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Effect of scan path on accuracy of complete arch intraoral scan

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PURPOSE. This study aimed to compare the accuracy of an alternative scan path with that of traditional scan paths to obtain a more accurate method for complete arch scans. **MATERIALS AND METHODS.** A mandibular stone cast, including tooth preparations for the inlay, crown, and fixed prosthesis, was scanned 10 times using four different scan paths (A, B, C, and D). The scans were converted into stereolithography files, resized, and superimposed onto a control file obtained from a desktop scanner. The scan time, total surface deviation, and local deviation of the mandibular teeth were measured. One-way analysis of variance (ANOVA) and Welch ANOVA were used for statistical analyses (α = .05). The relative standard deviation and standard error of the mean were calculated to evaluate accuracy. **RESULTS.** The total surface deviation differed significantly according to the scanning path despite a similar scan time. Path D had the highest accuracy and the most uniform color maps, showing minimal deformation of the digital model. Meanwhile, no significant differences were found in the local deviations in the individual tooth assessments, likely owing to issues with the superimposition method. **CONCLUSION.** Among all scan paths, the scan path with the shortest distance from the starting point to the end point showed the smallest total surface deviation and the highest accuracy. No differences were observed in the deviations of specific teeth based on the scan path. [J Adv Prosthodont 2024;16:319-27]

KEYWORDS

Accuracy; Complete arch; Intraoral scanning; Scan path; Scan time

INTRODUCTION

Advances in digital technology have influenced many areas of dentistry, including diagnosis, treatment, and prosthesis fabrication. Particularly, computer-aided design-computer-aided manufacturing (CAD-CAM) technology has had a major impact on the digital fabrication of dental prostheses by enabling the generation of three-dimensional (3D) models and the implemen-

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tation of such models using computer numerical control machine tools.[1] In comparison to conventional manual techniques, CAD-CAM technology is superior in the fabrication of dental prostheses with respect to speed and convenience, allowing for a more planned and precise fabrication process.[2]

Digital scanning methods for CAD-CAM technology can be classified as direct (using an intraoral scanner) and indirect (scanning a master cast made using the traditional impression method).[3] In the direct method, errors during the intraoral scanning stage can result in a poor fit of the definitive prosthesis.[4-7] As intraoral scanning devices are constantly improving based on technological advances, the continuous assessment of the accuracy of intraoral scanners is critical.[8] Menditto *et al*.[9] described the accuracy of digital scanning according to precision and trueness. Precision is considered high if the measurements are close to each other and low if they are far apart. However, precision is not related to the true value; therefore, the results can be precise but still differ from the true value. Trueness describes the closeness of measurements to the actual values. High trueness implies that the mean measured value is close to the actual value. Therefore, ensuring good trueness is crucial for achieving the desired outcome. Trueness and precision are measured using quantitative methods, and accuracy is qualitatively interpreted based on a combination of trueness and precision.[9,10]

Scan time and accuracy are affected by a number of scanning-related conditions.[11] The accuracy of intraoral scanners is affected by the device itself, scan distance, scan path, operator experience, rescanning and post-processing, tooth preparation, and the presence of proximal teeth.[12,13] Scan path refers to the path from the starting point to the end point of the scan. However, various scan paths can be used, leading to differences in the accuracy, convenience, and efficiency of the digital models. In general, intraoral scanning has a similar accuracy to traditional impression methods.[14,15] For partial arches, intraoral scanning has sufficient accuracy to be a suitable alternative to traditional methods using highly accurate impression materials.[14,15] However, the accuracy of intraoral scanning of the complete arch is still less reliable than that of traditional impression methods.[16] Van der Meer *et al*.[17] reported a higher risk of error in complete arch scans than in partial arch scans, owing to the potential accumulation of registration errors over the length of the arch. This is primarily because longer scan paths negatively affect the accuracy of the complete arch scans.[18]

It is important to determine an appropriate method for comparing the accuracy of digital models. Mai *et al*.[19] reported that digital measurement is the most useful method for reducing the variance between experiments. Methods for evaluating the accuracy of digital dental models include 2-dimensional cross-sectional analysis and best-fit 3D superimposition,[20] although the best-fit 3D superimposition is currently more frequently used. Given that the accuracy of digital models differs depending on the evaluation method used, the method should be chosen carefully.

The traditional scan path for complete arch intraoral scans begins at the occlusal surface, followed by the buccal and lingual surfaces. This method shows higher accuracy than other scanning paths, such as starting at the buccal surface and then moving to the occlusal surface or starting from one end and scanning all three surfaces while moving in a single direction.[21] Various factors related to the complete arch intraoral scan path have been reported to have important effects on the accuracy and efficiency of scan data.[22-24] Although intraoral scanners are constantly evolving, the scan path recommended by manufacturers remains the same. Therefore, this study aimed to compare the accuracy of scan data between previously studied complete arch intraoral scan paths and a new alternative path involving a shorter distance from the starting point to the endpoint of the scan. The null hypothesis was that the scan path does not affect the accuracy of the scan data.

MATERIALS AND METHODS

After obtaining the mandibular dentiform (Nissin Dental Production Inc., Kyoto, Japan) impression with an irreversible hydrocolloid (Hydrogum 5; Zhermack, Badia Polesine, Italy), a fast-setting stone (Neo Plumstone; Mutsumi Chemical Industry, Nigata, Japan) was used to create a cast for complete mandibular arch scanning. Tooth preparation was performed for

3-unit fixed prosthesis (mandibular left first premolar (LPM) to the left first molar (LM)), mesio-occlusal inlay in the mandibular right second premolar (RPM), and crown in the right first molar (RM) to compare the data to replicate a situation where restoration was required.

Four paths were compared: three paths previously analyzed by Gavounelis *et al*.[24] and a new alternative path for which the scan starting point was the mandibular right first premolar (Fig. 1). The scan paths were as follows: path A, starting from the occlusal surface, followed by the lingual and buccal surfaces, as the scan path recommended by the manufacturers; path B, buccal, occlusal, and lingual surfaces; path C, back and forth between the buccal and lingual surfaces; and path D, the LPM to the distal surfaces of the left and right mandibular second molars. On paths A, B, and C, the scan started from the left second molar and continued to the right second molar. However, on path D, the scan started from the LPM, which was the tooth closest to the middle of the arch among the teeth to be restored. After scanning the cast with a desktop scanner (Medit T-710; Medit, Seoul, Korea), scan files for the control group were generated and converted to stereolithography (STL) format using data management software (Meditlink v3.1.0; Medit, Seoul, Korea).

The stone cast was scanned ten times per scan path using an intraoral scanner (CEREC Primescan AC; Dentsply Sirona, Bensheim, Germany). All the scans were performed by an individual experienced in the use of intraoral scanners. No restrictions were imposed on the scan time, and each scan was performed until complete data were collected. A distance of 5 – 15 mm was maintained between the scanner tip and the cast.[25] Preliminary alignment of the STL files was performed using an analysis program (GOM Inspect; GOM GmbH, Braunschweig, Germany). Utilizing the "compute additional best fit" function, the total surface deviation of scan data was analyzed. To calculate the local deviation, the scanned and reference data were compared for a specific area in the coordinate system. (Fig. 2). Local deviations were analyzed in four areas: the LM, LPM, RPM, and RM. As the measured deviation values could be positive or negative depending on the direction, they were converted into absolute values for the analysis. A 3D color-coded comparison map was used to analyze the measurements of the scanned surface qualitatively.

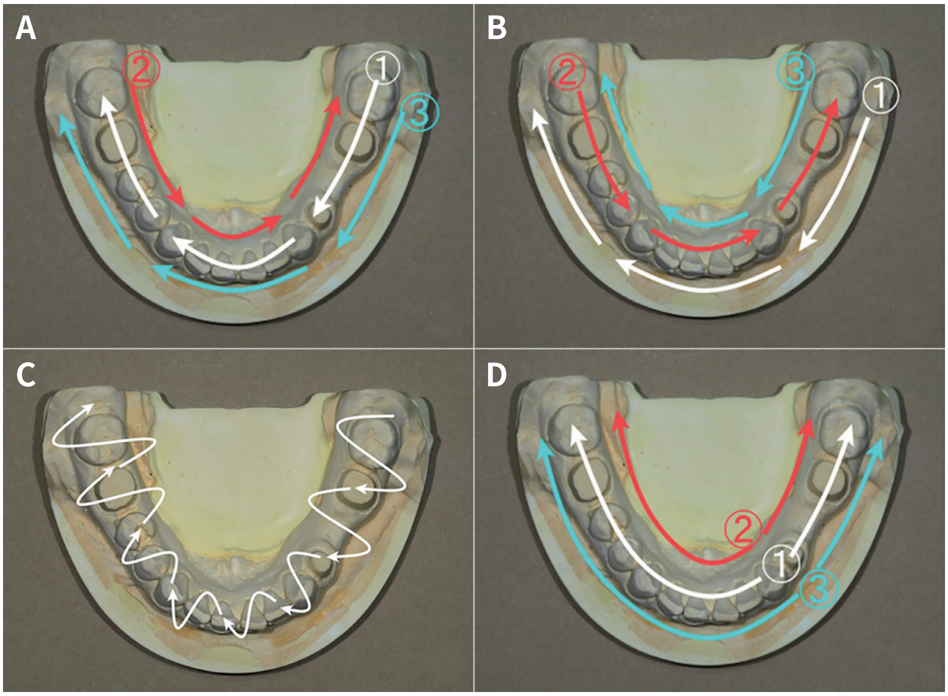

Fig. 1. Scan paths. (A) Path A, starting from the occlusal surface followed by lingual and buccal surfaces, (B) Path B, starting from the buccal surface followed by occlusal and lingual surfaces, (C) Path C, back and forth between the buccal and lingual surfaces, (D) Path D, modification of path A, starting from the mandibular left first premolar.

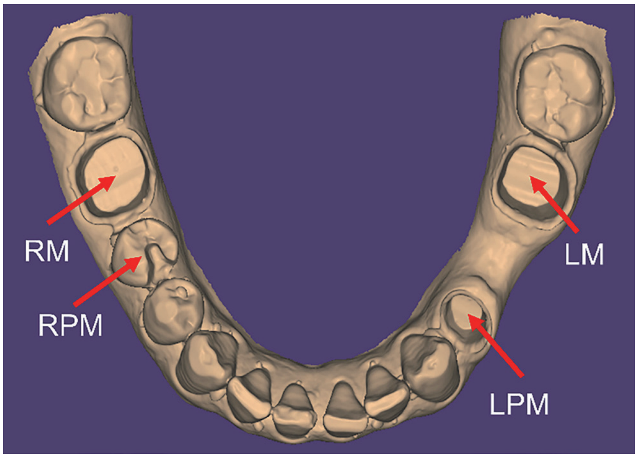

Fig. 2. Local deviation measurement area: red arrows, occlusal surface of the prepared mandibular left first molar (LM), occlusal surface of the prepared mandibular left first premolar (LPM), bottom surface of the prepared mandibular right second premolar (RPM), and occlusal surface of the prepared mandibular right first molar (RM).

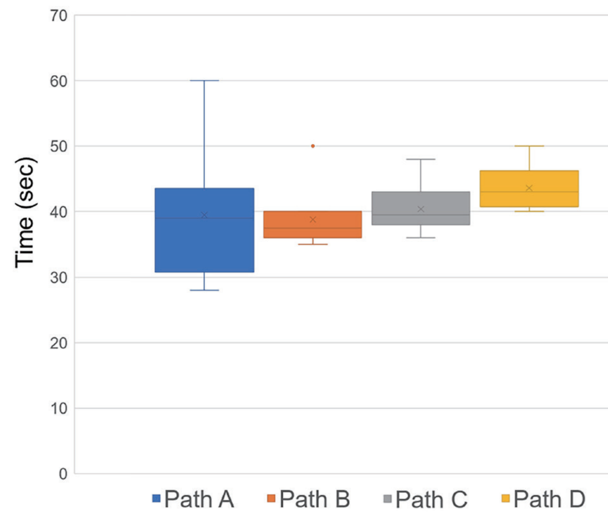

Fig. 3. Scan time for each scan path. sec, seconds.

Based on the total surface and local deviations, the trueness of the measurements was evaluated using the standard error of the mean (SEM) and the precision of the measurements was determined by calculating the relative standard deviation (%RSD).[9,10] Data analysis was performed using a statistical software program (IBM SPSS Statistics v25.0; IBM Corp., Armonk, NY, USA). Experimenter consistency was examined using intraclass correlation coefficients (ICCs). Normality was determined using the Kolmogorov-Smirnov test, and the homogeneity of variance in each group was verified using the Levene test. The scan time for each path satisfied the assumptions of normality and homogeneity of variance and was analyzed using one-way analysis of variance (ANOVA) and Scheffé post-hoc test. The total surface deviation satisfied the assumption of normality but not the homogeneity of variance. Welch's ANOVA was used to assess between-group differences, and the results were verified using the Games-Howell post-hoc test. The local deviation at each tooth did not satisfy either normality or homogeneity of variance and was thus analyzed using nonparametric tests. The Kruskal-Wallis test was used to evaluate the effects of the scan path and tooth position, and the results were verified using Dunnett's post-hoc test ($P < .05$).

RESULTS

The mean ICC was 98.3% ($P < .05$), indicating consistency between the experiments. The mean scan time varied among the scan paths, and the scan times were 39.5, 38.8, 40.4, and 43.6 seconds for paths A, B, C, and D, respectively (Fig. 3), although a one-way ANOVA indicated no significant differences ($P > .05$). The difference in the mean scan times between the shortest (path B) and the longest (path D) durations was 4.8 seconds.

After applying the "compute best fit," the total surface deviation was approximately 12 – 20 µm. The total surface deviation showed significant differences according to Welch's ANOVA ($P <. 05$), with a significantly lower deviation for path D (Table 1). The accuracy was qualitatively analyzed based on measurements of precision and trueness. The %RSD, which represents the precision of the measurements, was 8.24% for path D, which was lower than those for the other paths. The SEM, which represents trueness, was also the lowest for path D at 0.327.

Upon analysis of the color-coded comparison maps comparing the total surface deviation, path D showed a more even distribution of green with less red or blue than the other scan paths (Fig. 4). Total surface devi-

Table 1. Accuracy of each path

	Path A	Path B	Path C	Path D
Total surface deviation ± SD (μm)	20.37 ± 5.61[b]	17.88 ± 3.33[b]	16.76 ± 2.41[b]	12.54 ± 1.03[a]
%RSD	27.532	18.605	14.384	8.238
SEM	1.774	1.052	0.762	0.327

%RSD, relative standard deviation; SEM, standard error of the mean.
Different superscript letters indicate statistically significant differences ($P < .05$).

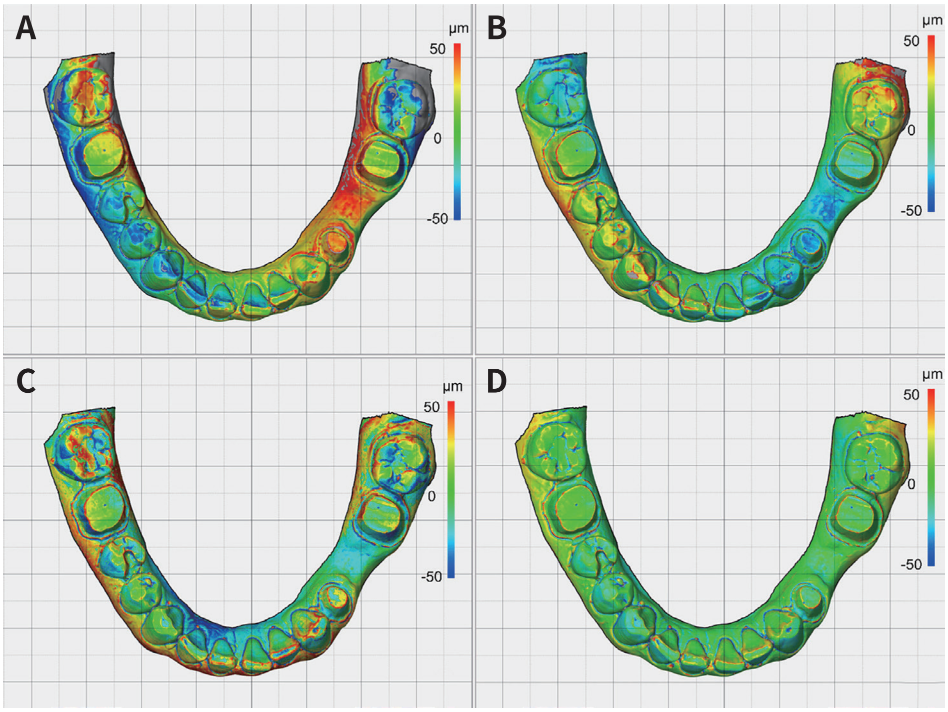

Fig. 4. Comparison of color-coded maps of the scan paths. (A) Path A, (B) Path B, (C) Path C, (D) Path D.

ation of the scanned full arch differed based on the scan path, and significant differences were observed in the deviation, depending on the scan path ($P < .05$). Deviations in locally marked areas were lower according to the scan path ($P = .520$). When the mean deviations at LM, LPM, RPM, and RM for all paths were converted into absolute values depending on the scan path, path D showed a lower mean deviation, %RSD, and SEM for LM, LPM, and RM. However, these differences were not significant ($P > .05$).

DISCUSSION

Because the total surface deviation differed according to the scan path, the null hypothesis was rejected. However, the scan time did not differ significantly among the scan paths. The scan time can be affected by various factors, including patient compliance, tooth condition, scanner performance, practitioner skill, oral cavity size and shape, environmental conditions, software performance, and the objective of the oral scan. In this study, extraoral scanning was performed using a stone cast to minimize confounding factors. Therefore, the possibility that the scan time during the intraoral scan affects the accuracy depending on other conditions such as saliva, prostheses, and surface lubrication cannot be ruled out.

The accuracy of the complete arch scan data was analyzed with respect to trueness and precision. The SEM of the total surface deviation for path D was 0.327, which was the lowest among all scan paths. A lower SEM indicates better trueness, implying that the

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trueness for path D was higher than that for the other three scan paths suggested by Gavounelis *et al*..[24] In the study by Gavounelis *et al*.,[24] path A had the highest trueness, whereas paths B and C had the same trueness. Conversely, in the present study, the newly suggested path D exhibited the highest trueness, with no differences in trueness among paths A, B, and C. In Gavounelis *et al*.'s study,[24] trueness was not compared statistically; the authors only presented descriptive statistics. Upon conversion of the precision values obtained by Gavounelis *et al*.[24] into %RSD, the values were 20.1% for path A, 35.0% for path B, and 25.3% for path C, which were inferior to the precision measurements obtained in this study. This discrepancy can be explained by the significantly better performance of the scanner used in this study than that of the scanner used in the previous study.[24] Nevertheless, path D showed higher trueness than the previously suggested paths.

%RSD is a measure of the variance in the data. The %RSD of the total surface deviation for path D was 8.2%, and the precision was the highest for path D, followed by paths C, B, and A. Because path D showed the highest trueness and precision among the scan paths evaluated, it can be concluded that use of path D for intraoral scanning can produce a more accurate digital model for complete arch prosthesis fabrication. This appeared to be because the distance from the scan start point to the end point was the shortest for path D, which reduced the deviation caused by the accumulation of registration errors. Registration errors refer to the errors accumulated in the process of connecting captured scan data during the scanning process, and they are closely related to the scan distance.[26] The high accuracy of the scan data resulted in fewer errors in the digital model and improved the similarity of the digital models with each digital scan. Path D, which provided more accurate digital models, can be recommended as a new scanning path for creating complete arch prostheses. Differences in the anatomical morphology of tooth surfaces and tooth alignment have been reported to significantly affect scan accuracy; however, advances in hardware and software have reduced the impact of these factors.[27]

Scan accuracy can be influenced by the method used for the comparative analysis. There are three types of comparative methods.[20] Local fit evaluation is an appropriate method when comparing only one area, but it is not appropriate when many areas are compared, such as in this study. Given that the tripod-fit evaluation directly sets the reference point, there is a high possibility that errors will occur when specifying the reference point. Meanwhile, 3D best-fit alignment is the most appropriate evaluation method to check the overall distortion and precision between each scan when the focus is on reducing the scan distance during a complete arch oral scan.[20]

There were no significant differences in accuracy among the scan paths at any tooth position (Table 2). However, this may be because the best-fit 3D superimposition analysis method is not appropriate for checking the deviation of a specific location. In best-fit 3D superimposition analysis, the two different coordinate systems of the source and target data must be converted into a single coordinate system. This was accomplished using one of the two methods. One method involves matching point identifications from the source and target data in 1:1 pairs and calculating and applying a transformation matrix.[28] The other method uses the iterative closest point method to repeatedly calculate and apply a transformation matrix to minimize the distance between the closest points.[29] Therefore, even if there is some loss of accuracy in individual data points, the coordinate system of the mesh data is transformed in a way that produces many pairs between the mesh data or point clouds in another part of the scan. This may explain the lack of a difference in accuracy based on the scan path at specific tooth positions. In paths A, B, and C, a large deviation was observed for LM to RM, which was the most distant point from the scan start point. However, for Path D, the starting point was the LPM. Because of the shorter LPM-to-LM and LPM-to-RM distances, there was less deviation. With the loss of the mandibular left second premolar and preparation of the LPM and LM, the right side involved more teeth than the left side, providing more possible reference points for best-fit 3D superimposition.

Although there was no statistical difference, the SEM was smaller for scan path D compared to the other paths at the LM and LPM, which were closer to the start of the scan, and it was the second smallest

Table 2. Data for each tooth position for each scan path (μm)

		Local deviation ± SD (μm)	RSD (%)	SEM (μm)
A	LM	28 ± 12.083	43.154	3.821
	LPM	19 ± 10.562	55.589	3.34
	RM	14.8 ± 8.176	55.243	2.585
	RPM	17.6 ± 9.348	53.114	2.956
B	LM	20.7 ± 16.473	79.58	5.209
	LPM	11.9 ± 8.621	72.445	2.726
	RM	14.9 ± 12.351	82.893	3.906
	RPM	26.4 ± 18.368	69.576	5.808
C	LM	23.9 ± 13.354	55.874	4.223
	LPM	24.3 ± 14.967	61.593	4.733
	RM	15.2 ± 6.795	44.704	2.149
	RPM	19.8 ± 8.025	40.53	2.538
D	LM	14.7 ± 9.661	65.721	3.055
	LPM	16.1 ± 8.504	52.82	2.689
	RM	17.7 ± 7.931	44.808	2.508
	RPM	26.5 ± 8.541	32.23	2.701

MD, mean deviation; SD, standard deviation; %RSD, relative standard deviation; SEM, standard error of the mean.

at the RM and RPM, which were most distant from the scan start. Therefore, the accuracy of path D at certain tooth sites was not worse than that of the other scan paths.

For path D, the total deviation was small, whereas the local deviation was not significantly different. Therefore, selecting the scan path with the shortest distance from the area to be restored in a full-arch scan is recommended.

However, these results should be interpreted with caution because the experiment described herein was performed on a stone cast. Accuracy can also differ depending on the intraoral scanner used. Despite these limitations, a significant benefit of path D is that image superimposition begins at the premolar, which is closer to the middle of the complete arch. This path involves a shorter distance from the area farthest from the scan starting point than the other scan paths. Therefore, considering that this path is easy to apply and has high trueness and limited distortion, path D is recommended over the previously suggested scan paths.

CONCLUSION

A new alternative scan path, D, was compared with the previously suggested scanning paths with respect to the total surface and local deviations for specific teeth. The scan times based on the scan paths were comparable when complete arch scanning was performed using an intraoral scanner. The trueness and precision across the entire surface were the highest for path D among all scan paths, and the digital model showed limited deformation. No significant differences were observed in the deviations of specific teeth based on the scan paths.

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