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Original article

Investigation of accuracy and reproducibility of abutment position by intraoral scanners

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ABSTRACT

Purpose: We examined the accuracy, including trueness and precision, of the intraoral scanners comparing with laboratory scanner to reveal the error level of intraoral scanners.
Methods: Measurements were performed using a computer numerical control coordinate measuring machine (CNCCMM) of the reference models as a control. Subsequently, intraoral scanners and a laboratory scanner were used for measurements of the reference trueness and precision of the distance were evaluated by image analyzing software.
Results: With regard to reference model, there was a significant difference between in the trueness measured by C.O.S. (COS) and that measured by the other scanners. The trueness measured by the second-generation 3M^{TM} true definition scanner (TDS2) and third-generation 3M^{TM} true definition scanner (TDS3) was bigger than the one by TRIOS (TR) and KaVo (KA). With regard to reference model "B," error of the trueness measured by COS was significantly bigger, compared with the one measured by the other scanners. However, error range of intraoral scanners, except for COS, was considerably small and it should be covered with cement space.
Conclusions: The results of this study indicated that an optical impression method with an intraoral scanner could be applied to the implant therapy for multiple teeth missing.

1. Introduction

Recently, with the rapid progress of information technology, the optical impression method using an intraoral scanner may bring a new era of dentistry. Newly developed pieces of equipment and technology in dentistry have enabled us to respond to various patient requirements [1]. The development of the optical impression method has centered on a system for measuring the three-dimensional shape of a working cast. Measuring methods have changed from contact system to non-contact system and the measurement speed has been considerably improved [1]. The efficiency of the production process has improved because of the advancements of

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laboratory scanners. On the other hand, making optical impressions using intraoral scanners has also been developed in which working casts were not fabricated [2].

In this method using an intraoral scanner, static images or videos of the oral cavity are taken and used to rapidly construct a three-dimensional model in order to simplify the clinical and technical operations. Consequently, impression materials and plaster become unnecessary. In addition, the application of a small intraoral scanner can be used to patients having trismus or vomiting reflexes, in which conventional impression method was not acceptable. Optical impressions using intraoral scanners are also expected to enable the improvements of compatibility of prosthetic appliances and to simplify their production methods and techniques [3]. In a ceramic restoration, a one-day treatment system has already been established, in which the processes of preparing abutments, acquiring an impression, producing a prosthetic appliance, and fitting are completed in one visit, referred to as the one day treatment system [4].

The application of this method to patients missing many teeth has also been expected. However, very few reports related to measurement error are available, and much remains unknown regarding the acquisition of optical impressions over a wide range. Furthermore, the acquisition may be affected by elements of the oral cavity environment, such as saliva, depending on the location in the oral cavity, which necessitates a longer operation time and may make an accurate measurement impossible.

Recently, a number of reports regarding optical impression studies have focused on the compatibility of optical impressions with crowns and bridges produced on the basis of the data obtained from optical impression [5–10]. Optical impression has been clinically applied to implant treatment; however, much remains unknown regarding the positional reproduction calculated by the data from special scanning abutments [11,12]. Therefore, the applications of optical impression are currently limited to some cases, and involving the missing of a single tooth is recommended.

To determine whether an intraoral scanner can be applied to the production of prosthetic appliances for the replacement of multiple implant treatment, we measured the distance between two implant ball abutments and evaluated its accuracy.

2. Materials and methods

2.1. Fabrication of reference model

A lower jaw study model for dental implant training (D16-EP.27, NISSIN, Kyoto, Japan) was used in this study (Fig. 1).

A reference ball for calibration (chromium steel ball, ϕ 10mm, grade 28, Sato Tekko Co., Ltd, Yokohama, Japan) was fixed to a lingual part. Following this, reference model A was fabricated, in which two implants having an external hex connection system (Branemark System MKIII Groovy RP, ϕ 4.0mm × 10.0mm, Nobel Biocare, Zurich, Switzerland) were placed corresponding to a mandibular left second premolar and a mandibular left first molar. Reference model B was fabricated, in which two implants were placed corresponding to a mandibular right second premolar and a mandibular right second molar.

Titanium ball abutments, each of ϕ 5mm × 5mm (ball abutment, Branemark System regular platform 5mm, Nobel Biocare, Zurich, Switzerland), were placed on the top of the implant, using a torque wrench (prosthetic torque wrench, Nobel Biocare, Zurich, Switzerland) and a driver (machines driver, Nobel Biocare, Zurich, Switzerland) to 15N. In this study, the reference models A and B with ball abutments were used to measure the distance between the centers of two ball abutments.

2.2. Measurement method

2.2.1. Computer numerical control three-dimensional coordinate-measuring machine (CNCCMM)

A CNC three-dimensional coordinate-measuring machine (UPMC 550-CARAT:Curl ZEISS, Oberkochen, Germany) and a stylus of ϕ 0.8mm (Curl Zeiss, Oberkochen, Germany) were used to calculate the reference for trueness (Fig. 2). The CNCCMM can measure the dimensions with high accuracy. This system follows Japanese Industrial Standards (JIS B7440-2), allowing for a maximum error of 0.8+L/600 μm (L=Length: mm) in the measurement of length. This system was calibrated before the measurement to adjust the error to be 1 μm or less. Subsequently, the three-dimensional coordinates of the center located on the top of the ball abutments mounted on reference models A and B were measured 10 times to calculate a reference for trueness.

2.2.2. Intraoral scanner

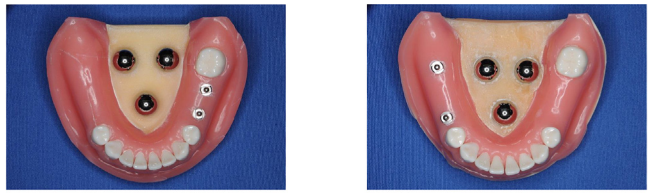
In this study, Lava™ C.O.S. (abbreviated as COS below, 3M, Minnesota, USA), second-generation 3M™ True Definition-scanner (abbreviated as TDS2 below, 3M), third-generation3M™ True Definition scanner (abbreviated as TDS3 below, 3M) with an active wavefront sampling method, and TRIOS (abbreviated as TR below, 3Shape, Copenhagen, Denmark) with a confocal method were used as intraoral scanners (Fig. 3). The characteristics of each scanner are shown in Table 1.

Before the measurement, titanium dioxide powders (Lava Powder: 3M) were sprayed onto the surface of the reference models for constant reflectivity. When the intraoral scanners were used, the reference model was fixed onto a laboratory table in a room excluding the influence of extraneous light for the accurate measurement.

The measurements were performed 10 times with each scanner following the instruction of each manufacturer by one operator. The measurements were performed facing an occlusal plane, a buccal plane, and a lingual plane, in that order, and no omission of the image data was confirmed. Following this, the obtained 3D data were converted and sent as STL (Standard Triangulated Language) data (Fig. 4).

2.2.3. Laboratory scanner

KaVo ARCTICA Auto Scan (abbreviated as KA below, KaVo Dental Excellence, Biberach, Germany) was used as a laboratory scanner (Fig. 3). After calibration, the measurement was performed 10 times, following the scan protocol of the manufacturer. No omission of the image data was confirmed,



Reference model A Reference model B

Fig. 1 – Reference models.

Fig. 2 – Reference models were measured by the CNCCMM (computer numerical control coordinate measuring machine). CNCCMM's stylus touches the surface of the ball abutments, determines the three dimensional position of the center of the abutments and calculates the distance between the two ball abutments.

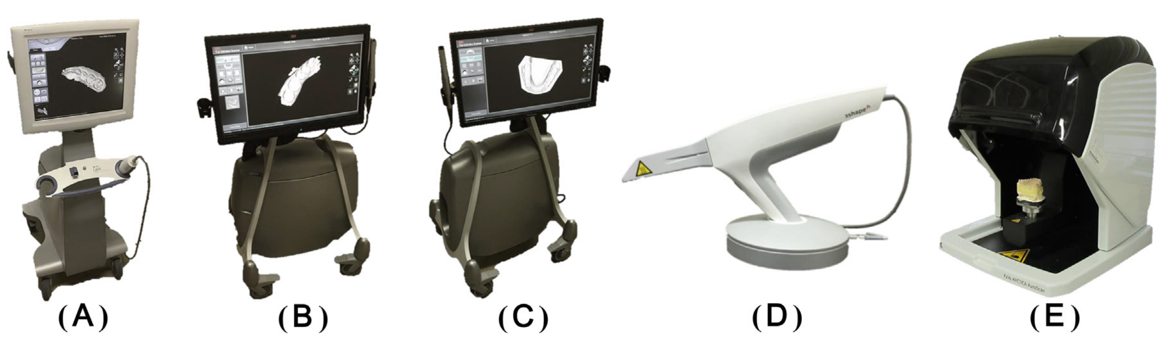


Fig. 3 – Intraoral scanner and laboratory scanner.
(A) Lava COS (COS)
(B) Second-generation 3M™ true definition scanner (TDS2)
(C) Third-generation 3M™ true definition scanner (TDS3)
(D) TRIOS (TR)
(E) KaVo ARCTICA Auto Scan

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Table 1 – Characteristics of the scanners.

Scanner	Manufacturer	Method	Light source	Type	Powder	Export
COS	3M	Active wavefront sampling	Blue pulsed visible light	Video	Yes	Original
TDS2	3M	Active wavefront sampling	Blue pulsed visible light	Video	Yes	Original
TDS3	3M	Active wavefront sampling	Blue pulsed visible light	Video	Yes	Original
TR	3shape	Confocal	White visible light	Image	No	STL
KA	KaVo	Triangulation	White visible light	Image	No	STL

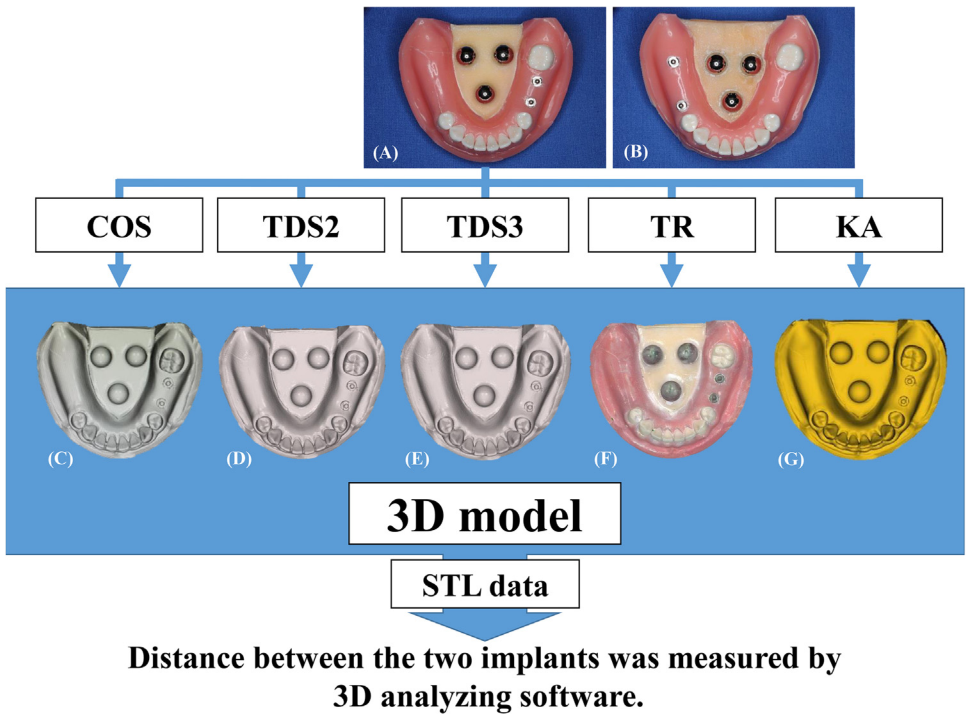

Fig. 4 – Overview of reference model and optical impression techniques.
(A) Reference model A
(B) Reference model B
(C) Reference model scanned with COS
(D) Reference model scanned with TDS2
(E) Reference model scanned with TDS3
(F) Reference model scanned with TR
(G) Reference model scanned with KA
The 3D models were exported as standard triangulation language data.
Distance between the two implants was measured by 3D analyzing software.

the obtained 3D data were converted, and sent as STL data (Fig. 4).

2.3. *Method of measuring the distance between ball abutments*

The STL data sent as outputs were entered into three-dimensional analysis software (Focus Inspection: Nikon, Tokyo, Japan). Three reference balls fixed to the lingual side of each reference model were used to obtain the reference points and reference planes necessary for initial setting the coordinates.

The center of the ball located at the top of the abutments was used for measuring the distance with the image analysis software (Fig. 5), and the distance between the center of two balls were calculated from the position coordinates. When the coordinates of the center of the ball abutment A were (xA, yA, zA) and the coordinates of the center of the ball abutment B were (xB, yB, zB), the distance between two ball centers was obtained by the following formula (Fig. 6).

$$D = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2}$$

Accuracy of scanners was evaluated in terms of trueness and precision. Trueness was defined as the differences of the distance when the reference values were compared with the measurement values of each scanner. Measurements were

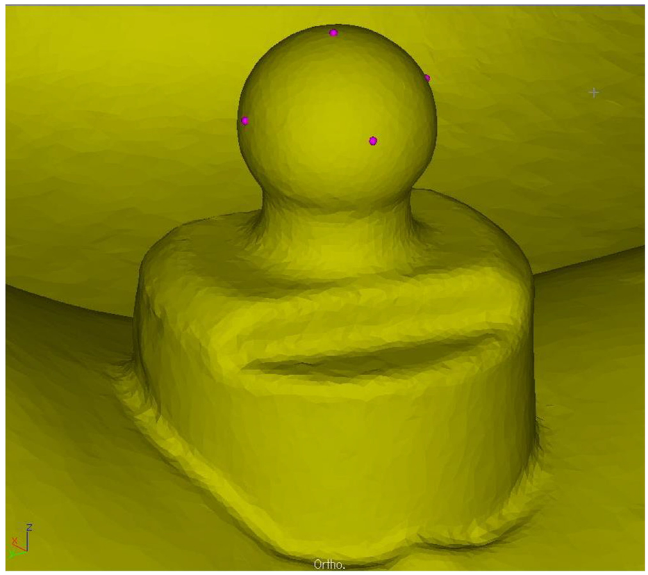

Fig. 5 – The centers of the ball abutments were identified by plotting six points of the surface of ball abutments.

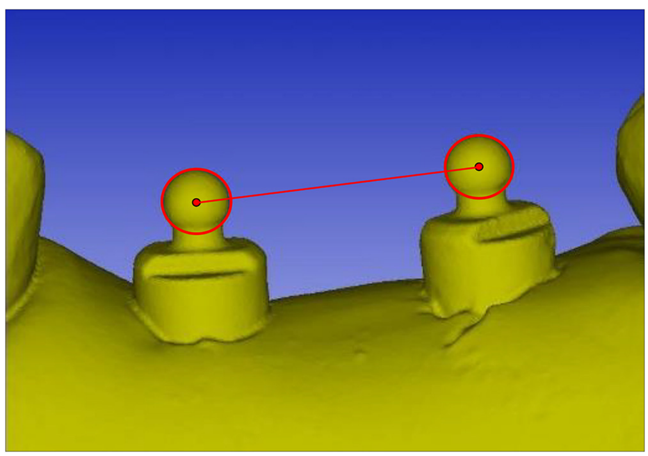

Fig. 6 – Distance between the center points of the ball abutments was measured.

repeated 10 times by each scanner, and errors from mean measured values were recorded to signify precision. Here we analyzed the distances between the centers of the two ball abutments on reference model A and on reference model B with five different scanners.

2.4. *Rate of change in error value of the distance between ball abutments*

After the measurements described above, we found the error values of both trueness and precision might tend to increase when the distance between ball abutments was extended. Then, the rate of error value per millimeter was calculated based on the measured distance data by each scanner. The mean value of data (mm) measured by CNCCMM was defined as l_0, and the mean value of data (mm) measured by each scanner was defined as l_1. The rate of error distance per millimeter for each scanner was defined as ΔL_c and calculated, using the following formula according to JIS 2554:2005.

$$\Delta L_c = \frac{l_1 - l_0}{l_0} \times 100$$

2.5. *Statistical analysis*

One-way analysis of variance and Bonferroni correction were used in statistical processing between groups of scanners of each type. In the statistical analysis, statistical analysis software (SPSS Statistic 19.0, IBM Japan, Tokyo, Japan) was used, and the significance level was set to 5%.

3. Results

3.1. *Analysis of the error in the distances between the ball abutments*

The mean distance between the centers of two ball abutments on reference model A measured with CNCCMM was 9560.6 μm.

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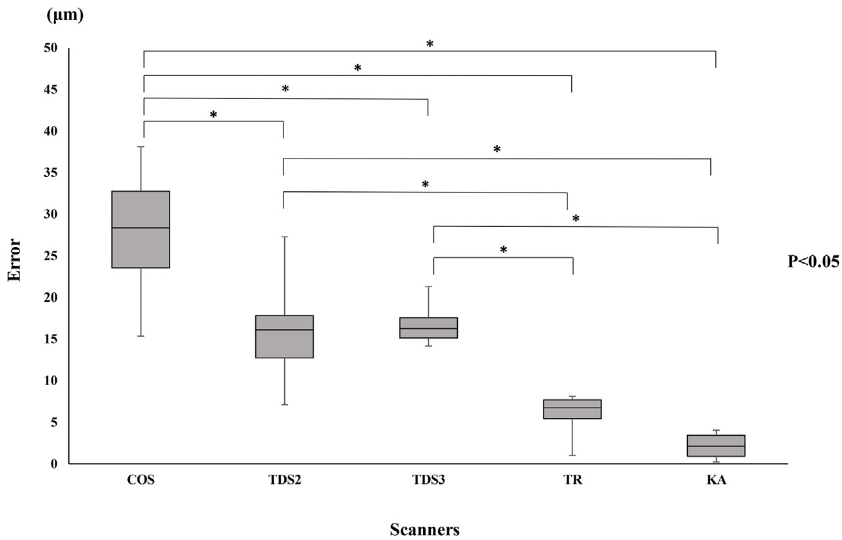

Fig. 7 – Trueness values of each scanner for reference model A.

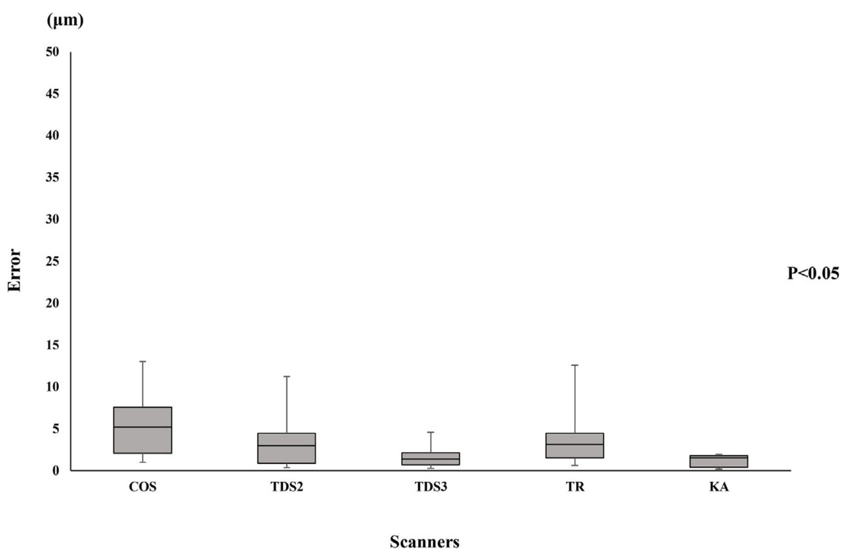

Fig. 8 – Precision values of each scanner for reference model A.

The mean distance between the centers of two ball abutments on reference model B measured with CNCCMM was 18426.5 µm. Mean distances between the centers of the two ball abutments on reference models A and B were regarded as reference values.

Investigations of trueness for reference model A indicated that the error range of COS was 15.4–38.1 µm. The error range of TDS2 was 7.2–27.3 µm. The one of TDS3 was 14.2–21.3 µm. The ones of TR and KA were 1.0–8.1 µm and 0.2–4.1 µm, respectively. COS showed significantly large errors compared to other scanners. There were significantly higher errors of trueness of TDS2 and TDS3 compared with TR and KA. (Fig. 7).

With regard to precision, the error range for COS was 1.0–13.0 µm, and for TDS2, the error range was 0.4–11.3 µm. For TDS3, the error ranged between 0.3–4.6 µm. For TR and KA, the error range was 0.6–12.6 µm and 0.2–2.0 µm, respectively. The errors between each scanner were considerably low (Fig. 8). With regard to the trueness for reference model B, the error range for COS was 58.5–103.5 µm; that for TDS2 was 56.7–85.9 µm; that for TDS3 was 46.5–69.2 µm; that for TR was 5.5–33.5 µm; and that for KA was 3.5–17.5 µm. For COS, there was a significantly greater error in the measurements compared with those of all the other scanners. With TDS2, there was a significantly greater error in the measurements compared with those of TDS3, TR, and KA. With regard to TDS3, there was a significantly greater error in the measurements compared with those of TR and KA (Fig. 9). With regard to precision: the error range for COS was 0.7–23.7 µm; that for TDS2 was 1.9–15.3 µm; that for TDS3 was 1.5–12.8 µm; that for TR was 0.7–13.7 µm; that for KA was 0.2–8.8 µm; and a significantly large error was found between COS and KA (Fig. 10).

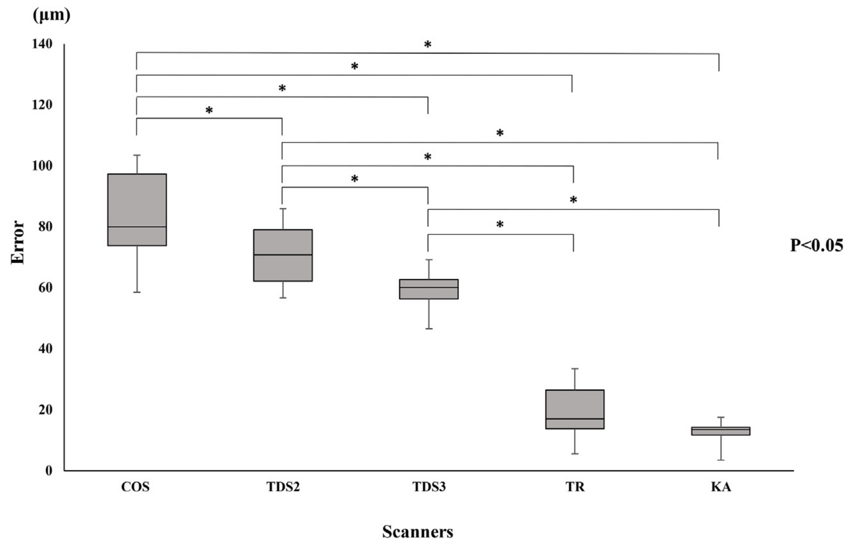

Fig. 9 – Trueness values of each scanner for reference model B.

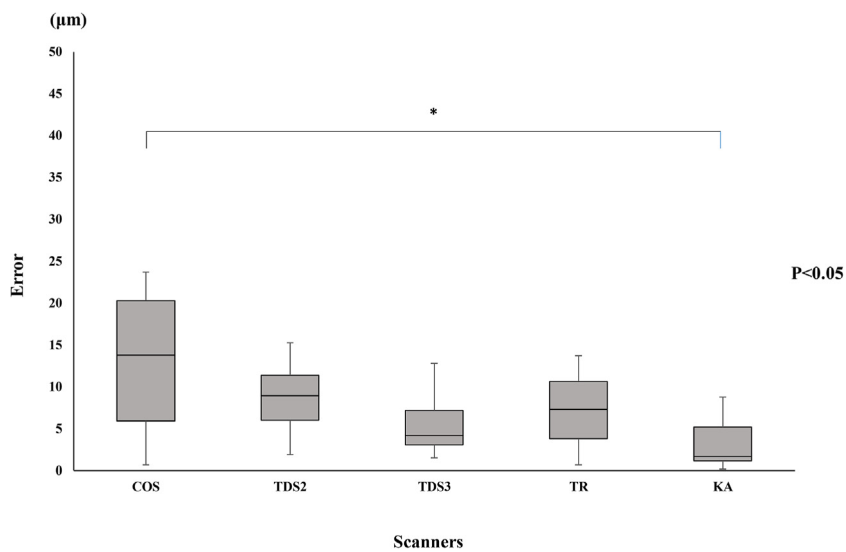

Fig. 10 – Precision values of each scanner for reference model B.

3.2. *Analysis of the rate of change in the distance between the ball abutments*

The error values of trueness tended to increase when the distance between ball abutments was extended (Table 2). The rate of distance error per 1mm, the formula was described in Materials and Methods, in reference model A was as follows: 0.297% for COS; 0.174% for TDS2; 0.167% for TDS3; 0.046% for TR; and 0.023% for KA. The rate of distance error per 1mm in reference model B was as follows: 0.446% for COS; 0.383% for TDS2; 0.322% for TDS3; 0.107% for TR; and 0.067% for KA. As described above, rate of change in the distance error became bigger when the distance between the ball abutments was longer. As a result, Table 2 shows that the rate of change in the distance error became almost double when the distance between the ball abutments was extended to twofold.

4. Discussion

4.1. *Clinical implications*

The CAD/CAM dental system that uses an intraoral scanner was first successfully applied to ceramic inlays only [1]. Although it has limited applications and it cannot perform the occlusal form of CAD, the advantages of early functional recovery and the introduction of new materials were accepted by clinicians [7]. Since the 1980s, the objective was to fabricate crowns and bridges after designing the occlusal plane on a computer. Precisely remake working casts were used as a beginning for CAD/CAM because it was difficult to make precise optical impressions of the crown abutment margins within the oral cavity. Therefore, a practical dental CAD/CAM system was developed for

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Table 2 – Analysis of the rate of change in the distance error between the ball abutments.

	Scanner				
	COS	TDS2	TDS3	TR	KA
Reference model A	0.297%	0.174%	0.167%	0.046%	0.023%
Reference model B	0.446%	0.383%	0.322%	0.107%	0.067%

primarily increasing the efficacy of the technical efforts. The CAD/CAM system has changed to prosthetic manufacturing processes, and nowadays this technology was used in daily clinical practice [13]. Current CAD/CAM system has been introduced to the implant therapy and esthetic dental treatment, and application of CAD/CAM to various prosthetic treatments is also expected in the future.

In the field of dental treatment, the CAD/CAM system can be used to perform a series of manufacturing processes. This has enabled precise machining of titanium and ceramic materials, because for which casting was difficult [14–17].

The CAD/CAM system offers several advantages, including improved diagnostic ability and communication with the patient, with cost reduction. Furthermore, with regard to the dental technician, CAD/CAM system provides an improved working environment, comfortable and safe prosthetic appliance design and manufacturing process, better productivity, and a shortened manufacturing time. With regard to clinical application, it is expected to improve medical services by offering minimally-invasive, comfortable, and safe treatment procedures. These advantages may provide several benefits for dentists, dental technicians, and patients [7].

In the field of implants, when the open tray method is used for making precise implant impressions with silicone impression materials, in which a driver is essential to tighten the screws. In the posterior molar region, although the mouth opening space is normal, impression operations are expected to accompany with difficulty. Conventional methods using silicone materials should not be applicable to patients with a strong vomiting reflex, several unstable teeth, or trismus. In such situations, applying optical impressions may be more advantageous. Employing optical impressions in implant treatment time is decreased. Furthermore, data including the abutment height, the rotation prevention mechanism positional relationship, and implant body diameter can be determined based on the shape of the head of abutment. Therefore, it is possible to perform manufacturing up the final superstructure by capturing the data of abutment head alone. Most reports on the current CAD/CAM's accuracy have covered laboratory scanners, contact measurements type, line lasers type, and so on [1,18–20]. On the other hand, there have been few reports regarding the precision of intraoral scanners, and optical impressions might not be reliable [21,22]. In particular, whether this method offers a level of accuracy that can match conventional methods of obtaining implant impressions using silicone impression materials is unclear. Therefore, in the present study, we comparatively investigated the precision of optical impression systems with intraoral and laboratory scanners to evaluate the usefulness of optical impressions with intraoral scanners. To reveal if intraoral scanner could be suitable for clinical application, we compared the accuracy of intraoral scanners to the one of a laboratory scanner that was used in the clinical setting.

4.2. *Research methods*

High levels of trueness and precision in making impression are required to fabricate precise prosthetic appliances. Numerous previous reports have, similar to our study, evaluated the trueness and precision in making optical impressions [21,23,24]. Some of these reports compared reference model with digital models by superimposing based on the best fit algorithm and determining the points at which deformations had occurred. This method enables visual representation of the overall deformation model and confirms the displacement with color mapping [5,23–27]. However, displacement detected by software, described above, is strongly dependent on the mechanical elements and is not suitable for the evaluation of error at specific points (e.g., the distance between the centers of two ball abutments) similar to those conducted in this study. Therefore, in the present study, we extracted the center of ball abutment coordinates and calculated distance between the centers of two ball abutments, exclusive of the best fit algorithm. This method enabled analyzing the specific precision of each scanner.

The two terms "trueness" and "precision" have been prescribed in ISO5725-1 to represent the accuracy of the measurement method [27,28]. Trueness expresses the degree of conformity when the obtained measurement values are compared with the gold standard reference values. Trueness can be used to confirm to what extent errors occur in the reference values obtained from the measured materials. Precision indicates the variation, expressing the degree of conformity between the results of the measurements performed multiple times. When evaluating error, the large variation in the measurement values indicates poor precision.The term "accuracy" is used to represent the both trueness and precision of these standards [28]. As measurement factors, trueness does not consider the variation in the measurement results, whereas precision results denote the error that occurs repeated measurements, and is not associated with the trueness of the values. Therefore, involvement of both trueness and precision is required for the following evaluation. When manufacturing prosthetic appliances, low accuracy can cause poor fitting of prosthetic appliances, resulting in mechanical issues, such as screw loosening or fracture, and poor occlusion. Moreover, the fitting of an incompatible prosthetic appliance may cause unfavorable biological effects to occur in peri-implant tissue [3]. It has been previously reported that the margin and internal fitting state of implant prosthetic appliances manufactured with the CAD/CAM system are compatible with the clinical application of superstructures [3]. However, reproducibility of implant position by optical impression was still controversial [29].

4.3. *Research results*

Concerning measurements of the distance between the centers of two ball abutments, COS which is the oldest type had the poorest trueness, whereas KA had the highest trueness. The results evaluation for precision was that COS had the poorest

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precision, whereas KA had the highest precision. When the laboratory scanner is working, natural light is blocked, the measurement object is fixed at a set distance, and the measurement is performed at various angles over a wide range using a high-performance camera. Then, the information gathered is automatically synthesized with the software to create STL data. As the results, the skill level of the practitioner or other elements should not affect the data value. Those facts might explain the high accuracy of laboratory scanner.

Although intraoral scanners are superior to laboratory scanners regarding measurement time and the smaller camera, the range for each scan is limited. In addition, during intraoral scanning, a large number of pieces of measured data are linked together and synthesized to compose the overall data, resulting in distortion of created STL data. Previously, Patzelt et al. [24] and Ender et al. [27] also investigated the reproducibility of overall dentition using intraoral scanners and reported the possibility of dental arch distortion.

It has been suggested that differences of scanning principles may affect the accuracy even in identical intraoral scanners [21]. Scanning principles can be broadly divided into two types: (1) COS, TDS2, and TDS3 employ active wavefront sampling (AWS) using a moving image format; and (2) TR uses the confocal method with an image format. With both imaging methods, environmental elements (e.g., inappropriate imaging distance, patient movement, saliva secretion, and moisture) can affect the precision of intraoral scanners. It has been reported that measurements using intraoral scanners are affected by trueness and precision due to the practitioner and their relative skill level [2]. In this study, intraoral scanning was performed by one dentist. Since our preliminary data demonstrated that there was no significant difference of error levels between multiple examiners and the examiner who conducted this study was well trained, one operator performed all the scanning.

In actual clinical settings, impressions are acquired from the dental arches of various sizes, from single tooth prosthetic appliances to multiple teeth prosthetics appliances for covering the entire jaw. Thus, it is relatively difficult to obtain accurate impressions of the long spans covering the left and right sides or the full arches. In the present study, we investigated the accuracy of optical impression, measuring the error value of trueness and precision in different dental arch length using reference model A (with a distance between the centers of two ball abutments of approximately 9.6 mm), and reference model B (with a distance between the centers of two ball abutments of approximately 18.4 mm). The results demonstrated that error of the intraoral scanner could be increased in the case of longer dental arch. The maximum error by the measurement with the intraoral scanner was obtained in the study model B that had longer distance between ball abutments. This may be attributed to the fact that the measurement of multiple teeth needs a greater frequency of data synthesis, resulting in bigger errors. In this study, an average value of the biggest error was 82.2 μm as shown in Fig. 9. This value obtained by intraoral scanner was quite high but it could be clinically permissible because Shim et al. reported that the cement space of 100 μm or less is acceptable [30,31]. The error of each intraoral scanner used in the model B was within the permissive range, suggesting that the error of intraoral scanner could be covered with the thickness of cement in the case of a few teeth missing.

On the other hand, laboratory scanners are used in combination with conventional silicone materials and subsequent working casts made of plaster. Ender et al. investigated the error that occurs during the manufacturing process, the error of trueness was $20.4 \pm 2.2\,\mu m$ and the error of precision was $12.5 \pm 2.5\,\mu m$ in plaster working cast [27]. The results of this study were similar to the one of our study in which the error of trueness was $22.5 \pm 12.4\,\mu m$ and the error of precision was $13.5 \pm 8.6\,\mu m$ in plaster working cast [32]. Based on this study, errors of some intraoral scanners were smaller than the one of plaster working cast. In the present study, laboratory scanners showed smaller errors than the intraoral scanners. However, in a clinical setting, laboratory scanners measure working casts; therefore, errors owing to impression materials or plaster cannot be eliminated. This suggests that intraoral scanners, which do not require the use of such materials, might offer the better trueness and precision, compared to laboratory scanners, and the clinical application of intraoral scanners for implant treatment is expected. However, the error value of trueness on intraoral scanner in study model B is higher than the one in study model A. Increase in rate of distance error per 1 mm was approximately two-times when the distance between prostheses was two-times longer. Thus, in the case of clinical application of intraoral scanners for multiple teeth superstructure, cement space must be considered during the designing of prostheses.

5. Conclusions

The followings were concluded by evaluating the distance between the implant ball abutments with intraoral and laboratory scanners.

The distance precision of intraoral scanners was within the same error range as that of a laboratory scanner, demonstrating that some intraoral scanners can precisely reproduce abutment positional relationships. Regardless of the distance, the laboratory scanner offered stable trueness and precision. Those results suggest that some scanners may offer dimensional stability that is close to trueness values because intraoral scanners can eliminate the errors associated with materials. Therefore, intraoral scanners might qualify the clinical application of the optical impression method for implant treatment of multiple teeth.

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