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Accuracy of Five Intraoral Scanners and Two Laboratory Scanners for a Complete Arch: A Comparative In Vitro Study

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Abstract: This study aims to evaluate the accuracy of five different intraoral scanners and two different laboratory scanners for a complete arch. A computer-aided design (CAD) reference model (CRM) was obtained using industrial scanners. A CAD test model (CTM) was obtained using five types of intraoral scanners (CS3500, CS3600, Trios2, Trios3, and i500) and two types of laboratory scanners (3shape E1 and DOF) (N = 20). In addition, the CRM and CTM were superimposed using a 3D inspection software (Geomagic control X; 3D Systems) and 3D analysis was performed. In the 3D analysis, the accuracy was measured by the type of tooth, the anterior and posterior region, and the overall region. As for the statistical analysis of the accuracy, the differences were confirmed using the Kruskal–Wallis H test ($\alpha = 0.05$). Also, the differences between the groups were analyzed by post-hoc tests including Mann–Whitney U-test and Bonferroni correction method ($\alpha = 0.0017$). There was a significant difference in the scanning accuracy of the complete arch according to the type of scanner ($P < 0.001$). The i500 Group showed the lowest accuracy (143 ± 69.6 μm), while the 3Shape E1 Group was the most accurate (14.3 ± 0.3 μm). Also, the accuracy was lower in the posterior region than in the anterior region in all types of scanners ($P < 0.001$). Scanning accuracy of the complete arch differed depending on the type of scanner. While three types of intraoral scanners (CS3500, CS3600, Trios3) can be recommended for scanning of a complete arch, the two remaining types of intraoral scanners (Trios2 and i500) cannot be recommended.

Keywords: intraoral scanner; accuracy; digital workflow; complete arch; dentistry

1. Introduction

While the conventional workflow depends on the operator's experience and technique, the introduction of computer-aided design and computer-aided manufacturing (CAD/CAM) has made it possible to apply the digital workflow in the field of dentistry [1–5]. The first digital workflow was a partially digital workflow accompanied by intraoral impression-taking and the production of a working model [1–3] The introduction of intraoral scanners in the 1980s allowed the use of a fully digital workflow [1,3], which reduced the errors that may occur from the operator's experience and the materials (impression material and plaster) used [1–3]. The recent digital workflow in dentistry has been improving the range of application and the accuracy of prosthetic fabrication due to the continuous development of dental CAD/CAM system [6].

The concept of intraoral scanner was first introduced for chairside use to perform fixed prosthetic treatment [1,5]. However, it can be applied to many other treatments including removable prosthetic treatment, orthodontic treatment, and implant procedure planning [7]. Faster and easier scanning of teeth and soft tissues in the oral cavity and 3D modeling suggest that it could be applicable in more areas [8]. In addition, intraoral 3D modeling may play an important role in the communication between the dentist, dental technician, and the patient [5].

A previous study compared the accuracy of a virtual model scanned from the actual oral cavity and that of a virtual model scanned from a working model [9]. Also, it was found that intraoral conditions (saliva and limited space) contribute to the inaccuracy of scanning [9–11]. In case of difficulty in using an intraoral scanner due to the intraoral conditions, a partially digital workflow (intraoral impression taking and working model production) can be applied [1,5,12].

In many studies, the accuracy of the scanning data was evaluated for application in various treatment methods and to test intraoral scanners under limited conditions in the oral cavity [7,8,10,13–17]. The accuracy of the CAD test model (CTM) obtained with an intraoral scanner is evaluated through three-dimensional (3D) comparison with the CAD reference model (CRM) obtained with a scanner with very high accuracy [7,8,10,13–15]. Using a 3D inspection software, the CTM and CRM are superimposed to the most similar position, and the mean of the distance of all point clouds of 3D modeling of CRM and CTM was used to calculate the root mean square (RMS) [8,13,15]. In addition, the RMS value is the standard for the evaluation of the accuracy of the scanning data in many studies [13–15,17]. The previous studies found that deviation of more than 100 µm from the complete arch resulted in an inaccurate fit of the final restoration in the maxilla and mandible [3,9] Also, an allowable range of less than 100 µm was proposed as an acceptable cement space for the prosthesis [3,18].

The accuracy of intraoral scanners for a complete arch has been evaluated in many previous studies [3,8,10,13–15,17–19]. It was found that the larger the range of scanning, the greater the error, suggesting that the complete arch was inappropriate as the range of intraoral scanning for prosthetic treatment [3].

The limited intraoral condition, the impact of the scanning accuracy on the prosthesis, and the impact of the increase in the range of scanning on the accuracy have been investigated for the development and application of intraoral scanners [3,7,8,10,11,13,20–23]. However, there are no studies investigating the accuracy of intraoral scanning according to the tooth type, and the anterior and posterior regions. In addition, there are few studies evaluating the scanning accuracy of a complete arch [10,14,15].

The first purpose of this study was to evaluate the accuracy of scanning the complete arch using five types of intraoral scanners (CS3500, CS3600, Trios2, Trios3, and i500) and two types of laboratory scanners (3shape E1 and DOF). The second purpose was to evaluate the difference in the accuracy according to the type of tooth and the anterior and posterior regions. The first null hypothesis is that there would be no difference in the accuracy of the eight types of scanners. The second null hypothesis is that there would be no difference in the accuracy according to the type of tooth and the anterior and posterior regions.

2. Materials and Methods

This study was conducted using the following steps: fabrication of a reference model for the production of the CRM and its digitization using an industrial scanner; the digitization of the reference model using intraoral scanners and laboratory scanners for the production of CTM; and the superimposition and 3D analysis of the CRM and CTM using an inspection software (Figure 1).

First, to determine the sample size, a pilot experiment was conducted five times and using a power analysis software (G*Power v3.1.9.2, Heinrich–Heine–Universität, Düsseldorf, Germany), the number of samples was calculated to be 20 (actual power = 99.2%; power = 99%; $\alpha = 0.05$). The results indicated that this study needed at least N = 20 subjects to ensure a power >99%. The actual power achieved with this N (99.20%) is slightly higher than the requested power.

A reference model (dental typodont, ANKA-4 V CER, Frasaco GmbH, Tettnang, Germany) was fabricated using dental stone (Type IV, Durone, Dentsply, Catanduva, Brazil). For the reference model, a CRM file was produced using a high-precision industrial 3D scanner with a resolution of 2 × 5 Mpx and Blue LED (Solutionix C500, MEDIT, Seoul, Korea). For accuracy, an industrial 3D scanner expert calibrated the equipment prior to performing the CRM scanning.

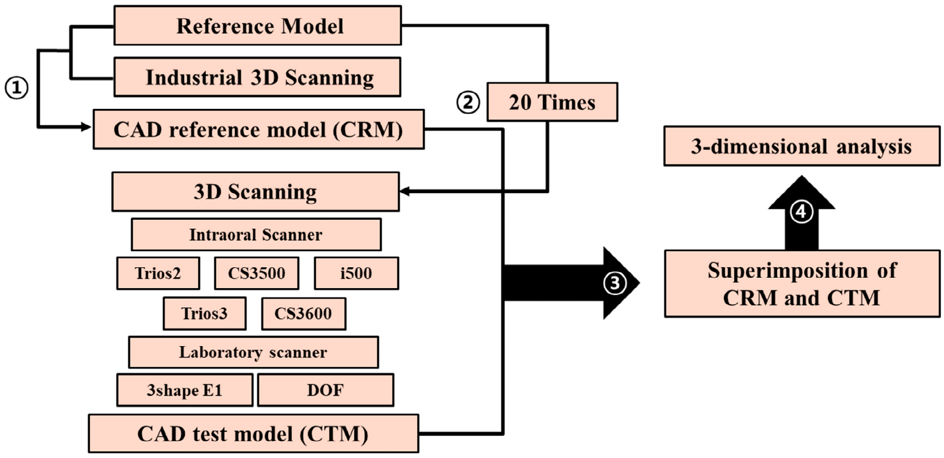

Figure 1. Experimental design.

To obtain the CTM of the reference model, five types of intraoral scanners, including CS3500 (Carestream Dental, Atlanta, GA, USA), CS3600 (Carestream Dental, Atlanta, GA, USA), Trios2 (3Shape, Copenhagen, Denmark), Trios3 (3Shape, Copenhagen, Denmark), and i500 (MEDIT, Seoul, Korea) and two laboratory scanners, including E1 (3Shape, Copenhagen, Denmark) and DOF Freedom HD (DOF, Seoul, Korea) were used.

Based on the complete arch scan manufacturer's instructions and a review of the literature on the accuracy of various scan strategies, the order of scanning was decided (Figure 2) [3]. In accordance with ISO-12836, each scanner was operated at an ambient temperature of 23 ± 2 °C, and the scanning was performed 20 times by one operator (K.S.) skilled in the use of each of the five types of intraoral scanners. In addition, stereolithography (STL) files were extracted for 3D analysis.

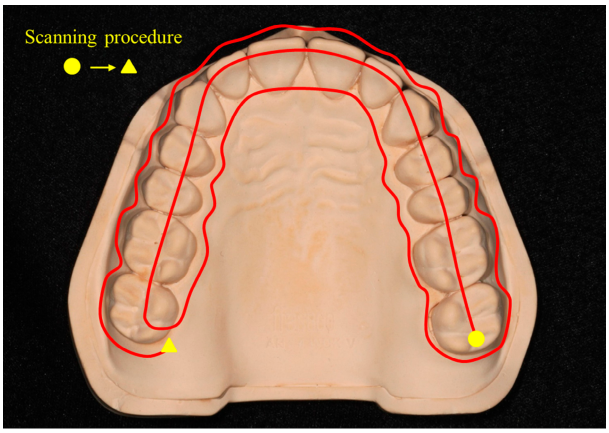

Figure 2. Strategies for complete arch scanning.

The use of various 3D inspection software, each with a different protocol can result in differing results of the 3D analysis [3]. Thus, Geomagic's 3D inspection software (release 2018.0.0, Geomagic control X, 3D Systems, Rock Hill, SC, USA) recommended by ISO-12836 was used in this study [3].

First, for the 3D comparison of each tooth in the analysis program, the CRM file was divided according to each tooth. In addition, to see the distortion of the set of teeth, a plane was created based on a virtual line from the incisor to the half of the second molar tooth in the sagittal plane. After the CRM file was prepared, the CTM file was retrieved and the initial alignment was performed. Also, they were superimposed by the best fit alignment based on all the divided teeth. The sampling rate was set at 100%.

The dimensional differences between CRM and CTM were calculated for all data point clouds of the divided teeth. At this time, the data point was calculated with the root mean square (RMS), and the formula is as follows:

$$RMS = \frac{1}{\sqrt{n}} \cdot \sqrt{\sum_{i=1}^{n} (X_{1,i} - X_{2,i})^2}. \quad (1)$$

where $X_{1,i}$ is the measurement point of i of the CRM, $X_{2,i}$ is the measurement point of i of the CTM, and n is the number of all points measured in each analysis.

The RMS value shows how the deviation between two different sets of data is different from zero. Thus, a low RMS value represents a high degree of 3D conformity of the superimposed data. The 3D comparison was shown as a color difference map, and a range of ±1 mm (20 color segments) and a tolerance range of ±10 µm (green) were designated. The red zone (0~1 mm) indicates the positive errors of CTM compared to CRM, and the blue zone (0–1 mm) indicates the negative errors of CTM compared to CRM. In addition, the green zone (±10 µm) indicates accuracy.

All data were analyzed using statistical software (SPSS, release 25.0, IBM, Chicago, IL, USA). First, the normal distribution of data was investigated through the Shapiro–Wilk test. As a result, since there was no normal distribution, the differences between the groups were analyzed using the Kruskal–Wallis test ($\alpha = 0.05$) and Mann–Whitney U-test and Bonferroni correction method as post-hoc tests ($\alpha = 0.0017$).

3. Results

There were significant differences in the accuracy of scanning all teeth among the scanners ($P < 0.001$) (Table 1). Except for the two types of laboratory scanners (3Shape E1 and DOF), all intraoral scanners showed improved accuracy from the posterior (first premolar to second molar) to the anterior (first incisor to the canine tooth) (Table 1, Figure 3).

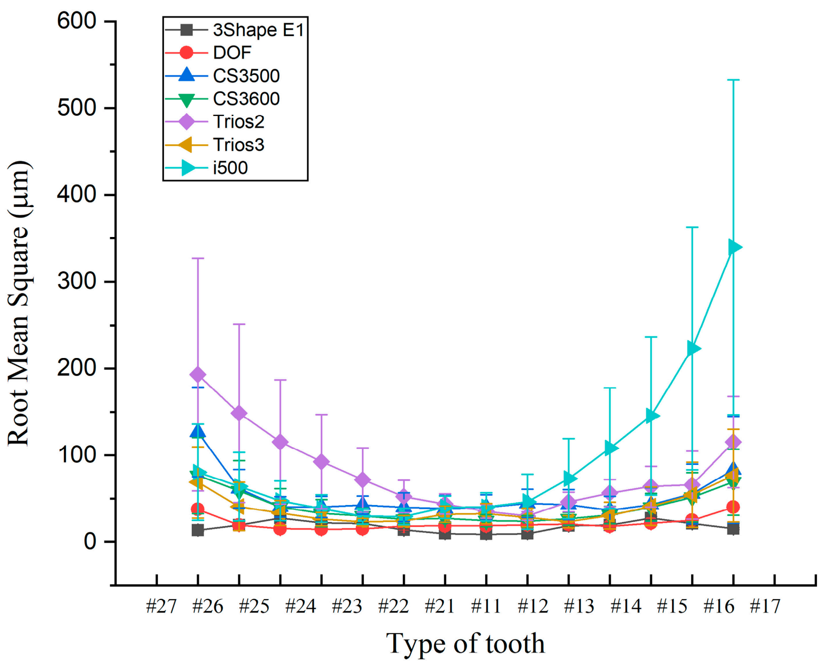

Figure 3. Comparison of the RMS value per tooth (#27~#17) according to the scanner.

Table 1. Comparison of the root mean square (RMS) values per tooth using five intraoral scanners and two dental laboratory scanners.

Tooth Type	3Shape E1	DOF	CS3500	CS3600	Trios2	Trios3	i500	*P*
	RMS (μm), Mean ± SD							
#27	13.7 ± 1.2 [a]	37.6 ± 1.5 [ab]	126.8 ± 51.6 [c]	76.6 ± 43.6 [abc]	192.9 ± 134.1 [d]	68.8 ± 40.9 [abc]	80.4 ± 55.2 [bc]	<0.001
#26	19.5 ± 0.9 [a]	19.6 ± 1.1 [a]	61.5 ± 22 [a]	59.1 ± 35 [a]	148.5 ± 102.9 [b]	41 ± 27.7 [a]	64 ± 39.2 [a]	<0.001
#25	27.5 ± 2.7 [a]	15.4 ± 0.7 [a]	40.6 ± 11.6 [a]	40.4 ± 21.2 [a]	115.5 ± 71.6 [b]	33.5 ± 14.3 [a]	47.5 ± 22.9 [a]	<0.001
#24	22.3 ± 1.6 [ab]	14.8 ± 0.8 [a]	40.6 ± 12.4 [b]	33.3 ± 15.7 [ab]	92.7 ± 54 [c]	26.6 ± 7.8 [ab]	38.7 ± 15.8 [ab]	<0.001
#23	21.3 ± 0.9 [a]	15.2 ± 0.7 [a]	42.6 ± 10.4 [b]	30.2 ± 9 [ab]	71.6 ± 37.1 [c]	23.1 ± 4.2 [a]	29.7 ± 9.1 [ab]	<0.001
#22	13.9 ± 1.1 [a]	18.6 ± 0.4 [a]	40 ± 16.5 [bc]	26.3 ± 5.4 [ab]	52.5 ± 18.5 [c]	24.2 ± 6.2 [a]	29.6 ± 9.5 [ab]	<0.001
#21	9.5 ± 0.2 [a]	18.7 ± 0.3 [ab]	38.6 ± 15.3 [c]	27.3 ± 5 [bc]	44 ± 11.6 [c]	32.2 ± 9.3 [bc]	40.3 ± 12.8 [c]	<0.001
#11	9 ± 0.2 [a]	18.7 ± 0.5 [ab]	40 ± 14.4 [c]	24.6 ± 7 [abc]	35.5 ± 7.8 [bc]	32.8 ± 11.6 [bc]	40.4 ± 16.2 [c]	<0.001
#12	9.5 ± 0.3 [a]	19.9 ± 0.4 [ab]	44.7 ± 16.1 [c]	23.9 ± 6.7 [ab]	30.1 ± 4.8 [bc]	28.3 ± 10.6 [bc]	46.4 ± 31.6 [c]	<0.001
#13	18.8 ± 1.5 [a]	20.5 ± 0.4 [ab]	43.1 ± 17.2 [bc]	27 ± 7.2 [abc]	46.3 ± 11 [c]	23.6 ± 6.9 [abc]	73 ± 46.2 [d]	<0.001
#14	19.5 ± 2 [a]	18.3 ± 0.6 a	36.8 ± 15.7 [ab]	31.2 ± 10.1 [ab]	56.4 ± 15.4 [b]	30.6 ± 15.4 [ab]	108.2 ± 69.5 [c]	<0.001
#15	27.6 ± 1.6 [ab]	21.8 ± 0.5 [a]	43.3 ± 19.1 [ab]	40.3 ± 15.8 [ab]	64 ± 23.3 [b]	41.3 ± 22 [ab]	145.3 ± 90.9 [d]	<0.001
#16	21.3 ± 1.1 [a]	25.2 ± 0.6 [a]	55.5 ± 34.2 [a]	51.5 ± 28.2 [a]	65.8 ± 39.2 [a]	54.6 ± 37.6 [a]	223 ± 139.8 [b]	<0.001
#17	15.5 ± 2 [a]	40.3 ± 0.9 [ab]	83.2 ± 61.4 [ab]	69.1 ± 38 [ab]	115.2 ± 52.6 [b]	76.6 ± 53.3 [ab]	339.6 ± 193 [c]	<0.001
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	

RMS: root mean square. Significant by Kruskal–Wallis test; $P < 0.05$. Different letters indicate the significant differences among the scanner groups by Mann–Whitney U-test and Bonferroni correction method ($P < 0.0017$).

In all the scanners, there was a significant difference in the accuracy between the anterior and posterior regions ($P < 0.001$) (Table 2). The accuracy was much better in the anterior region than in the posterior region (Table 2, Figure 4).

Table 2. Comparison of the RMS values of the anterior and posterior regions using five intraoral scanners and two dental laboratory scanners.

	3Shape E1	DOF	CS3500	CS3600	Trios2	Trios3	i500	*P*
	RMS (μm), Mean ± SD							
Anterior	14.3 ± 0.3 [a]	24.3 ± 0.4 [ab]	62.4 ± 19.8 [cd]	49.3 ± 21.1 [bc]	92.8 ± 32.7 [d]	44.2 ± 15.7 [abc]	143 ± 69.64 [e]	<0.001
Posterior	23.6 ± 0.6 [a]	28.7 ± 0.4 [a]	56.5 ± 25.5 [a]	59.9 ± 26.8 [a]	112.3 ± 50.9 [b]	47.6 ± 23 [a]	164.1 ± 84.7 [c]	<0.001
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	

RMS: root mean square. Significant by Kruskal–Wallis test; $P < 0.05$. Different letters indicate the significant differences among the scanner groups by Mann–Whitney U-test and Bonferroni correction method ($P < 0.0017$).

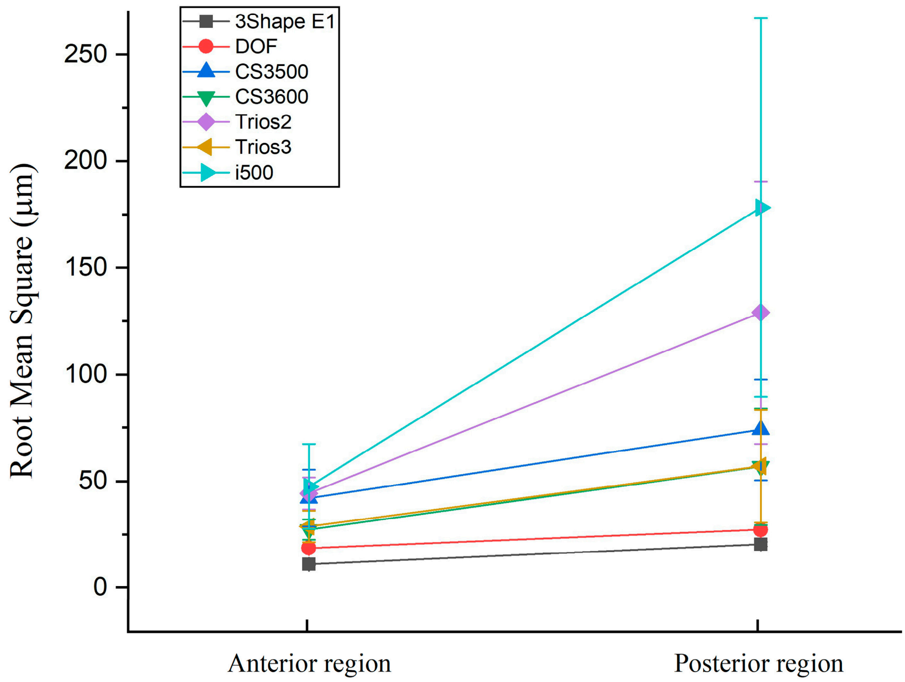

Figure 4. Comparison of the RMS value per anterior and posterior region according to the scanner.

As for the accuracy of the overall region and on the virtual plane, the laboratory scanners (3Shape E1 and DOF) showed an accuracy of lower than 30 μm, and laboratory scanners had no significant difference ($P > 0.05$); however, there was a big deviation ranging from 44.2~164.1 μm in the intraoral scanners by type, and intraoral scanners had a significant difference ($P < 0.001$) (Table 3, Figure 5).

Table 3. Comparison of the overall and virtual plane RMS values using five intraoral scanners and two dental laboratory scanners.

	3Shape E1	DOF	CS3500	CS3600	Trios2	Trios3	i500	*P*
	RMS (μm), Mean ± SD							
Overall	14.3 ± 0.3 [a]	24.3 ± 0.4 [ab]	62.4 ± 19.8 [cd]	49.3 ± 21.1 [bc]	92.8 ± 32.7 [d]	44.2 ± 15.7 [abc]	143 ± 69.64 [e]	<0.001
Plane	23.6 ± 0.6 [a]	28.7 ± 0.4 [a]	56.5 ± 25.5 [a]	59.9 ± 26.8 [a]	112.3 ± 50.9 [b]	47.6 ± 23 [a]	164.1 ± 84.7 [c]	<0.001

RMS: root mean square. Significant by Kruskal–Wallis test; $P < 0.05$. Different letters indicate the significant differences among the scanner groups by Mann–Whitney U-test and Bonferroni correction method ($P < 0.0017$).

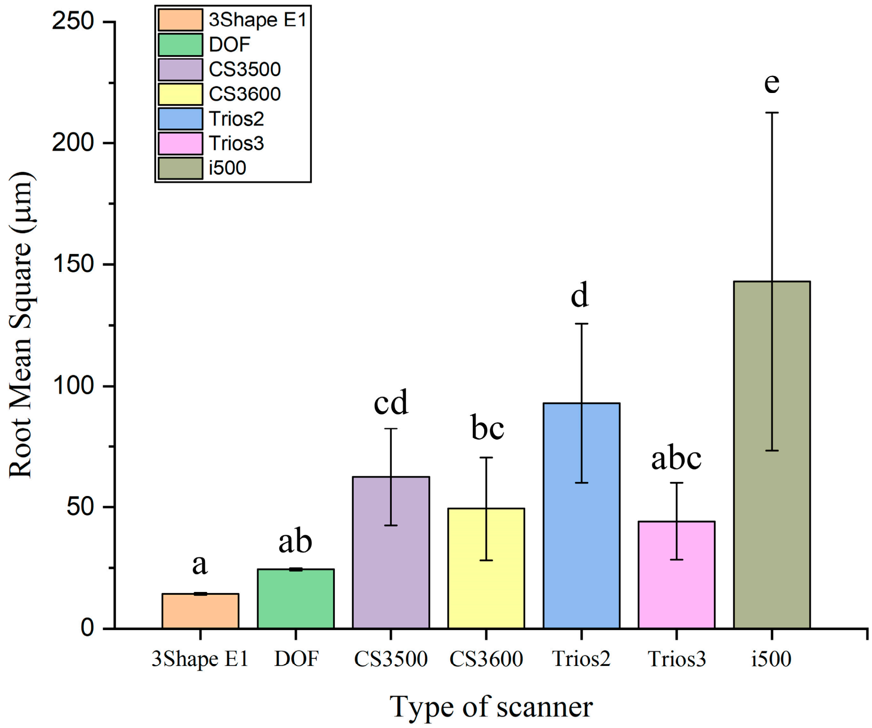

Figure 5. Comparison of the RMS value of the overall region according to the scanner. Different letters indicate the significant differences among the scanner groups by Mann–Whitney U-test and Bonferroni correction method ($P < 0.0017$).

On the color difference map, the range of green zone appeared the most in the laboratory scanners (Figure 6A,B), while the range of green zone was smaller in the intraoral scanners (Figure 6C–H).

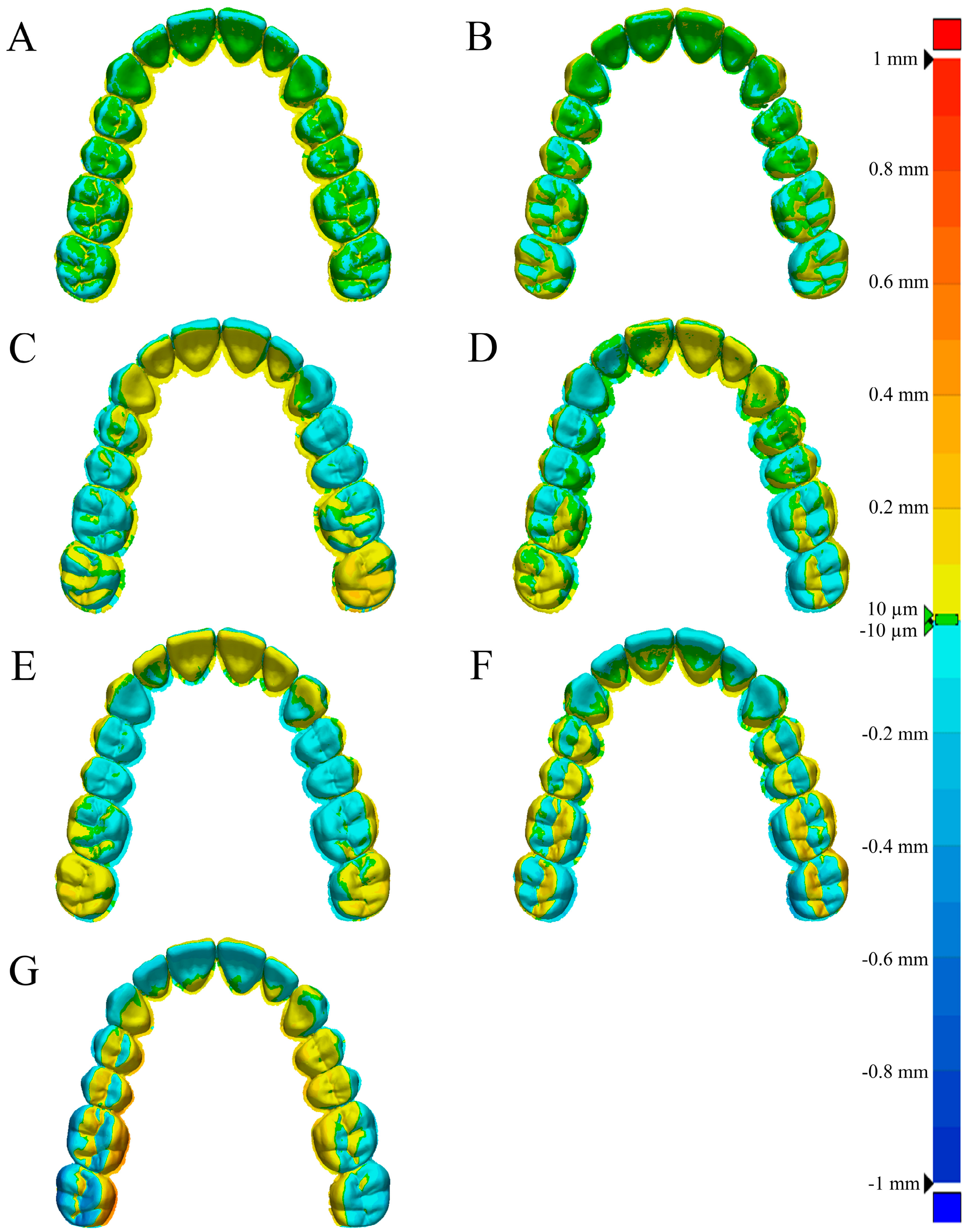

Figure 6. Comparison of the color difference map according to the scanner. (**A**) 3shape E1. (**B**), degree of freedom (DOF). (**C**) CS3500. (**D**) CS3600. (**E**) Trios2. (**F**) Trios3. (**G**) i500.

4. Discussion

The results of this study showed a significant difference in the accuracy of the eight types of scanners ($P < 0.001$), and there was a significant difference according to the type of tooth and the anterior and posterior regions ($P < 0.001$) (Tables 1–3). Thus, both the null hypotheses of the study were rejected. The accuracy of the scanner cannot be confirmed only by the comparison of the overall accuracy of the maxilla and mandible. During the process of creating virtual models with the scanners, the 3D displacement may occur, and the mean value of the distance of all point clouds cannot represent the error in a specific part [3]. Thus, in this study, each tooth was divided to examine the accuracy of each tooth, the anterior region, and the posterior region separately. Forming a virtual plane, this study examined the planar displacement value (Tables 1–3).

This study showed a significant difference in the accuracy according to the anterior and posterior regions in all eight scanners (Table 2). Previous studies showed a difference in the accuracy according to the size and shape of the object scanned [2,19]. The accuracy was found to be poor in the posterior region in this study, suggesting that the manufacturer should improve this. Also, the findings of this study regarding accuracy could provide important information for developing a more improved intraoral scanner.

In numerous previous studies, poor accuracy was found to adversely affect the fit of fixed prosthesis [12,20]. The scanning data plays the most essential role to produce prostheses and poor scanning accuracy provides the prostheses with a bad fit for patients [20,21]. The previous studies evaluated the accuracy of the scanning data based on 100 µm [3,9,18]. Therefore, this study concluded that three types of intraoral scanners (CS3500, CS3600 and Trios3) could be recommended for scanning of the complete arch, whereas two other types of intraoral scanners (Trios2 and i500) could not be recommended.

This study is significant in that the overall accuracy of the Trios2 Group (92.8 ± 32.7 µm) was within the range of the clinically allowable scanning accuracy (<100 µm); however, it is difficult to consider it to be within the clinically allowable range for complete arches in terms of horizontal displacement (112.3 ± 50.9 µm) in the virtual plane. The scanning accuracy of the left 2nd molar in the CS3500 Group (126.8 ± 51.6 µm) deviated from the allowable range, but the overall accuracy (62.4 ± 19.8 µm) and the horizontal displacement (56.5 ± 25.5 µm) were within the range of accuracy for a complete arch. In conclusion, it is difficult to recommend intraoral scanners for use based only on the comparison of the overall accuracy, which were evaluated in previous studies. Thus, in the results of this study, it would also be necessary to evaluate the horizontal displacement and the scanning accuracy of each tooth in addition to the 3D evaluation method.

Many previous studies have evaluated the accuracy of a complete arch using intraoral scanners. In the studies by Park et al. [3], the accuracy of complete arch using intraoral scanner of Trios 2, Trios 3, CS3500, and CS3600 showed 343.4 ± 56.4 µm, 183.9 ± 49.7 µm, 209.9 ± 53.7 µm, and 118.9 ± 42.1 µm, respectively. The reason for the poor accuracy compared to the results of this presented study is due to the difference in the alignment method between CRM and CTM. The alignment method by Park et al. confirmed the distortion of the arch by aligning only the teeth at which the scan begins [3], but in this presented study, the accuracy of the entire arch was determined by aligning all the scanned teeth. In the studies by Michael Braian et al. [14], five intraoral scanners were used to evaluate the accuracy of the complete arch. The accuracy of the complete arch in the five intraoral scanners was <193 µm, and the use of the intraoral scanner to scan the complete arch was not recommended. The results of this presented study ranged from 44.2 to 164.1 µm, and three intraoral scanners (CS3500, CS3600, and Trios3) were recommended, with the exception of two intraoral scanners (Trios2 and i500). The reason for this result is the difference in the evaluation method of accuracy. The evaluation method of accuracy by Michael Braian et al. [14], analyzed the accuracy through the error of the arch distance, but in this presented study, it was evaluated as 3D analysis of the accuracy by inspection software.

This study has a few limitations. First, this study used in vitro experiments, which did not reflect the conditions that might occur in the oral cavity (moist environment and limited space). A previous study found that these intraoral conditions might affect the accuracy of the scanner [23]. Thus, it would be necessary to conduct additional studies to evaluate the accuracy by mimicking the conditions that might occur in the oral cavity. The previous studies found that the accuracy of the intraoral scanner might differ depending on the operator's experience and learning [16,22]. To minimize the impact of this variation in this study, a single operator (K.S.) conducted the evaluations after sufficiently practicing the use of each intraoral scanner. This presented study shows the overall accuracy of scanning for the complete arch, but it does not mean the recommended scan range for fixed prostheses. Therefore, according to the results of the presented study, dental practitioners can be applied to the dental clinic with the intraoral scanners recommended for the scanning of the complete arch. The use of the recommended intraoral scanner for a complete arch allows the acquisition of virtual models with excellent accuracy (<100 µm).

5. Conclusions

Based on the findings of this in vitro study, the following conclusions were drawn:

1. There was a significant difference in the accuracy of scanning a complete arch according to the type of scanner ($P < 0.001$).
2. While two types of intraoral scanners (Trios2 and i500) cannot be recommended, three other types of intraoral scanners (CS3500, CS3600, and Trios3) can be recommended for scanning a complete arch.
3. Both types of intraoral and laboratory scanners showed better accuracy in the anterior region compared to the posterior region ($P < 0.001$), so care should be taken in the posteriorregion scanning.

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