determined using a contact-type coordinate measuring instrument. Alginate (AI group) and silicone (SI group) impressions were taken and converted into cast models using dental stone; the models were scanned using desktop scanner. As an alternative, intraoral scans were taken using an intraoral scanner, and digital models were generated from these scans (IOS group).

Twelve linear-distance measurement combinations were calculated between different sphere-centers for all digital models. There were no significant differences among the three groups using total of six linear-distance measurements. When limited to five linear-distance measurement, the IOS group showed significantly higher accuracy compared to the AI and SI groups. Intraoral scans may be more accurate compared to scans of conventional impression/plaster models.

MATERIALS AND METHODS

Generation of “gold-standard” reference measurements from dental models

A normal occlusion epoxy model (D1-500A, Nissin, Tokyo, Japan) was used for this study. Eight ceramic spheres (9/32 inches in diameter; Amatsuji, Osaka, Japan) were embedded half in the buccal regions of the premolars and molars of this model and bonded using instant glue (Fig. 1). The model were stored for 24 h at 20°C prior to taking measurements. Contact measurements were taken from the reference model using a high-accuracy
coordinate-measuring instrument (H503, Mitutoyo, Kanagawa, Japan) (Fig. 2). Five replicate measurements were taken at five different points on each ceramic sphere (buccal, cervical, occlusal, mesial, distal) using a probe with a ball-shaped tip (2 mm diameter). Center coordinates were then calculated for each sphere (URP, upper-right premolar region; ULP, upper-left premolar region; URM, upper-right molar region; ULM, upper-left molar region; LRP, lower-right premolar region; LLP, lower-right premolar region; LRM, lower-right molar region; LLM, lower-left molar region). Twelve linear-distance measurements were calculated between these sphere-centers using the software associated with the coordinate-measuring instrument (Fig. 3). These 12 distance measurements served as the “gold standard” reference values for this study.

Generation of digital models by desktop-scanning of conventional impression (alginate and silicone) and plaster models

Ten alginate (Starmix, Morita, Tokyo, Japan) and ten silicone (vinyl polysiloxane; JM Silicone, Nissin) impressions were taken of each model according to the manufacturer's instructions. Each impression was then used to make a cast model of super-hard dental stone (Super Rock Ex, Kuraray-Noritake Dental, Tokyo, Japan). Cast models were created by mixing stone powder with water according to the manufacturer's instructions (100 g stone powder to 20 mL distilled water) and pouring this mixture into each impression. Cast were not trimmed, eliminating the possibility of additional expansion through absorption of atmospheric water, and were allowed to set for 2 h, according to the manufacturer's recommendations. Resulting models were then scanned using a desktop-scanner (Rexcan DS2, Sea Force, Tokyo, Japan) to generate a total of 10 maxillary and 10 mandibular stone-model images. These digital dental models were designated as either the alginate-impression group (AI group) or the silicone-impression group (SI group). Four spheres were virtually abstracted for each group using 3D polygon editing software (RapidForm 2006, Inus Technology, Seoul, South Korea). These idealized spheres were then automatically inserted into the measured spheres using 3D analysis software (Imageware 10.6, Siemens PLM Software, Plano, TX, USA) to determine sphere-center coordinates (x, y, z). These methods have been described in a previous publication. Six sphere-center distances were then calculated for each model using these coordinates.

Generation of digital models by intraoral scanning

Ten intraoral scans of maxillary and mandible regions were performed under extraoral conditions using a dental intraoral scanner (Trios, 3Shape, Copenhagen, Denmark). These digital data were then used to generate digital dental models using 3Shape (Ortho Analyzer) software. These models were designated as the intraoral-scanned group (IOS group). Six sphere-center distances were calculated for each model using the coordinates (x, y, z) of four sphere-centers that were attached to the models prior to scanning.

Statistical analysis

Statistical analysis was performed using PASW Statistics for Windows software (ver. 18.0J, IBM,
Twelve linear-distance measurement combinations were calculated from the distances between sphere-centers. URP-ULP, distance between URP and ULP; URM-ULM, distance between URM and ULM; LRP-LLP, distance between LRP and LLP; LRM-LLM, distance between LRM and LLM; URP-URM, distance between URP and URM; ULP-ULM, distance between ULP-ULM; LRP-LRM, distance between LRP and LRM; LLP-LLM, distance between LLP and LLM; URP-ULM, distance between URP and ULM; ULP-URM, distance between ULP and URM; LRP-LLM, distance between LRP and LLM; LLP-LRM, distance between LLP and LRM.

Table 1 Mean values and standard deviations (SD) of linear-distance measurements calculated for the gold standard and three experimental groups

|                   | Gold standard | AI group | SI group | IOS group |
|-------------------|---------------|----------|----------|-----------|
|                   | Mean          | SD       | Mean     | SD        | Mean     | SD        | Mean     | SD        |
| URP-ULP           | 52.4857       | 0.0005   | 52.5165  | 0.0945    | 52.5752  | 0.0184   | 52.4235  | 0.0635    |
| URM-ULM           | 65.8232       | 0.0027   | 65.9415  | 0.1106    | 65.9328  | 0.0438   | 65.7774  | 0.1129    |
| URP-URM           | 16.1188       | 0.0054   | 16.1526  | 0.0234    | 16.0991  | 0.0084   | 16.0730  | 0.0194    |
| ULP-ULM           | 15.7850       | 0.0011   | 15.8344  | 0.0276    | 15.8166  | 0.0109   | 15.7953  | 0.0166    |
| URP-ULM           | 60.6992       | 0.0007   | 60.7840  | 0.1306    | 60.8040  | 0.0339   | 60.6482  | 0.0703    |
| ULP-URM           | 61.0936       | 0.0008   | 61.1654  | 0.0835    | 61.1735  | 0.0295   | 61.0273  | 0.0871    |
| LRP-LLP           | 45.5168       | 0.0023   | 45.5736  | 0.0444    | 45.6124  | 0.0127   | 45.4589  | 0.0454    |
| LRM-LLM           | 62.4391       | 0.0005   | 62.5499  | 0.1020    | 62.5735  | 0.0146   | 62.3255  | 0.0725    |
| LRP-LRM           | 18.7122       | 0.0005   | 18.7225  | 0.0769    | 18.7478  | 0.0061   | 18.7004  | 0.0155    |
| LLP-LLM           | 18.4014       | 0.0002   | 18.4296  | 0.0337    | 18.4269  | 0.0065   | 18.3919  | 0.0154    |
| LRP-LLM           | 56.2808       | 0.0025   | 56.3680  | 0.0775    | 56.4002  | 0.0132   | 56.2188  | 0.0646    |
| LLP-LRM           | 56.6105       | 0.0004   | 56.6886  | 0.0669    | 56.7256  | 0.0115   | 56.5097  | 0.0520    |

Armonk, NY, USA). Mean (absolute) values were calculated by subtracting each measured distance from its corresponding gold standard reference value. Mean values were then statistically compared using one-way analysis of variance (ANOVA) followed by Tukey’s test. For all statistical tests, the significance threshold was set at $p<0.05$.

## RESULTS

Mean linear distances and their standard deviations are listed in Table 1 for both reference and experimental models. Figures 4 and 5 show comparisons of accuracy values for the maxillary and mandibular dentitions, respectively, which were calculated by subtracting the measured linear distances from their reference values.
Fig. 4  Comparison of accuracy values for maxillary dentition, calculated as the difference between reference and measured linear-distance values. Median values are represented by boxed horizontal bars; 50% of all values fall within the boxed range. The horizontal bars represent the complete range of values. Averages are represented as smaller boxes within the median boxes. Outliers are plotted as white diamonds. a, URP-ULP; b, URM-ULM; c, URP-URM; d, ULP-ULM; e, URP-ULM; f, ULP-URM.

Fig. 5  Comparison of accuracy values for mandibular dentition, calculated as the difference between reference and measured linear-distance values. Median values are represented by boxed horizontal bars; 50% of all values fall within the boxed range. The horizontal bars represent the complete range of values. Averages are represented as smaller boxes within the median boxes. Outliers are plotted as white diamonds. a, LRP-LLP; b, LRM-LLM; c, LRP-LRM; d, LLP-LLM; e, LRP-LLM; f, LLP-LRM.

With the exception of the ULP-ULM distance value, all other measurements for the IOS group were negative. In contrast, all measurements for the AI and SI groups were positive, with the exception of the URP-URM distance value (Figs. 4 and 5). Table 2 provides a statistical comparison of the absolute values (representing accuracy) calculated by subtracting the measured linear-distance values from reference values. There was no significant
Table 2  Comparison of accuracy (absolute) values calculated as the difference between reference and measured linear-distances values

|                  | AI group - Gold standard | SI group - Gold standard | IOS group - Gold standard | p-values |
|------------------|--------------------------|--------------------------|---------------------------|----------|
|                  | Mean  | SD    | Mean  | SD    | Mean  | SD    |          |          |
| URP-ULP          | 0.0767 | 0.0665 | 0.0894 | 0.0194 | 0.0781 | 0.0288 | 0.7740  |          |
| URM-ULM          | 0.1503 | 0.0635 | 0.1096 | 0.0462 | 0.0898 | 0.0725 | 0.1010  |          |
| URP-URM          | 0.0369<sup>a,b</sup> | 0.0192 | 0.0197<sup>a</sup> | 0.0084 | 0.0466<sup>b</sup> | 0.0202 | 0.0050  |          |
| ULP-ULM          | 0.0547<sup>a</sup> | 0.0153 | 0.0316<sup>b</sup> | 0.0115 | 0.0157<sup>c</sup> | 0.0122 | 0.0000  |          |
| URP-ULM          | 0.1408<sup>a</sup> | 0.0701 | 0.1048<sup>a,b</sup> | 0.0357 | 0.0798<sup>b</sup> | 0.0361 | 0.0360  |          |
| ULP-URM          | 0.0864 | 0.0720 | 0.0799 | 0.0311 | 0.0948 | 0.0443 | 0.8160  |          |
| LRP-LLP          | 0.0685<sup>a,b</sup> | 0.0239 | 0.0956<sup>a</sup> | 0.0134 | 0.0653<sup>b</sup> | 0.0356 | 0.0280  |          |
| LRM-LLM          | 0.1401 | 0.0582 | 0.1344 | 0.0154 | 0.1140 | 0.0758 | 0.5550  |          |
| LRP-LRM          | 0.0613<sup>a</sup> | 0.0501 | 0.0357<sup>a,b</sup> | 0.0064 | 0.0134<sup>b</sup> | 0.0148 | 0.0060  |          |
| LLP-LLM          | 0.0409<sup>a</sup> | 0.1701 | 0.0255<sup>b</sup> | 0.0069 | 0.0165<sup>b</sup> | 0.0080 | 0.0000  |          |
| LRP-LLM          | 0.1044 | 0.0548 | 0.1194 | 0.0140 | 0.0775 | 0.0472 | 0.1010  |          |
| LLP-LRM          | 0.0979 | 0.0334 | 0.1151 | 0.0121 | 0.1030 | 0.0499 | 0.5440  |          |

Values are mean and standard deviations (SD). p<0.05 (Tukey’s t-test). Mean values followed by the same letter are not significantly different.

difference among the three groups (AI, SI, and IOS groups) using the six linear-distance measurement combinations. However, when only five linear-distance measurement combinations were including for the IOS models (ULP-ULM, URP-ULM, LRP-LRM, LLP-LLM, LRP-LLP), this group demonstrated significantly higher accuracy compared to either the AI and the SI group. Conversely, both scanned impression/plaster-model groups (AI and SI groups) demonstrated significantly higher accuracy compared to the IOS group for the URP-URM linear distance measurement.

**DISCUSSION**

Multiple factors may contribute to variability among scanned data (ISO 5725-1), including operator error, equipment performance, calibration status, environmental factors (temperature, humidity), and time elapsed between measurements<sup>15</sup>. It is important to establish a reliable reference model, in this study referred to as the “gold standard,” to evaluate the reliability of digital data. Here we took linear-distance measurements of a dental epoxy model using a contact-type coordinate-measuring instrument (H503, Mitutoyo) to establish reliable, gold standard reference values. Highly precise values (standard deviation=±0.00018 to ±0.00540 μm) were obtained from our five replicate measurements. These results suggest that our measurements are suitable for use as reference values, and support the manufacturer’s claims of high accuracy (±2.8+5L/1000 μm) for the H503.

In recent years, many researchers have investigated the dimensional accuracy of digital models generated by intraoral scanning and scanning of conventional impression and plaster models<sup>6,8,10,12</sup>. Reports suggest, generally, that accuracy is high for these digital models. For example, Wiranto <sup>6</sup> et al. reported mean tooth-size differences from plaster models of ±0.24 mm. Naidu and Freer<sup>12</sup> also reported that mean tooth-size values measured using digital methods were 0.024 mm larger compared to reference values. On the other hand, we observed mean differences among the three experimental groups, which varied by 0.013 to 0.150 mm, even though our linear measurement reference points were separated by greater distances. These results suggest that the accuracy of method employed this study would be acceptable for clinical applications. Measurement accuracies up to 0.1 mm are generally accepted as clinically adequate, and are not thought to compromise the diagnostic value of these models<sup>6,8</sup>.

To compare the accuracy and precision of intraoral scanning versus desktop-scanning of conventional impression plaster-model methods, this study employed a Trios (3Shape) as a representative dental intraoral scanner. Most values from the IOS group were negative, and therefore smaller compared to reference values, while all values for the AI and SI groups were positive, with the exception of the URP-URM distance measurement. These results appear to be partially supported by previous findings: Santoro <sup>16</sup> et al. measured a plaster model by hand using a digital caliper, and compared this to a digital model generated from an alginate impression...
using OrthoCAD (Cadent, Fairview, NJ, USA). His study reported that all tooth-size measurements from the digital model were smaller compared to the plaster model, which may be due to shrinkage of impression, expansion of gypsum, or distorted digital data. Flügge et al. compared intraoral and extraoral scanning using the same scanner (iTero, Align Technologies, San Jose, CA, USA), and reported that intraoral scanning was less accurate than extraoral scanning. These investigators suggested that intraoral conditions, such as the production of saliva and limited scan space, may influence scan accuracy. They also found that scanning of the maxillary dentition was less accurate compared to scanning of the mandibular dentition. Lastly, this study compared digital models acquired from two different intraoral scanners, and showed that the iTero (Align Technologies) (29.84±12.08 µm) proved to be less precise than the Trios (3Shape) (22.17±4.47 µm). The results of the present study demonstrate that mean differences from reference values acquired by the Trios instrument varied from −114 to 10 µm. Although data were generated under extraoral conditions and the oral environment was not simulated, these results suggest that the Trios had clinically acceptable accuracy. Future in vivo study on the practical application and precision of intraoral scanning is worthwhile.

CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. Linear-distance measurements calculated from intraoral scanned models were generally smaller than their reference values, while measurements calculated from scanned models of conventional impressions were larger than their reference values.

2. Digital linear-distance measurements calculated from both conventional impression/plaster model scans and intraoral scans demonstrate high accuracy, and may be suitable for clinical applications.

3. Intraoral scanning may be more accurate compared to conventional impression/plaster model methods.

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