THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

An in vitro 3D evaluation of the accuracy of 4 intraoral optical scanners on a 6-implant model

Toni Sami, DDS,[a] Gary Goldstein, DDS,[b] Dean Vafiadis, DDS,[c] and Taylor Absher, MFA[d]

ABSTRACT

Statement of problem. Although numerous studies have been performed on the accuracy of intraoral scanners, determining the clinical significance of the results is problematic.

Purpose. The purpose of this in vitro study was to evaluate the trueness and precision of 4 intraoral optical scanners (IOSs) on a 6-implant model and provide a method to help determine clinical significance.

Material and methods. A polymer mandibular edentulous model with 6 hexagonal scan bodies (Ritter) was fabricated, and a control scan was made by using an industrial laser line probe (FARO Edge HD Arm). Four IOSs (True Definition, TRIOS, CEREC Omnicam, Emerald Scanner) were used to scan the same model 5 times: the 20 standard tessellation language (STL) files were individually imported to a 3D inspection software program (Geomagic Control X) and superimposed over the computer-aided design (CAD) control scan. The tolerance was set at a limit of ±0.01 mm.

Results. None of the tested scanners were true even 10% of the time at the ±0.01-mm tolerance, and the Emerald scanner was true less than 5% of the time. Within scanners, results were precise, showing variations of no more than 2% over repeated scans. When a ±0.05-mm tolerance was selected, the percentage within tolerance increased dramatically. This made the performance of the scanners to appear better but obscured valuable information. The 3D color map was the best method for understanding the data. The color maps showed how much was within tolerance and, equally important, the amount and direction of out of tolerance, providing an easily understandable qualitative and quantitative image.

Conclusions. No statistical or clinical differences were found among the scanners tested. The 3D map was the best method for observing the data. (J Prosthet Dent 2019;■:■-■)

Computer-aided design and computer-aided manufacturing (CAD-CAM) systems rely on 3 components: data acquisition, data processing, and manufacturing.[1] The digital practice begins with an intraoral scan, and accuracy is a major factor in the clinicians' evaluation of digital scanning systems.[2] To be able to manufacture an accurate physical replica, maintaining such accuracy throughout the entire process is of importance and begins with an accurate digital scan. Digital scans have become as, or more, accurate than conventional impressions, and improvements are consistently being made in both the hardware and software.[3-13]

To standardize the terminology, the International Standards Organization (ISO) has defined the accuracy of measurements as consisting of 2 components, trueness and precision (ISO-5725-1). "Trueness refers to the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. Precision refers to the closeness of agreement between test results."[14]

Numerous studies have compared the accuracy of digital scanners on teeth. One compared 7 scanners with conventional quadrant impressions and found that, even though there were statistical differences among the scanners tested, the authors felt they were not clinically significant.[4] Seelbach et al[5] in a study comparing the internal fit of a single crown fabricated from digital scanning and conventional impressions reported similar

[a]Graduate student, Advanced Education Program in Prosthodontics, New York University College of Dentistry, New York, NY.
[b]Professor Emeritus, New York University, New York, NY.
[c]Clinical Associate Professor, Ashman Department of Periodontics and Implant Dentistry, New York University College of Dentistry, New York, NY.
[d]Senior Academic Technology Specialist, IT at NYU, Research Technology, LaGuardia Studio New York University, New York, NY.

Clinical Implications

Means and standard deviations of the average deviation of the multiple points derived from a 3D inspection software program are only 1 method of evaluating data. Applying a narrow tolerance range and viewing the within-tolerance and the under- and over-tolerance numbers, along with the 3D maps, allow for a better understanding of trueness and precision and are helpful in determining clinical significance. It also allows clinicians and programmers to locate discrepancies, providing a tool for designing future software revisions.

accuracy for both. Shembesh et al[6] compared the marginal adaptation of 3-unit fixed dental prostheses by using both digital scanning and conventional impressions and reported that all methods generated clinically acceptable (120 μm) marginal gaps. Another study compared the accuracy of 5 intraoral scanners to indirect digitizing and found that all the intraoral scanners tested, despite statistical differences, had similar acceptable clinical accuracy when limited to a single quadrant.[7] A study using a partially edentulous model with prepared complete coverage abutments of 5 teeth concluded that the shorter the span, the more accurate the scan.[8]

An in vivo study using steel balls on posterior mandibular teeth found the conventional impression technique more accurate than the digital,[10] and another in vivo study with 15 participants reported that 73% of them preferred the alginate impressions.[11] One study found that the PlanScan (Planmeca) was the most accurate for sextant scanning, while the 3Shape TRIOS was the best for complete arch scanning.[15] Another compared 5 digital intraoral scanners and found that Fastscan (IOS Technologies), iTero (Align Technology), and TRIOS had similar values for precision and trueness.[16] Lee et al[17] compared an intraoral scanner to a cast scanner and found that images gathered from the intraoral scanner had better trueness than the cast scanner but both had similar precision. Nadelcu and Persson[18] reported significant differences between scanners requiring coating and those without coating. They suggested limiting the use of intraoral scanning to short-span restorative treatments. Another study using a model of a complete arch of prepared teeth to compare 4 different intraoral scanners found that all scanners, except the CEREC, showed similar levels of trueness and precision.[19] A study testing 2 scanners to determine whether tooth alignment and scanning sequence affected the precision of the resultant casts reported that, despite statistical differences, both were acceptable clinically.[20]

Implant dentistry is another area where digital scans can be a valuable aid to clinicians. Ajioka et al,[9] testing a partially edentulous model with 2 implant healing abutments in the mandibular left edentulous space from the first molar to the first premolar, compared the accuracy of the digital scanning and conventional impressions and reported a slightly greater distance error with the digital scans. A study using partially edentulous models with multiple implants scanned by using 3 intraoral scanners and a laboratory scanner reported that the precision of the intraoral scanners decreased with an increase in the distance between the scanbodies, while the laboratory scanner was not affected by the distance.[12] Amin et al[13] tested an edentulous model with 5 scan bodies and reported that the 2 scanners tested showed higher accuracy (trueness) for complete arch digital scans than for the conventional splinted open tray impression technique. Another study evaluated the accuracy of 2 scan bodies in the mandible and concluded that the distance and angulation errors were too large for clinical applications.[21] Gimenez et al,[22] testing an edentulous model with 6 scan bodies of varying distances and angulations and a CEREC Bluecam intraoral scanner, reported that the angulation and depth of implants did not significantly affect the deviations in distance. Marghalani et al[23] used 2 intraoral scanners and a conventional impression technique to study the accuracy of 2 partially edentulous mandibular casts with 2 implant analogs with a 30-degree angulation and found that, while some differences were statistically significant, the accuracy of all scanning and impression techniques was clinically acceptable.

Manufacturers have introduced new software programs to enhance the accuracy of intraoral scanners, and new metrology software has increased the ability to determine accuracy in the micrometer range. Nevertheless, in all the articles quoted, determining the clinical significance of the results and the parameters used to judge the appropriateness of the method is difficult. The purpose of this study was to evaluate the trueness and precision of 4 intraoral scanners on a 6-implant digitized model and to suggest a clinically relevant method of evaluating the data. The research hypothesis was that no difference would be found among scanners.

MATERIAL AND METHODS

A reference edentulous mandibular polymer model fabricated with 6 implant analogs (1A-3.75; Ritter Implants) embedded approximately 5 mm apart had 6 screw-retained hexagonal scan bodies (3DSPA-8; Ritter Implants) attached and was hand tightened (Fig. 1). These scan bodies were selected because of their fairly constant, multifaceted anatomy that would allow 3D digital comparison. The polymer model was scanned by

Figure 1. Reference model.

using an industrial grade laser line probe (Edge ScanArm HD; FARO) by an experienced independent technician (T.A.) and used as the control.

For the test scans, 4 intraoral scanner systems were used: True Definition (TD) (software version 5.2.1; 3M ESPE), TRIOS (TS) (software version 1.4.7.5; 3shape), Omnicam (CE) (software version 4.5.0 CEREC; Dentsply Sirona), and Emerald Scanner (EM) (software version 4.6.0; Planmeca). One investigator (D.V.), experienced with all 4 systems, performed 5 scans with each system. A second investigator (T.S.), blinded to the scanner used, performed all the digital superimpositions and data analysis.

The control scan and the 20 study scans were individually imported to a 3D design and print software program (Geomagic Design X; 3D Systems). The control scan was trimmed so that only the scan bodies and thin strips connecting the scan bodies were visible and were saved as a CAD reference file. All standard tessellation language (STL) files were trimmed in the same manner. The files were then imported into a metrology software program (Geomagic Control X; 3D Systems), from which the 3D, linear, and superimposition measurements were calculated.

Each individual superimposition was carried out as follows: the CAD control scan was imported and recognized as a reference measurement model, the study scan was imported and recognized as a measured data model, and superimposition was performed with the "Best Fit Scenario." Three-dimensional analysis was then completed by using both ±0.01 mm and ±0.05 mm tolerance levels and ±1 mm and ±0.2 mm for the maximum and minimum range at a Sigma 6 range.

For data analysis, Control X, which automatically calculated the arithmetic average (AA); root mean square (RMS); and the within tolerance, overtolerance, and undertolerance at the defined tolerance range, was used. The primary approach to the comparison of scanner accuracy focused on the analysis of the observations within the defined range of tolerance, ±0.01 mm. Second, the AA and RMS of the deviations for each scanner were calculated with caution as those values can hide serious, but offsetting, overmeasurements and undermeasurements. All analyses were made by using a statistical software program (IBM SPSS Statistics, v24; IBM Corp).

RESULTS

Descriptive statistics generated from the 3D software are presented in Tables 1 and 2. With a change in the tolerance level, the AA remained the same. However, the within-tolerance and the out-of-tolerance percentages, which were broken down into under (smaller) and over (larger) amounts did change. Figure 2 shows the distribution of the true values achieved by each of the scanners at the ±0.01-mm tolerance level. None were true even 10% of the time, and the Emerald scanner was true less than 5% of the time. Within scanners, results were precise, showing variations of no more than 2% over repeated scans. When ±0.05-mm tolerance was selected, the percentage within tolerance increased considerably. This setting made the scanners appear better, but valuable information was obscured. The histograms for the scanners, which showed the amount of data at any gap distance, also did not change with the change in tolerance and were almost identical.

The metrology software reported outcomes in 3D, providing a 3D color map to best understand the data. The color maps showed how much was within tolerance and, equally important, showed the amount and direction of out of tolerance, giving an easily understood qualitative and quantitative image. Figure 3 shows the average color map for each scanner.

The overlapping AA confidence intervals, the similar histograms, and the 3D mapping demonstrated no differences among the scanners tested.

DISCUSSION

No statistical or clinically relevant differences were noted among the scanners tested; therefore, the research hypothesis was accepted. For each statistical analysis performed (on AA, RMS, or in or out of tolerance), a 3D data set was converted into a 1-dimensional analysis. The conundrum is how does a 1-dimensional statistic adequately explain a 3D finding? The arithmetic average is the mean of all the gap distances, some critical and some not. It does not identify the amount of deviation, nor the direction, and may not be helpful in determining how to use the data. The AAs and standard deviations of the data, as well as the RMS, remain the same regardless of the tolerance level selected, as all of the points in the scan are computed. What does change is the undertolerance and overtolerance numbers, as well as the 3D color images which visually demonstrate the amount and location of the actual discrepancies.

Table 1. Mean arithmetic average and 95% confidence intervals, root mean square, and within and outside of tolerance at ±0.01 mm

Scanner	AA mm (CI)	RMS	% Within (CI)	% Over (CI)	% Under (CI)
TD	-0.02 (-0.09, 0.78)	0.70 (0.62, 0.78)	7.9 (6.1, 9.8)	55.7 (50.3, 61.1)	36.4 (31.6, 41.1)
TS	-0.13 (-0.21, 0.86)	0.74 (0.62, 0.86)	6.8 (5.3, 8.3)	47.2 (37.2, 57.2)	46.0 (36.1, 56.0)
CER	-0.13 (-0.22, -0.04)	0.75 (0.70, 0.79)	6.3 (4.5, 8.1)	52.3 (43.6, 61.1)	41.3 (37.2, 45.4)
EM	-0.05 (-0.09, -0.02)	0.81 (0.77, 0.85)	3.9 (3.6, 4.2)	58.9 (55.8, 62.0)	37.2 (34.0, 40.5)

Table 2. Mean arithmetic average and 95% confidence intervals, root mean square, and within and outside of tolerance at ±0.05 mm

Scanner	AA mm (CI)	RMS	% Within (CI)	% Over (CI)	% Under (CI)
TD	-0.02 (-0.09, 0.78)	0.70 (0.62, 0.78)	36.8 (30.0, 43.8)	37.3 (31.8, 42.9)	25.9 (21.7, 30.1)
TS	-0.13 (-0.21, 0.86)	0.74 (0.62, 0.86)	31.0 (26.1,35.9)	32.5 (24.4, 40.6)	36.5 (28.0, 45.0)
CER	-0.13 (-0.22, -0.04)	0.75 (0.70, 0.79)	30.1 (21.1, 39.1)	37.7 (30.9, 44.4)	32.2 (21.3, 43.1)
EM	-0.05 (-0.09, -0.02)	0.81 (0.77, 0.85)	19.2 (17.5, 20.9)	50.2 (47.5, 52.8)	30.6 (27.1, 34.2)

Looking at the 3D color map is the ideal way to understand what is happening and where. In Figure 3, where the tolerance was set at ±0.01 mm and the minimum and maximum at ±1 mm, the location of the discrepancies among the scans are easily observed. On the right-hand side, the breakdown shows the quantitative differences, within the minimum and maximum range, related to the color. In Figure 4A, where the tolerance was set at ±0.05 mm with a minimum and maximum at ±1 mm, changing the tolerance made the difference between the 2 less dramatic. In Figure 4B, where the tolerance was set at ±0.10 mm, the trueness and precision appear ideal, but only artificially so. If the out-of-tolerance numbers were closely clustered around the in-tolerance numbers, the minimum and maximum values could be decreased, for example, to ±0.2 mm, to have a more detailed view of the distribution at these levels.

The words accuracy, trueness, and precision are important when referring to these measurements. Historically, accuracy referred to how close a measured value was in relation to a known value or standard. However, the International Organization for Standardization (ISO) uses "trueness" for this definition while keeping the word "accuracy" to refer to the combination of trueness and precision. Precision is related to how close several measurements of the same quantity are to each other. Trueness, zero deviations from the original, is desired but is rarely accomplished.

Understanding trueness and precision is accomplished by considering the target analogy. In Figure 5A, the points are highly true and precise. In Figure 5B, the scatter points are true but not very precise. In Figure 5C, the points are neither true nor precise. Targets come with predetermined requirements based on the distance and whether it is to measure a dart, an arrow, a pistol shot, or a rifle shot. In Figure 6A, we can see that 1 set of scatter points, those in the bullseye, are true and precise, while the second set in the middle ring are precise but not true. If we alter the tolerance of the target by eliminating the inner circle and expanding the bullseye to incorporate the second ring (Fig. 6B), it now appears that both sets of scatter points are true and precise. Enlarging the bullseye would make the game easier and less competitive. This demonstrates why tolerance is a critical determinant in demonstrating trueness.

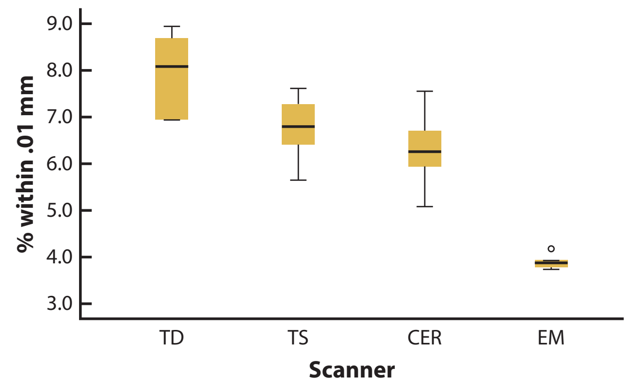

Figure 2. Boxplots showing distribution of values within tolerance of ±0.01 mm.

The objective in research should be to evaluate at the lowest tolerance level available, in this case ±0.01 mm, which has the advantage of not obscuring data that could be useful to both clinicians and program developers. Ultimately, the digital scan will be used to either mill or print a dental prosthesis. When designing algorithms, knowing the trueness and precision of the files that will be used as the matrix in the CAD-CAM protocol is important. In the lost wax technique, investment materials were formulated for specific metals to compensate for the contraction of the alloy during casting and to ensure accurate restorations. The same requirement may hold true with CAD-CAM systems. All the scanners tested had less than 10% within tolerance when applying a tolerance level of ±0.01 mm. At ±0.05 mm, the percentage of within tolerance increased. It is not only how much is out of tolerance but where the out of tolerance lies and how much it deviates. If most of the out of

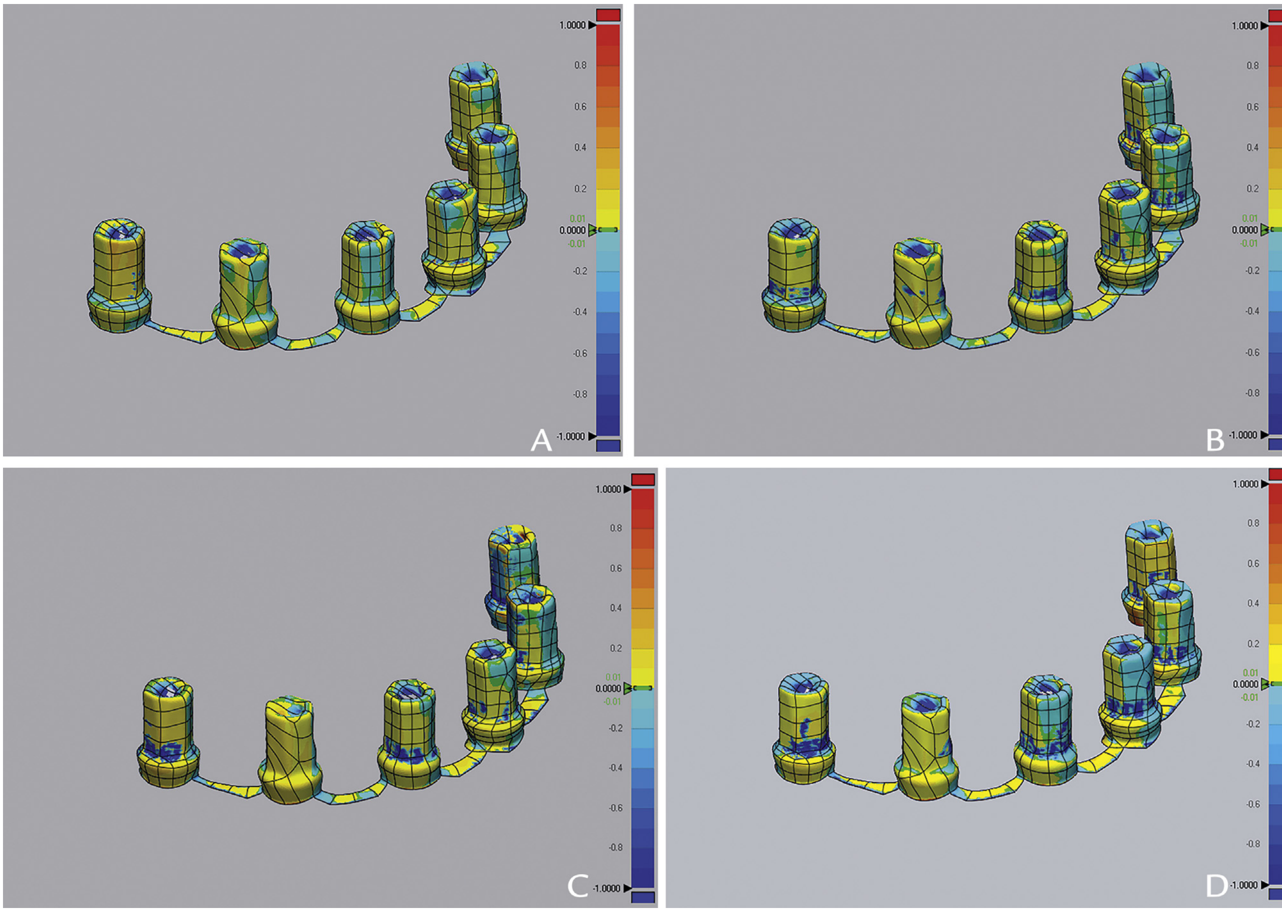

Figure 3. Scans at ±0.01-mm tolerance and ±1-mm minimum/maximum. A, True Definition. B, TRIOS. C, CEREC; D, Emerald.

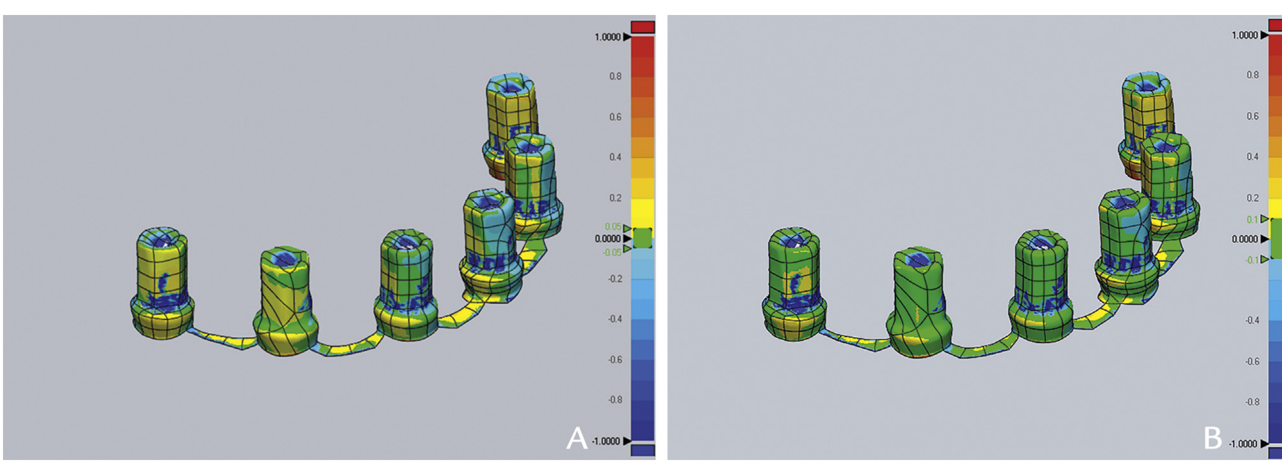

Figure 4. Emerald scans. A, ±0.05-mm tolerance and ±1-mm minimum/maximum. B, ±0.10-mm tolerance and ±1-mm minimum/maximum.

tolerance is skewed to the plus or minus side, it is different compared with out of tolerance equally divided between plus and minus. The 3D map allows manufacturers to visually determine how to improve future scanners or software and allows dental technicians the ability to create corrective algorithms when milling or printing.

To the clinician, regardless of the statistical significance, how much variability would be acceptable? Ultimately, what is clinically significant is determined by the clinician based on the use of the data. Milling a multiunit fixed prosthesis requires a different level of accuracy than printing a diagnostic cast or scanning an implant scanbody where there are known algorithms to correct for any

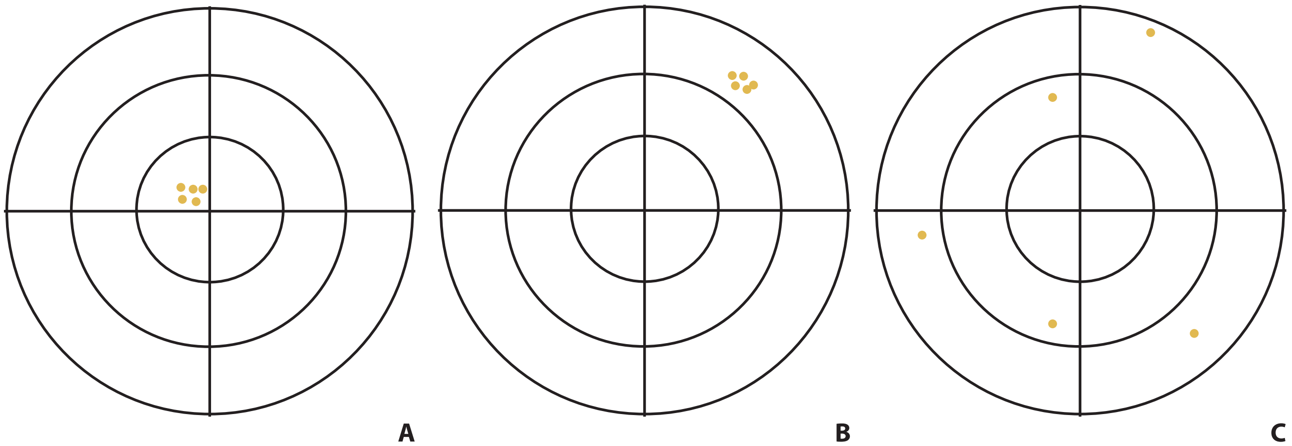

Figure 5. Visual representation of trueness and precision. A, High precision and trueness. B, High precision and low trueness. C, Low precision and trueness.

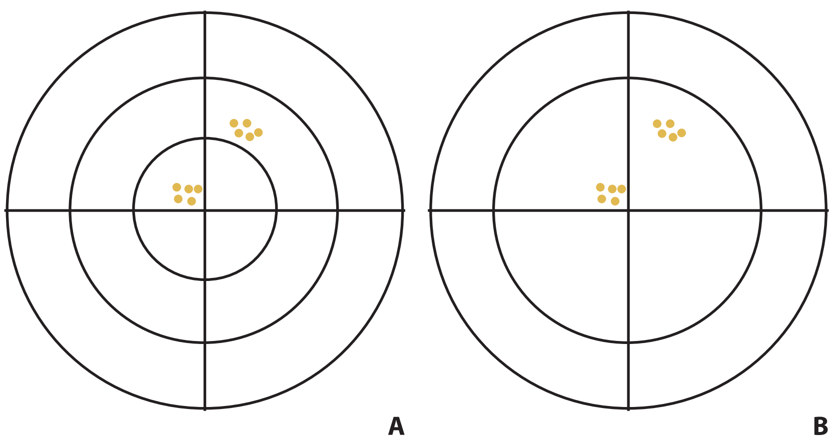

Figure 6. How changes in tolerance alter trueness outcome. A, Typical bullseye target. B, Enlarged bullseye.

deviations. What is needed is a standardization of the parameters used for research with highly accurate 3D outcome measures so that the clinician can compare the results from multiple projects.

CONCLUSIONS

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

1. No statistical or clinical differences were found among the scanners tested.
2. The 3D map was the best method for observing the data.

REFERENCES

1. van Noort R. The future of dental devices is digital. Dent Mater 2012;28:3-12.
2. Christensen GJ. Will digital impressions eliminate the current problems with conventional impressions? J Am Dent Assoc 2008;139:761-3.
3. Güth JF, Edelhoff D, Schweiger J, Keul C. A new method for the evaluation of the accuracy of full-arch digital impressions in vitro. Clin Oral Investig 2016;20:1487-94.
4. Ender A, Zimmermann M, Attin T, Mehl A. In vivo precision of conventional and digital methods for obtaining quadrant dental impressions. Clin Oral Investig 2016;20:1495-504.
5. Seelbach P, Brueckel C, Wostmann B. Accuracy of digital and conventional impression techniques and workflow. Clin Oral Investig 2013;17:1759-64.
6. Shembesh M, Ali A, Finkelman M, Weber HP, Zandparsa R. An in vitro comparison of the marginal adaptation accuracy of CAD/CAM restorations using different impression systems. J Prosthodont 2016;26:581-6.
7. Güth JF, Runkel C, Beuer F, Stimmelmayr M, Edelhoff D, Keul C. Accuracy of five intraoral scanners compared to indirect digitalization. Clin Oral Investig 2017;21:1945-55.
8. Vecsei B, Joós-Kovács G, Borbély J, Hermann P. Comparison of the accuracy of direct and indirect three-dimensional digitizing processes for CAD/CAM systems - an in vitro study. J Prosthodont Res 2017;61:177-84.
9. Ajioka H, Kihara H, Odaira C, Kobayashi K, Kondo H. Examination of the position accuracy of implant abutments reproduced by intra-oral optical impression. PLoS One 2016;11:e0164048.
10. Kuhr F, Schmidt A, Rehmann P, Wöstmann B. A new method for assessing the accuracy of full arch impressions in patients. J Dent 2016;55:68-74.
11. Grünheid T, McCarthy D, Larson BE. Clinical use of a direct chairside oral scanner: an assessment of accuracy, time, and patient acceptance. Am J Orthod Dentofacial Orthop 2014;146:673-82.
12. Flügge TV, Att W, Metzger MC, Nelson K. Precision of dental implant digitization using intraoral scanners. Int J Prosthodont 2016;29:277-83.
13. Amin S, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Digital vs. conventional full-arch implant impressions: a comparative study. Clin Oral Implants Res 2017;28:1360-7.
14. International Organization for Standardization. ISO 9693-1. Dentistry compability testing. Part 1: metal-ceramic systems. Geneva: International

Organization for Standardization; 2012. ISO Store Order: OP-184149 (Date: 2017-06-09). Available at: http://www.iso.org/iso/home.html.
15. Renne W, Ludlow M, Fryml J, Schurch Z, Mennito M, Kessler R, et al. Evaluation of the accuracy of 7 digital scanners: an in vitro analysis based on 3-dimensional comparisons. J Prosthet Dent 2017;118:36-42.
16. Park JM. Comparative analysis on reproducibility among 5 intraoral scanners: sectional analysis according to restoration type and preparation outline form. J Adv Prosthodont 2016;8:354-62.
17. Lee JJ, Jeong ID, Park JY, Jeon JH, Kim JH, Kim WC. Accuracy of single-abutment digital cast obtained using intraoral and cast scanners. J Prosthet Dent 2017;117:253-9.
18. Nedelcu RG, Persson AS. Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimensional analysis. J Prosthet Dent 2014;112:1461-71.
19. Patzelt SBM, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig 2014;18:1687-94.
20. Anh JW, Park JM, Chun YS, Kim M, Kima M. A comparison of the precision of three-dimensional images acquired by 2 digital intraoral scanners: effects of tooth irregularity and scanning direction. Korean J Orthod 2016;46:3-12.
21. Andriessen FS, Rijkens DR, van der Meer WJ, Wismeijer DW. Applicability and accuracy of an intraoral scanner for scanning multiple implants in edentulous mandibles: a pilot study. J Prosthet Dent 2014;111:186-94.
22. Gimenez B, Özcan M, Martínez-Rus F, Pradíes G. Accuracy of a digital impression system based on active triangulationtechnology with blue light for implants: effect of clinically relevant parameters. Implant Dent 2015;24:498-504.
23. Marghalani A, Weber HP, Finkelman M, Kudara Y, El Rafie K, Papaspyridakos P. Digital versus conventional implant impressions for partially edentulous arches: An evaluation of accuracy. J Prosthet Dent 2018;119:574-9.

Corresponding author:
Dr Gary Goldstein
One UN House
SIDS Street
Tuana'imato
SAMOA
Email: gary.goldstein@nyu.edu

https://doi.org/10.1016/j.prosdent.2019.10.013