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Scanning Accuracy of 10 Intraoral Scanners for Single-crown and Three-unit Fixed Denture Preparations: An In Vitro Study

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Objective: *To evaluate the accuracy of 10 intraoral scanners for single-crown and three-unit preparation models.*

Methods: *A maxillary partially edentulous model was fabricated. A dental cast scanner was used to obtain standard tessellation language (STL) data. Ten intraoral scanners, namely Trios 2 (TR2; 3Shape, Copenhagen, Denmark), True Definition (TD; 3M, Saint Paul, MN, USA), CEREC AC Omnicam (OM; Dentsply Sirona, Charlotte, NC, USA), Organical Scan Oral (OS; R+K, Berlin, Germany), PlanScan (PS; Planmeca, Helsinki, Finland), DWIOP (DW; Dental Wings, Montreal, Canada), Xianlin (XL; Hangzhou Xianlin, Hangzhou, China), DL-100 (DL; Guangzhou Longcheng, Guangzhou, China), Trios 3 (TR3; 3Shape) and i500 (MD; MEDIT, Seoul, South Korea) were used to obtain stereolithography data as test groups. Trueness, precision and surface accuracy were evaluated by deviation analysis using 3D image processing software. One tooth with a three-unit preparation for each test group was registered with the reference scan data, and the absolute distance from another tooth was calculated as the absolute accuracy. The data were analysed using a Mann-Whitney U test and Dunn-Bonferroni test ($\alpha = 0.05$).*

Results: *The best trueness, precision and surface accuracy of scanning single crown preparation were recorded with TD (trueness 2.9 µm and precision 1.9 µm) and XL (surface accuracy 20.3 ± 2.9 µm). The best trueness, precision, surface accuracy and absolute accuracy of three-unit preparations were recorded with TD (2.6 µm), XL (1.9 µm), OM (27.1 ± 5.2 µm) and TR3 (79.2 ± 19.6 µm), respectively. There was no statistically significant difference in trueness between single- and multiple-unit preparations for any of the intraoral scanners ($P > 0.05$). A statistically significant difference in the surface accuracy between single and multiple preparations was found for TR2, TD, OM, DW, XL, DL and MD ($P < 0.05$).*

Conclusion: *The trueness and precision of intraoral scanners for scanning three-unit preparations were nearly the same as those for single-crown preparations; however, with the exception of OS, PS and TR3, the surface accuracy of single-crown preparations was significantly better than that for three-unit preparations.*

Key words: *intraoral scanner, scanning accuracy, single crown preparation, surface accuracy, three-unit fixed denture preparation*

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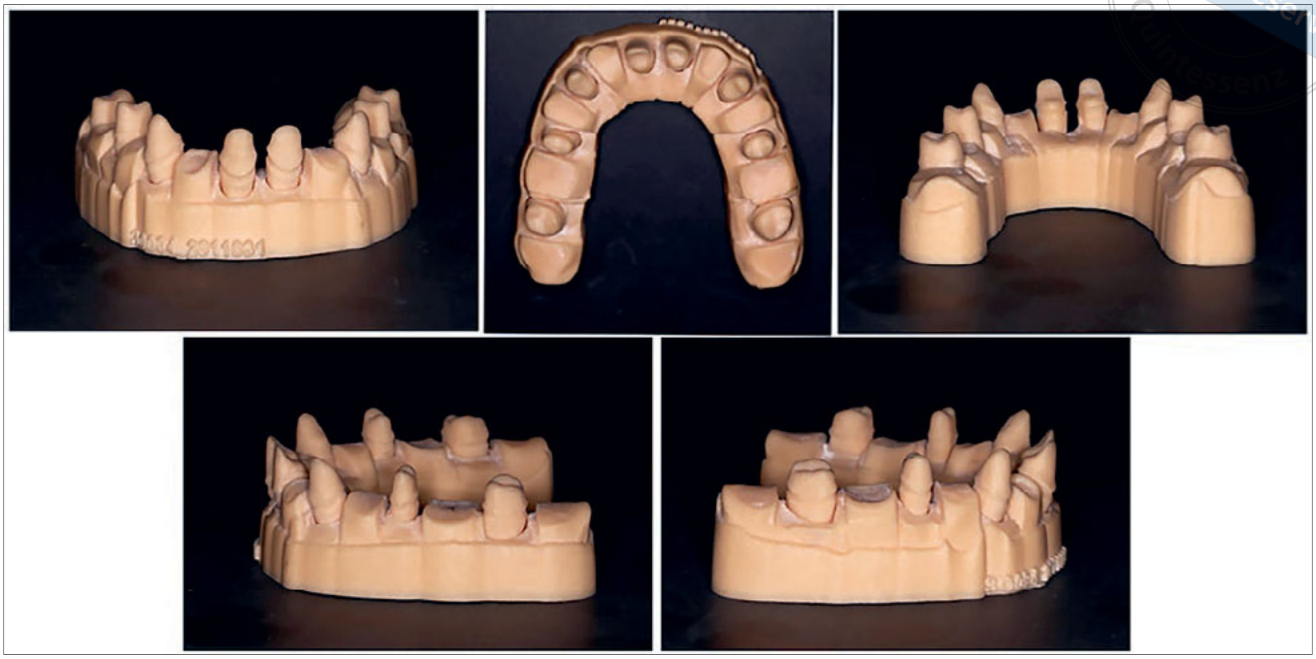

Fig 1 Multi-angle images of the partially edentulous maxillary model. The model can be regarded as eight single-crown preparations or six three-unit fixed denture preparations. (Single crown preparation: the left and right central incisors, canine, second premolar and second molar were abutment preparations; three-unit fixed denture preparation: left and right second molar and second premolar, second premolar and canine, canine and central incisor preparations.)

Digital dental technology has recently gained considerable popularity and is being incorporated into the workflow for fixed prosthodontics. The quality and accuracy of scanning data are crucial to digital dental restorations. Compared with dental cast scanners, intraoral scanners need to be placed in the patient's mouth. The range of scanning focal length is limited by the structure of the scanning head and the adjacent teeth. The scanning blind zone decreases the scanning quality, and the number of images stitched together is much greater than that for dental cast scanners, which increases the number of data processing errors.

Evaluation of the accuracy of intraoral scanners is often carried out using the scan data from the model scanner[1-3]. Previous related studies have often obtained trueness and precision by taking multiple scans of measured objects[4-9]. Accuracy consists of both precision and trueness; however, the trueness can only reflect the consistency of the scan data and the overall size of the scanned object but cannot reflect the consistency of the surface morphology. The consistency of the surface morphology is critical for accurate matching between the oral prosthesis and the remaining oral tissue, such as the fitness of the outer margin of the full crown preparation shoulder and the corresponding area of the zirconia full crown margin. In the present study, scanning accuracy was evaluated using three indexes: trueness, precision and surface accuracy. Trueness refers to the degree of agreement between the mean and reference values obtained from many test results, indicating the systematic error of the measurement results; precision refers to the degree of agreement between independent test results under specified conditions, indicating the random error of the measurement process[9,10]; and surface accuracy refers to the degree of coincidence of the scanned data points with the surface morphology of the scanned object.

The present study sought to measure the scanning trueness, precision, surface accuracy and other indexes to evaluate the accuracy of 10 intraoral scanners for scanning single-crown preparations and three-unit fixed denture preparation models, ignoring the impact of the oral environment, to provide a reference for relevant research into evaluation criteria and clinical application.

Materials and methods

Experimental materials, equipment and software

A maxillary standard dentition plaster model (Stone, Heraeus Kulzer, Hanau, Germany) was selected to pre-

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Table 1 Characteristics of scanners used in the study.

Scanner type	Model	Manufacturer	Software	Country	Imaging principle
Intraoral	Trios 2	3Shape	1.3.4.3	Denmark	Confocal microscopy
Intraoral	True Definition	3M	4.2.1	United States	Active wavefront sampling
Intraoral	CEREC AC Omnicam	Dentsply Sirona	Cerec SW 4.4.1	Germany	Triangulation
Intraoral	Organical Scan Oral	R+K	Exocad DentalDB 2012.12	Germany	Confocal microscopy
Intraoral	PlanScan	Planmeca	4.1.1.0	Finland	Triangulation
Intraoral	DWIOP	Dental Wings	1.8.0.038	Canada	Triangulation
Intraoral	Xianlin	Hangzhou Xianlin	V1.1.2	China	Triangulation
Intraoral	DL-100	Guangzhou Longcheng	V1.1.3	China	Triangulation
Intraoral	Trios 3	3Shape	1.4.7.5	Denmark	Confocal microscopy
Intraoral	i500	MEDIT	2.0.3	South Korea	Triangulation
Dental cast	Activity880	Smart Optics	2.6	Germany	Triangulation

pare the partially edentulous maxillary model; the left and right lateral incisors, first premolars and first molars were missing and the left and right central incisors, canines, second premolars and second molars were abutment preparations. A dental cast scanner (10 µm; Activity 880, SmartOptics, Bochum, Germany) was used to obtain standard tessellation language (STL) data for the model, and computer-aided design (CAD) software (Dental System 2013, 3Shape, Copenhagen, Denmark) was used to design the prototype, which was then printed using a high precision resin printer (VisiJet SL e-Stone, Projet 6000, 3D Systems, Rock Hill, SC, USA) to obtain a reference model (Fig 1). The 10 intraoral scanners used, namely Trios 2 (TR2), True Definition (TD), CEREC AC Omnicam (OM), Organical Scan Oral (OS), PlanScan (PS), DWIOP(DW), Xianlin (XL), DL-100 (DL), Trios 3 (TR3) and i500 (MD), and the dental cast scanner used in the study, are listed in Table 1.

Research methods

Obtain the STL scan data of the partially edentulous maxillary model

The dental cast scanner was used once to obtain STL data as a reference scan, then 10 intraoral scanners were used three times to obtain STL data for test groups by the same trained experimenter who was skilled in use of all the intraoral scanners, under the same experimental environment. The scanning path of the scanning head was a single optical path, that is, it scanned the occlusal surface first and then the lingual side to the buccal side.

Evaluation of scanning accuracy

With regard to trueness and precision, in Geomagic Studio 2013 software (3D Systems), the authors selected the surface of each preparation as a common area and registered the scan data with the reference data using the best-fit alignment command. The deviation analysis of the command was used to obtain the mean distance (Formula a), analysing the deviation of every point between the test group and reference group. The average value for mean distance (absolute value) was calculated as trueness for scanning single-crown preparations and three-unit fixed denture preparations (Formula b), and the standard deviation of the trueness per group was calculated as precision (Formula c).

$$md = \frac{\sum_{i=1}^{n} x_i - x_{i-actual}}{n} \qquad a$$

$$tr = \frac{\sum_{i=1}^{m} |md_i|}{m} \qquad b$$

$$pr = \sqrt{\sum_{i=1}^{m} \frac{(|md_i| - tr)^2}{m}} \qquad c$$

m, number of subjects; md, mean distance; n, number of points of subjects; pr, precision; tr, trueness; x_i, test value; $x_{i-actual}$, reference value.

Surface accuracy

In Geomagic Studio, we used the deviation analysis of the software command to calculate the root mean square (RMS) (Formula d) and calculated the mean value and

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standard deviation (SD) of the RMS to obtain surface accuracy (Formulae e and f).

$$RMS = \sqrt{\sum_{i=1}^{n} \frac{(x_i - x_{i-actual})^2}{n}} \quad \text{d}$$

$$sa_{av} = \frac{\sum_{i=1}^{m} RMS_i}{m} \quad \text{e}$$

$$sa_{sd} = \sqrt{\sum_{i=1}^{m} \frac{(RMS_i - sa_{av})^2}{m}} \quad \text{f}$$

m, number of subjects; n, number of points of subjects; $s\alpha_{av}$, average value of surface accuracy; $s\alpha_{sd}$, standard deviation of surface accuracy; x_i, test value; $x_{i\text{-actual}}$, reference value.

Absolute accuracy

The left second molar was selected as the common area, each test group was superimposed over the reference scan data and deviation analysis was performed using the best-fit method. We calculated the distance of the occlusal surface, mesial surface, distal surface, buccal side and lingual side of the left second premolar in the test group from the reference scan data and obtained five distances for each tooth preparation. The offset distance of the faces was the absolute accuracy of scanning three-unit fixed denture preparations.

Statistical methods

A Shapiro-Wilk normality test was performed, and some data were abnormally distributed. A Dunn-Bonferroni test was used to compare ten groups in pairs. Statistical differences between the accuracy indexes of the single-crown preparation and the three-unit fixed denture preparation of 10 scanners were analysed using an independent samples Mann-Whitney U test. Statistical analyses were conducted using SPSS (v20.0; IBM, Armonk, NY, USA) ($\alpha = 0.05$).

Results

The representative deviation patterns of single-crown preparations and three-unit fixed denture preparations are presented in Figs 2 and 3. The colour distribution showed the positive and negative distribution of deviation; green represents the area with a small amount of deviation, red represents positive deviation and blue represents negative deviation. The overall deviation of the 10 scanners was relatively small, but OS showed a greater negative deviation of the occlusal surface of the posterior teeth and the lingual fossa of the anterior teeth. It also showed greater positive deviation of the incisal end of the anterior teeth and the cusp of the posterior teeth. Negative deviations may cause the manufactured restorations to not fit properly on the preparation, and positive deviations may lead to poor retention of the restorations.

An overview of the results and statistics is presented in Tables 2 to 4. The trueness of 10 scanners for scanning single-crown preparations ranged from 2.9 to 24.7 µm, precision ranged from 1.9 to 18.4 µm and surface accuracy ranged from 22.0 ± 5.0 µm to 89.3 ± 58.3 µm. The trueness of scanning three-unit fixed denture preparations ranged from 2.6 to 19.2 µm, precision ranged from 1.9 to 15.1 µm and surface accuracy ranged from 27.1 ± 5.2 µm to 102.6 ± 41.6 µm. TD showed the best trueness for scanning single-crown preparations and three-unit fixed denture preparations, TD and XL showed the best precision and TD showed the best accuracy in general. OS displayed the worst surface accuracy but was clinically acceptable. Absolute accuracy ranged from 79.2 ± 19.6 µm to 333.9 ± 68.7 µm. Absolute accuracy of scanning three-unit fixed denture preparations for PS and DW was over 300 µm, showing that the suitability of the outer margin of the full crown preparation may beyond the tolerance range.

The Dunn-Bonferroni test results showed that OS was significantly worse than the other groups in terms of mean distance for scanning single-crown and three-unit fixed denture preparations ($P < 0.05$). XL was significantly better than the other groups except for TD and OM, whereas OS and PS were significant worse than the others in terms of surface accuracy for scanning single-crown preparations ($P < 0.05$). TR3 was significantly better than TR2, OS, PS and DL, whereas OS was significantly worse than the other groups in surface accuracy for scanning three-unit fixed denture preparations ($P < 0.05$). TR3 performed significantly better than the other groups except for MD, whereas PS and DW were significantly worse than the other groups in absolute accuracy for scanning three-unit fixed denture preparations ($P < 0.05$). Statistical analysis showed that there was no significant difference in trueness between single-crown preparations and three-unit fixed denture preparations in any of the intraoral scanners ($P > 0.05$). For surface accuracy between the single-crown preparation and the three-unit fixed denture preparation, the differences for TR2, TD, OM, DW, XL, DL and MD were statistically significant ($P < 0.05$).

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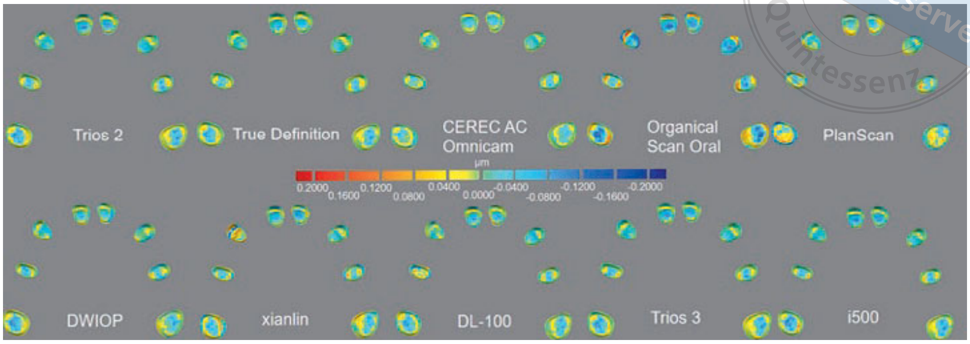

Fig 2 Colour-coded deviation maps of single-crown preparation. The range of deviation is colour-coded from −200 mm (blue) to 200 mm (red).

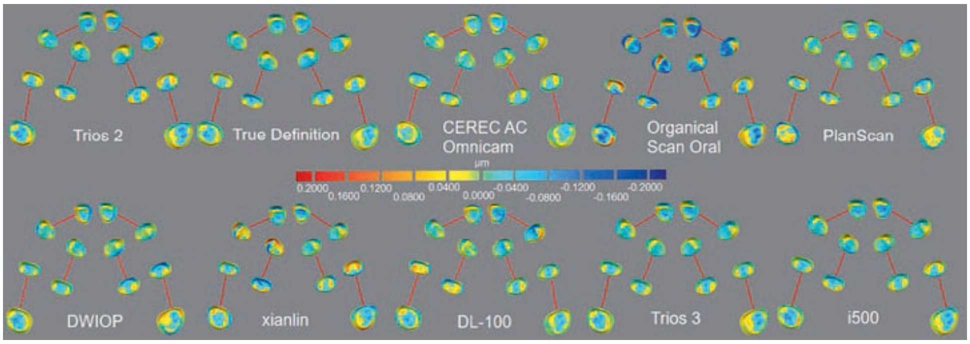

Fig 3 Colour-coded deviation maps of three-unit fixed denture preparation. The range of deviation is colour-coded from −200 mm (blue) to 200 mm (red).

Table 2 Accuracy indexes for scanning single-crown preparations and three-unit fixed denture preparations (micron).

Group		TR2	TD	OM	OS	PS	DW	XL	DL	TR3	MD
Intraoral scanner		Trios 2	True Definiton	CEREC AC Omnicam	Organical Scan Oral	PlanScan	DWIOP	Xianlin	DL-100	Trios 3	i500
Single-crown	Trueness (n = 24)	4.4	2.9	4.1	24.7	10.8	4.3	4.1	5.2	5.7	7.4
	Precision (n = 24)	2.2	1.9	2.0	18.4	9.5	2.9	3.2	4.2	3.9	5.8
	Surface accuracy (n = 24)	25.7 ± 4.2	22.0 ± 5.0	22.3 ± 3.4	89.3 ± 58.3	40.8 ± 9.9	24.8 ± 0.4	20.3 ± 2.9	36.4 ± 39.5	24.7 ± 4.2	24.9 ± 4.0
Three-unit fixed denture	Trueness (n = 18)	4.3	2.6	3.6	19.2	6.8	3.7	3.0	3.4	4.8	5.6
	Precision (n = 18)	2.2	2.0	2.2	15.1	7.5	2.8	1.9	2.1	3.4	4.3
	Surface accuracy (n = 18)	36.8 ± 8.0	31.3 ± 9.3	27.1 ± 5.2	102.6 ± 41.6	46.1 ± 12.3	31.0 ± 7.1	44.1 ± 25.2	37.8 ± 20.4	27.8± 4.8	31.0 ± 5.0
	Absolute accuracy (n = 15)	200.7 ± 34.6	176.6 ± 49.3	135.7 ± 26.1	182.4 ± 63.9	316.5 ± 19.9	333.9 ± 68.7	131.8 ± 29.1	164.1 ± 32.8	79.2 ± 19.6	101.4 ± 41.4

Discussion

The existing intraoral scanning technology is mainly a non-contact measurement method, and the main working principles include confocal microscopy, active wavefront sampling, triangulation, laser-based visual and optical coherence tomography technology[11-13]. This study involved three scanning principles: confocal microscopy for TR2, OS and TR3, active wavefront sampling for TD and triangulation for OM, PS, DW, XL, DL and MD. No common law between scanning principle and accuracy was found; OS performed worse than the other two scanners with the same scanning principle. The nominal scanning accuracy and evaluation methods given by different manufacturers are different. This study evaluated the accuracy of the scanners from single-crown and three-unit fixed denture preparations to the local microscopic data points, providing a more objective evaluation for clinical use. The trueness values were all smaller than those for surface accuracy. This was because when calculating trueness, the mean deviation between the test group and the reference group was positive or negative, causing a certain positive and negative offset.

The results of the statistical analysis showed that there was no statistically significant difference in the

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Table 3 A Dunn-Bonferroni test examined the differences among the ten groups. The first value for each group is the *P* value of mean distance for scanning single-crown preparations, the second is the *P* value of surface accuracy for scanning single-crown preparations, the third is the *P* value of mean distance for scanning three-unit fixed denture preparations, the fourth is the *P* value of surface accuracy for scanning three-unit fixed denture preparations and the last is the *P* value of absolute accuracy for scanning three-unit fixed denture preparations.

Group	TR2	TD	OM	OS	PS	DW	XL	DL	TR3
TD	0.071, 0.009*, 0.037*, 0.056, 0.336								
OM	0.720, 0.015*, 0.336, 0.001*, 0.000*	0.148, 0.870, 0.259, 0.207, 0.123							
OS	0.000*, 0.000*, 0.001*, 0.000*, 0.365	0.000*, 0.000*, 0.000*, 0.000*, 0.955	0.000*, 0.000*, 0.000*, 0.000*, 0.110						
PS	0.055, 0.000*, 0.873, 0.170, 0.017*	0.000*, 0.000*, 0.054, 0.001*, 0.001*	0.023*, 0.000*, 0.423, 0.000*, 0.000*	0.001*, 0.225, 0.000*, 0.027*, 0.001*					
DW	0.633, 0.563. 0.352. 0.051, 0.011*	0.184, 0.044*, 0.247, 0.968, 0.000*	0.905, 0.064, 0.976, 2.222, 0.000*	0.000*, 0.000*, 0.000*, 0.000*, 0.001*	0.017*, 0.000*, 0.441, 0.001*, 0.876				
XL	0.427, 0.000*, 0.117, 0.285, 0.006*	0.312, 0.292, 0.603, 0.398, 0.074	0.663, 0.223, 0.543, 0.035*, 0.807	0.000*, 0.000*, 0.000*, 0.000*, 0.065	0.007*, 0.000*, 0.159, 0.015*, 0.000*	0.752, 0.002*, 0.523, 0.376, 0.000*			
DL	0.974, 0.565, 0.280, 0.409, 0.157	0.076, 0.002*, 0.313, 0.276, 0.651	0.744, 0.003*, 0.906, 0.019*, 0.275	0.000*, 0.000*, 0.000*, 0.000*, 0.508	0.051, 0.001*, 0.358, 0.028*, 0.000*	0.656, 0.249, 0.882, 0.259, 0.000*	0.446, 0.000*, 0.625, 0.807, 0.182		
TR3	0.653, 0.466, 0.880, 0.003*, 0.000*	0.024*, 0.062, 0.053, 0.296, 0.000*	0.419, 0.089, 0.417, 0.828, 0.012*	0.000*, 0.000*, 0.000*, 0.000*, 0.000*, 0.000*	0.143, 0.000*, 0.992, 0.000*, 0.000*	0.353, 0.879, 0.435, 0.315, 0.000*	0.213, 0.002*, 0.156, 0.059, 0.024*	0.630, 0.192, 0.353, 0.033*, 0.000*	
MD	0.325, 0.530, 0.863, 0.086, 0.000*	0.005*, 0.049*, 0.024*, 0.843, 0.002*	0.179, 0.072, 0.257, 0.144, 0.117	0.000*, 0.000*, 0.002*, 0.000*, 0.006*	0.352, 0.000*, 0.739, 0.002*, 0.000*	0.144, 0.960, 0.270, 0.812, 0.000*	0.075, 0.000*, 0.082, 0.518, 0.186	0.309, 0.229, 0.210, 0.373, 0.008*	0.593, 0.919, 0.747, 0.214, 0.347

*$P < 0.05$.

mean distance for scanning single-crown preparation and three-unit fixed denture preparations with 10 scanners. This indicates that the trueness and precision of 10 scanners can reach the same level as scanning a single crown when scanning a three-unit fixed denture preparation.

The numerical comparison showed that the surface accuracy of three-unit fixed denture preparations was

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Table 4 A Mann-Whitney U test was used to examine the differences between the accuracy indexes of 10 scanners between scanning single-crown preparations and three-unit fixed denture preparations.

	TR2	TD	OM	OS	PS	DW	XL	DL	TR3	MD
Mean distance	$Z = -0.165$, $P > 0.05$	$Z = -0.611$, $P > 0.05$	$Z = -0.776$, $P > 0.05$	$Z = -1.207$, $P > 0.05$	$Z = -1.627$, $P > 0.05$	$Z = -0.496$, $P > 0.05$	$Z = -0.789$, $P > 0.05$	$Z = -1.106$, $P > 0.05$	$Z = -0.572$, $P > 0.05$	$Z = -0.559$, $P > 0.05$
Surface accuracy	$Z = -4.500$, $P < 0.05$	$Z = -3.482$, $P < 0.05$	$Z = -2.899$, $P < 0.05$	$Z = -1.906$, $P > 0.05$	$Z = -1.081$, $P > 0.05$	$Z = -3.102$, $P < 0.05$	$Z = -4.844$, $P < 0.05$	$Z = -2.631$, $P < 0.05$	$Z = -1.691$, $P > 0.05$	$Z = -3.750$, $P < 0.05$

Mean distance denotes the mean distance when scanning the single-crown preparation and the 3-unit fixed denture preparation; surface accuracy denotes the surface accuracy when scanning the single-crown preparation and the three-unit fixed denture preparation.

larger than single-crown preparations. The differences between groups were statistically significant except for OS, PS and TR3. The calculation method for surface accuracy avoids the offset of the scanning errors of the two abutments, indicating that the surface accuracy of the fixed bridge was inferior to that of the single crown, which explains that surface accuracy is more representative for the measurement of the overall surface morphology.

At present, there is no uniform international standard for the evaluation of the accuracy of intraoral scanners. To avoid the interference of intraoral factors, the accuracy studies are usually performed in vitro[2,6,8,14-16]. Previous accuracy studies often used repeated measurements to obtain systematic and random errors but ignored the floating degree of point cloud data relative to real data in a single scan[2,8,15], which was the surface accuracy proposed in the present study. This is especially important for the suitability of all digital restorations based on this data (e.g., undercut area, shoulder margin). Thus, in the previous study, we evaluated two intraoral scanners and proposed the concept and evaluation method of trueness of the scanner and precision of the scanned data[3] and evaluated the data of the scanned single-crown preparation. In the present study, the same method was used to evaluate the trueness and precision of scanning the single-crown preparation and the three-unit fixed denture preparation with 10 intraoral scanners. At the same time, the concept of surface accuracy was proposed to represent the degree of consistency between the scanned data points and the surface morphology of the scanned object. For fixed dentures, in addition to the aforementioned accuracy indexes, absolute accuracy is closely related to clinical suitability, that is, the suitability between the fixed retainer and the preparation after the fixed denture has been fully seated on the one-sided abutment. It is closely related to inaccuracies such as warping that often occurs when clinical fixed dentures are in place. Thus, it is also one of the indicators of this study.

The results showed that the deviation of absolute accuracy in the 10 intraoral scanners was higher than the surface accuracy. This was because surface accuracy considered the three-unit fixed denture preparation as a whole and there was an overall error cancellation phenomenon in the deviation analysis, whereas the absolute accuracy was based on one of the three-unit fixed denture preparations as the reference, and the mean distance of the other preparation from the reference group, therefore there was no error cancellation.

Conclusion

This study proved that 10 scanners can scan single-crown preparations and three-unit fixed denture preparations successfully and reach clinical requirements. TD, TR2, XL, TR3 and OM showed good scanning accuracy, but OS and PS performed poorly. This study initially explored the accuracy evaluation methods of 10 intraoral scanners scanning single-crown and three-unit fixed denture preparations. In future studies, more units of preparation should be evaluated to explore the maximum unit span to meet clinical needs. The accuracy indicators of this study can correspond to different types of clinical significance and guide the clinical selection of appropriate scanning equipment to meet clinical needs.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Author contribution

Dr Xin Yue ZHANG contributed to the experiments, study design, data analyses and manuscript writing; Dr Yue CAO contributed to the data analyses, visualisation and manuscript writing; Dr Zhe Wen HU contributed to the data analyses and conceptualisation; Dr Hu CHEN and Prof Yu Chun SUN contributed to the study

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design, manuscript revision and editing. All the authors reviewed the manuscript.

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