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RESEARCH AND EDUCATION

A comparison of accuracy of 3 intraoral scanners: A single-blinded in vitro study

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ABSTRACT

Statement of problem. Measuring both the trueness and precision of an intraoral scanner (IOS) will provide a thorough understanding of its accuracy.

Purpose. The purpose of this in vitro study was to measure the complete-arch trueness and precision of 3 commercially available intraoral scanners equipped with the latest software version and compare them by using a laboratory scanner as reference.

Material and methods. Nineteen maxillary and 19 mandibular completely dentate stone casts previously acquired from 19 patients by using a polyvinyl siloxane (PVS) dual mix impression and stock trays were scanned with 3 intraoral scanners (TRIOS 3; 3Shape, i500; Medit, and Emerald; Planmeca) using their latest software versions. The same casts were also scanned with a laboratory scanner (E3; 3Shape) that served as the reference scanner. Files were exported in standard tessellation language (STL) format and inserted into a metrology 3D mesh comparison software program (CloudCompare).

Results. In terms of trueness, a significant difference was found among the scanners (F (2.37)=239.7, $P<.001$). Planmeca Emerald had significantly lower trueness values than either the Medit i500 ($P<.001$) or the 3Shape TRIOS 3 ($P<.001$). No significant difference in trueness was found between the Medit i500 and the 3Shape TRIOS 3 scanner ($P=.365$). In terms of precision, a significant difference was found among the scanners (F (2.89)=301.2, $P<.001$). The 3Shape TRIOS 3 scanner was significantly more precise than the other scanners ($P<.001$ for both the Medit i500 and Planmeca Emerald). The Planmeca scanner was significantly more precise than the Medit i500 scanner ($P<.001$). Concerning the ability of the scanners to reproduce the files of the reference scanner without overestimation or underestimation, the Medit i500 produced files that significantly underestimated the reference scanner's files (t (37)=−12.4, $P<.001$). The other scanners did not significantly either underestimate or overestimate the files of the gold standard (t (37)=−1.91, $P=.062$ for the 3Shape and t (37)=1.64, $P=.101$ for the Planmeca)

Conclusions. With regard to completely dentate arch trueness, the Planmeca Emerald IOS had statistically lower trueness. With regard to complete dentate arch precision, the 3Shape TRIOS3 IOS was the statistically more precise scanner. With regard to reference scanner file estimation, the Medit i500 IOS produced files that significantly underestimated the reference scanner files. All 3 tested scanners exhibited a completely dentate arch average accuracy below 100 μm in vitro. (J Prosthet Dent 2019;■:■-■)

The use of digital methods, such as computer-aided design and computer-aided manufacturing (CAD-CAM), has increased rapidly in dentistry in recent years.[1] The first step in this digital workflow is the acquisition of a digital scan by means of an intraoral scanner, a method that has been reported to provide excellent accuracy for short-span prostheses, both tooth- and implant-supported, compared with conventional impression methods.[1,2] Controversy still exists, however, regarding the accuracy of IOSs for scanning complete arches. Evidence has supported the superiority of conventional impressions for complete arches,[3-7] but data from newer

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Clinical Implications

Newest generation intraoral scanners exhibit a completely dentate arch accuracy of under 100 μm in vitro. Some IOSs tend to underestimate the arch size.

studies testing the latest IOS hardware and software versions tend to support the implementation of digital scan for complete arches.[8-14] An IOS should achieve clinically acceptable levels of accuracy, often specified at 100 μm,[15-17] although a definitive consensus and a scientific correlation between global deviation and actual marginal prosthesis misfit is lacking.

Trueness and precision are terms used for direct and indirect dental digitization. According to the ISO international standard number 5725, trueness is the ability of a measurement or measuring device to match the actual value of the quantity being measured, whereas precision is the ability of a measurement or measuring device to consistently repeat a particular measurement.[18] Trueness and precision are both measures of accuracy.

New scanners are being introduced to the dental market every year.[19] The TRIOS 3 color Pod, now in its fourth generation, was launched by 3Shape in 2016, the Emerald (Planmeca) in 2017, and the i500 (Medit) in 2018. However, studies that compared different intraoral scanners in terms of dentate complete-arch accuracy are sparse and have reported conflicting results because of methodological, statistical, and technical issues.[5,7-9,11,12,17,19-27] The authors are unaware of studies comparing these 3 scanners for accuracy in dentate complete arches.

The purpose of this in vitro study was to measure the complete-arch trueness and precision of 3 recently introduced intraoral scanners, the TRIOS 3 color Pod (3Shape), the Emerald (Planmeca), and the i500 (Medit) equipped with their latest software versions and to compare them with a laboratory scanner as reference. The null hypotheses were that no statistically significant difference would be found in the complete-arch trueness of the tested scanners and that no statistically significant difference would be found in the complete-arch precision of the tested scanners.

MATERIAL AND METHODS

Thirty-eight Type IV stone casts (Hera Moldastone; Kulzer GmbH) recently acquired from completely dentate adult patients[13] were used in the study. The stone casts (19 maxillary, 19 mandibular) were scanned with the desktop laser scanner (E3; 3Shape), as a reference against which the meshes were compared, and the 3 intraoral scanners. The E3 is a scanner used in dental laboratories and commonly used for the digitization of stone casts to design and manufacture CAD-CAM dental prostheses. Its accuracy, as reported by the manufacturer, is 7 μm. The resultant triangular meshes of the stone casts (STL files) were used as the control. For the IOS digital scans, the recommended scan strategy per manufacturer was used to ensure optimal accuracy.

For the TRIOS 3 scanner, the maxillary scanning initiated from the left posterior area and proceeded occlusally with a zig-zag movement in the anterior teeth toward the right posterior area. It then turned buccally toward the contralateral side, and the scan was completed on the palatal side with a left to right direction of scan. For the mandible, scanning initiated from the posterior left quadrant and proceeded occlusally with a zig-zag movement in the anterior teeth toward the contralateral side. It then turned lingually toward the left quadrant and was completed on the buccal side with a left-to-right movement.

For the i500 scanner, the maxillary scan started on the posterior left occlusal area and proceeded toward the contralateral side with a zig-zag movement in the anterior teeth area. It then turned palatal and ended on the buccal side of the right side. For the mandibular casts, the scan was initiated on the posterior left occlusal area and proceeded toward the contralateral side with a zig-zag movement in the anterior teeth. It then turned lingually toward the left quadrant and terminated on the buccal side of the right posterior quadrant.

For the Emerald scanner, the maxillary and mandibular scans followed identical paths. They initiated from the left posterior occlusal surfaces in the maxilla and the left posterior occlusal surfaces in the mandible and proceeded toward the contralateral side with a 45-degree movement against the incisal area of the anterior teeth. It then turned buccally toward the left side and terminated on the palatal and lingual side of the right maxillary and right mandibular posterior teeth. Digital scanning was performed at room temperature by 1 experienced operator (G.M.) proficient with the Medit i500 and 3Shape TRIOS 3 scanners and by a different experienced operator (A.T.) proficient with the Planmeca Emerald scanner. This minimized the operator experience bias reported to influence scan accuracy.[28]

The scanners were calibrated before each scan session according to the manufacturers' instructions. The scanning mode was set to model scan for all 3 scanners. For the i500 IOS, the scanning parameters used were a blue light mode with a filtering level 2 and a focal length of 17 mm.

All digital scans were automatically postprocessed by using the proprietary software before being exported and saved as STL files. For the i500, the Fill Major Holes option was elected before postprocessing. Software versions for the IOS used are shown in Table 1. All the files were coded and sent to the second author (D.A.) for

Table 1. Intraoral scanner and software versions used

Intraoral Scanner	Software Version
Medit i500	Medit Link version 2.0.3 build 376 Revision 27 520
3Shape TRIOS 3	Dental Desktop 1.6.9.1 (insane mode)
Planmeca Emerald	Romexis 5.3.2.13

analysis. As a result, all the analyses were blinded to the brand of each scanner.

Four sets of triangular meshes were available for comparison, totaling 152 STL files, n=38 for each IOS and n=38 for the control desktop scanner. For every arch, 4 meshes (3S, IM, PE, and GS) were imported for computational manipulation in a dedicated mesh and point cloud handling software program (CloudCompare, version 2.11 alpha; Anoia). The triangular mesh derived from the desktop laser scanning was used as a reference, and no other manipulation was performed. The 3S, IM, and PE originated meshes were then initially roughly registered together by using a minimum (3 to 5) number of points and then were again finely registered with each other by using the iterative closest point (ICP) algorithm, calculated on a sample of 50 000 pairs of points. This resulted in 3 meshes for each arch overlapping one another. The meshes were then simultaneously cropped, thus leaving only the teeth up to approximately the middle of the clinical crown of the second molar bilaterally and 3 to 5 mm of the gingiva. The result was 3 triangular meshes representing the same arch, with clinically relevant and almost identical remaining anatomy. Finally, each of these meshes was again separately, roughly, and finely registered to the GS (control). This resulted in 3 different meshes for each arch, which were finely registered to the control. The absolute distance of every face of each test mesh to a point on the surface of the reference mesh was computed, indicating the difference between this mesh and the control. The median value of the differences and the interquartile range (IQR) for each pair were noted.

Additionally, the signed (that is, positive and negative) distances of each mesh to the reference file were calculated, and the mean and standard deviation of the measurements were noted. These measurements were only used to estimate the ability of each scanner to correctly replicate (without overestimation or underestimation) the file produced by the control and were not used to calculate the accuracy of the intraoral devices.

The first stone cast (patient 1, maxillary) was scanned with each of the IOS scanners 10 times to estimate the precision of the intraoral scanners. The 10 meshes were simultaneously cropped and were finely registered with each other, following the same procedure described previously. Each of the meshes acquired was sequentially used as a reference, resulting in a total of 90 pairs of meshes for each intraoral scanning device. The average standard deviation of the differences of the meshes was used as a measure of repeatability for the scanners. All the handling and analysis of the STL files was performed by the same operator (D.A.), who was blinded to the brand of the scanner.

To estimate the repeatability of the reference scanner, the first stone cast (patient 1, maxillary) was scanned with the desktop scanner 10 times. The 10 meshes were simultaneously cropped and then finely registered with each other. Pairwise comparisons were conducted between the meshes. This resulted in 90 pairs of meshes whereby each of the meshes acquired was sequentially used as a reference. The average standard deviation of the differences of the meshes was used as a measure of repeatability for the desktop scanner. The handling of the files from the reference scanner was not blinded.

To estimate the precision of the registration software, 1 laser-scanned mesh was used. The mesh was imported into the software and cloned 4 times; the clones were then roughly and finely registered with each other and with the original mesh by using the same procedure described previously. This resulted in 20 pairs of meshes, with each of the meshes sequentially used as a reference. The standard deviation of the differences was used as a measure of its precision.

Because of the relatively large sample size and by virtue of the central limit theorem, parametric methods were used to draw inferences. For the estimation of trueness, descriptive statistics were calculated, and inferences were drawn by using repeated-measures 1-way ANOVA with a fixed factor "brand of intraoral scanner" (TRIOS 3, i500, and Emerald) and a dependent variable "the difference between the intraoral scanners and the control." Post hoc analysis was conducted by pairwise *t* tests. To estimate precision, descriptive statistics were calculated and inferences were drawn by using repeated-measures 1-way ANOVA with a fixed factor "brand of scanner" (TRIOS 3, i500, Emerald, and E3) and a dependent variable "the pairwise differences between the meshes for each of the scanners." Post hoc analysis was conducted by pairwise *t* tests. In relation to the ability of the scanners to correctly reproduce (without overestimation or underestimation) the files produced by the reference desktop scanner, 1 sample *t* test was used to draw inferences about the mean distance of the differences from zero for each of the scanners (α=.05 with familywise Bonferroni correction where appropriate). A spreadsheet (Excel 2016; Microsoft Corp) with the XRealStats add-in was used for the statistical analysis. All values were reported in μm. The statistical analysis concerning the accuracy of the intraoral scanner was performed blinded by 1 of the authors (D.A.), and the brands of the scanners were revealed after the results had been computed.

Table 2. Precision (standard deviation) of control scanner and of mesh handling software

Measurement	SD
Reference scanner (N=90)	1.9
Mesh handling software (N=20)	0.051

SD, standard deviation. Values in μm.

Table 3. Results of trueness study

Intraoral Scanner	No. of Tests	Mean	SD
Medit i500	38	15.8	5.9
3Shape TRIOS 3	38	16.8	3.8
Planmeca Emerald	38	56.5	15.2

SD, standard deviation. Values in μm.

RESULTS

The results for the precision of the reference scanner and of the mesh handling software are presented in Table 2. The results of the trueness comparison between the IOS devices based on the absolute differences between the files produced by each of the scanners and the files produced by the control are presented in Table 3. For each of the 38 situations, the median value of the difference from the control was calculated, but for inferences, the average (mean) and standard deviation (SD) of all the median values for each scanner were used as seen in Figure 1.

Concerning trueness, a significant difference was found among the scanners (F (2.37)=239.7, *P*<.001). The trueness of Planmeca Emerald was significantly lower than that of either the Medit i500 or the 3Shape TRIOS 3 (both *P*<.001). No significant difference in trueness was found between the Medit i500 and the 3Shape TRIOS 3 scanners (*P*=.365). Color maps of trueness for the tested devices regarding the complete arch are seen in Figure 2. Color maps regarding trueness in the anterior segment of the same complete arch are seen in Figure 3. Blue represents areas of agreement with the reference scan, and other colors represent areas of deviation from the control.

The results for IOS precision are presented in Table 4. A significant difference was found among the scanners (F (2.89)=301.2, *P*<.001). The 3Shape TRIOS 3 scanner was significantly more precise than the other scanners (*P*<.001). The Planmeca Emerald scanner was significantly more precise than the Medit i500 scanner (*P*<.001).

Concerning the ability of the scanners to reproduce, without overestimation or underestimation, the files of the reference scanner, the Medit i500 produced files that significantly underestimated the reference scanner files (t (37)=-12.4, *P*<.001). The other scanners did not significantly either underestimate or overestimate the files of the reference scanner (t (37)=1.91, *P*=.062 for the 3Shape TRIOS 3 and t (37)=1.64, *P*=.101 for the Planmeca Emerald), even though it became apparent that the Planmeca Emerald had the largest variability of all as seen by the large standard deviation of the results and as also seen in the boxplot in Figure 4. Signed differences are presented in Table 5.

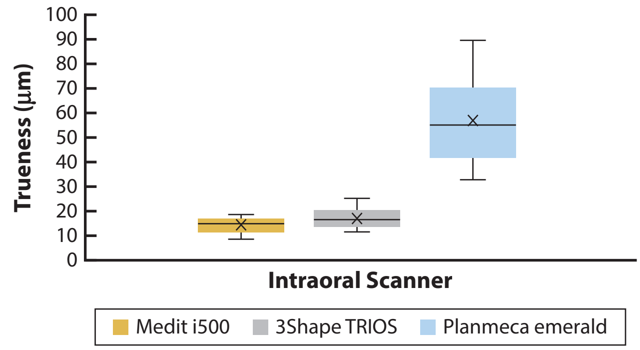

Figure 1. Trueness study. X in boxes represents mean values (μm).

DISCUSSION

To the authors' knowledge, this was the first in vitro study comparing the TRIOS 3, the i500, and the Emerald scanners for complete-arch accuracy. Statistically significant differences among the devices, both in terms of complete-arch trueness and complete-arch precision, were detected; therefore, both null hypotheses were rejected.

The TRIOS 3 IOS (3Shape) has been extensively tested in vitro, but only a few studies have looked into the trueness and precision of its latest hardware and software version. Ender et al[12] reported mean complete-arch trueness of 51.1 μm and mean complete-arch precision of 57.4 μm for the TRIOS 3 (insane mode). The results of the present study are not in agreement with those of the study by Ender et al.[12] This can be attributed to the teeth on their test cast that were constructed from ceramic material, which has a higher translucency and therefore a different refractive index compared with teeth constructed from dental gypsum in the present study.[29] In another in vitro study,[21] the TRIOS 3 IOS yielded mean complete-arch trueness of 69.9 μm and mean complete-arch precision of 105.6 μm. The scanned teeth in the study by Renne et al[21] were previously restored with complete coverage polymethyl methacrylate (PMMA) crowns, and so the difference in scanning substrates used may account for the different trueness and precision values between the study of Renne et al[21] and the present study. The refractive index of the scanned substrate has been shown to influence IOS complete-arch accuracy, with enamel being less accurate than dentin because of its higher translucency.[30] In a recent study using a human cadaver with a completely dentate maxilla maintained in relative humidity, the complete-arch trueness of the TRIOS 3 was reported to be 78.4 μm, and complete-arch precision value was 71.3 μm.[11] The authors reported that the crown

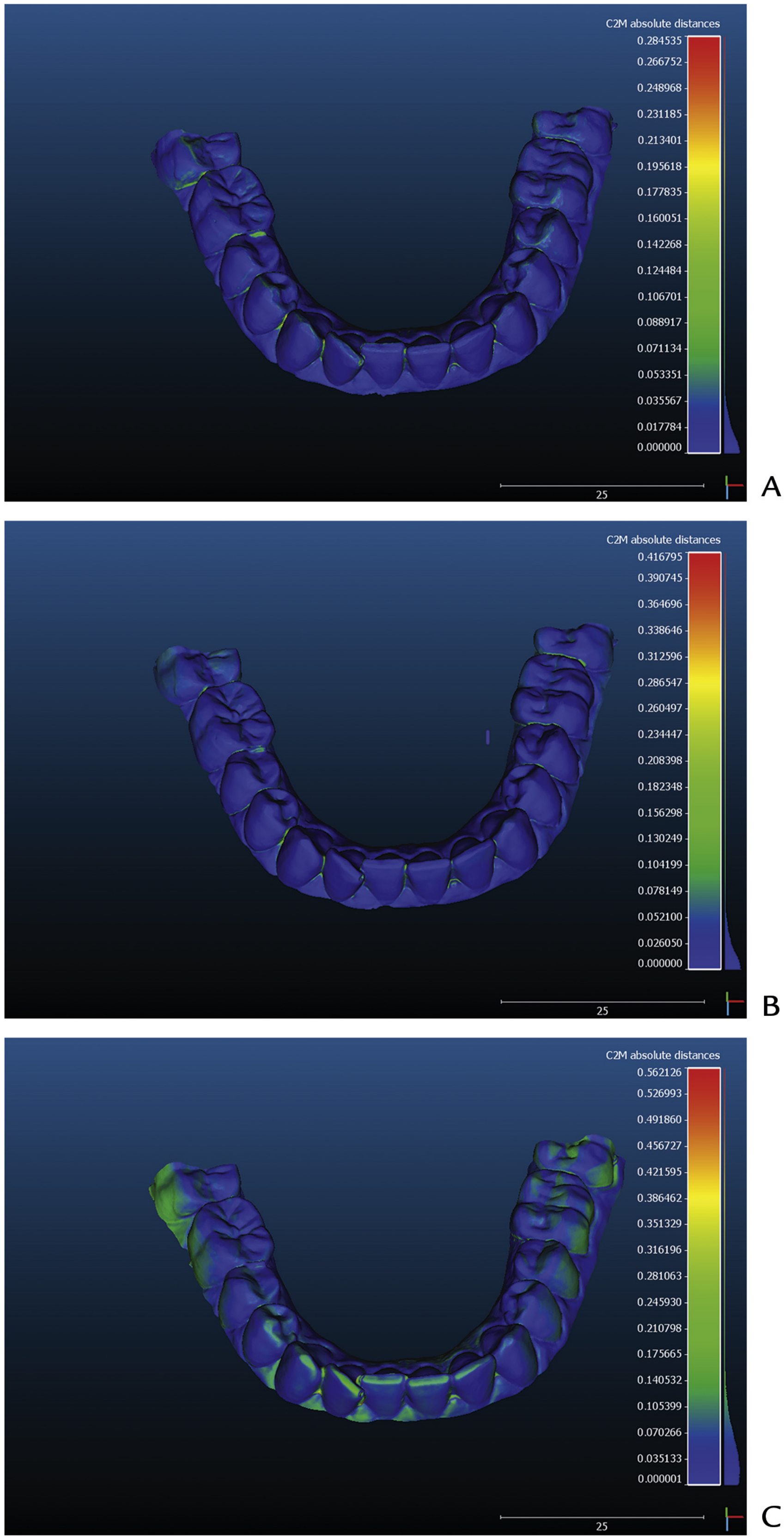

Figure 2. Trueness study (complete arch). A, 3Shape TRIOS 3. B, Medit i500. C, Planmeca Emerald IOS.

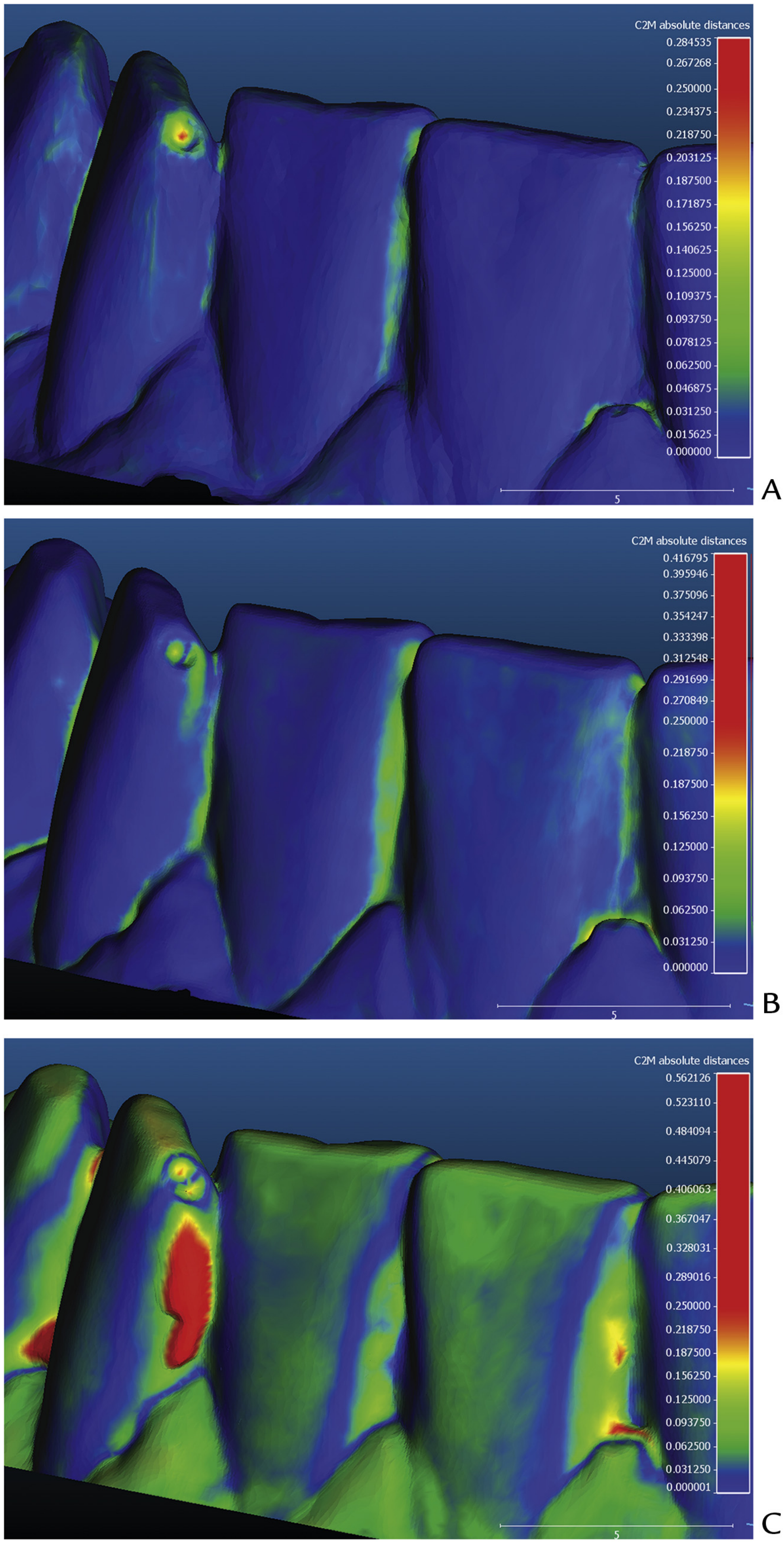

Figure 3. Trueness study (anterior segment enlarged). A, 3Shape TRIOS 3. B, Medit i500. C, Planmeca Emerald IOS.

Table 4. Precision study

Intraoral Scanner	No of Tests	SD
Medit i500	90	20.0
3Shape TRIOS 3	90	11.0
Planmeca Emerald	90	15.0

SD, standard deviation. SD of differences represents precision of each scanner. Values in µm.

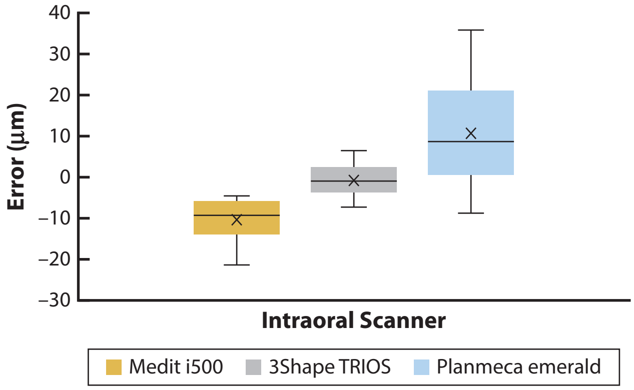

Figure 4. Signed differences between tested scanners and control. X in boxes represents mean values.

preparations included in the digital scan were scanned with higher trueness than the complete arch, and they attributed this, among other factors, to the different refractive index of enamel and dentin. In a study where dental gypsum casts were used as the scanned substrate, Sfondrini et al[14] reported mean complete-arch accuracy for the TRIOS 3 mono IOS to be 28.9 µm and 28.07 µm for the maxilla and mandible, respectively. Additionally, in a study of reproducibility of dental stone cast scans, albeit with a previous TRIOS 3 hardware and software version,[31] the authors reported mean completely dentate arch precision to be 19 µm, a finding that is in agreement with the results of the present study, indicating that scanning accuracy of this particular IOS remains constant when dental gypsum is used as a substrate.[14,31]

The i500 (Medit) IOS was introduced in 2018, and therefore, the literature regarding its accuracy is limited. In vitro complete-arch precision values for this scanner range from 52.3 to 66.3 µm[12,26] and are higher than those reported in the present study. Although it is not stated in these studies whether the recommended scan strategy was used, in the study by Lee et al,[26] the authors used the same scanning parameters as in the present study. The difference in the reported precision values can also be attributed to the different scanning substrates, as discussed,[11,21,29,30] and to the earlier IOS software versions used.[12,26]

The Emerald (Planmeca) IOS has also been recently launched, and therefore, available evidence on its complete-arch accuracy is limited. In a study examining the trueness and precision in complete arch scans of a

Table 5. Signed differences revealing overall discrepancy between files produced by intraoral scanners and reference scanner

Intraoral Scanner	No. of Tests	Mean	SD
Medit i500	38	-10.0	4.9
3Shape TRIOS 3	38	-1.4	4.5
Planmeca Emerald	38	7.4	27.9

SD, standard deviation. Values in µm.

human cadaver maxilla, Mennito et al[11] reported a mean complete-arch trueness value of 90.1 µm and a mean complete-arch precision value of 55.3 µm. The difference between the reported values and those of the present study can also be attributed to the different scanning substrates.

The results of the signed difference analysis revealed statistically significant differences among the scanners in the overall discrepancy between the files produced by the 3 IOS and the reference scanner. The i500 was the only scanner found to significantly underestimate the reference file size (mean: -10 µm, SD: 4.9 µm). The TRIOS 3 tended to marginally and not statistically significantly underestimate the reference file size (mean: -1.4 µm, SD: 4.5 µm), a finding that has also been reported in the literature, albeit for an older TRIOS hardware and software version.[22] The Planmeca Emerald scanner, even though it did not significantly overestimate or underestimate the reference scans, presented the largest standard deviation (mean: 7.4 µm, SD: 27.9 µm) compared with that of the other IOS devices tested, and this may be considered a measure of its reduced accuracy.

Different metrology software versions use different best-fit algorithms for the superimposition of data sets. This may result in different spatial values for the calculation process.[32,33] The high precision (0.051 µm) of the specific version of the metrology software used in the present study has been reported by the present authors in a previous study.[34]

A limitation of the present study was its in vitro design. Clinical confounding factors that have been found to influence in vivo complete-arch scanning accuracy, such as saliva, patient movement, and accessibility to posterior teeth, were not investigated, and therefore, an actual clinical situation was not replicated.[35] Another limitation was that only 3 different brands of IOS devices were tested. Additionally, access to an industrial reference scanner was not possible, and a commercial laboratory scanner (E3; 3Shape) was used instead. Nevertheless, its precision value (1.9 µm) in combination with its accuracy as reported by the manufacturer (7 µm) makes this scanner an accurate alternative to an industrial reference scanner. That global registration of the files was used to estimate the differences between them was also a limitation. The software used the least squares algorithms to calculate the best fit of the models, based on all the points of the tested STL file. In this way, the errors were averaged over the whole file area, and local differences may be misrepresented. However, the global mean error calculated in the present study was representative of the global differences that exist between the control and the tested scanners. Local areas were not evaluated, and only the global over-estimation or underestimation of the reference file by the tested scanners was reported. Further studies incorporating an in vivo design with a large sample size and sufficient IOS devices should investigate trueness and precision of the available intraoral scanners.

CONCLUSIONS

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

1. With regard to dentate complete-arch trueness, the Planmeca Emerald IOS had statistically significant lower trueness values.
2. With regard to dentate complete-arch precision, the 3Shape TRIOS 3 IOS was statistically the most precise scanner.
3. With regard to reference scanner file estimation, the Medit i500 IOS produced files that significantly underestimated the reference scanner files.
4. All 3 tested scanners exhibited in vitro dentate complete-arch average accuracy below 100 μm.

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