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ORIGINAL RESEARCH ARTICLE

Comparative Analysis of the Accuracy of Dentate Complete-Arch Scans of Six Intraoral Scanners

Münir Demirel [1], *, Faruk Emir [2], Gülsüm Ceylan [3] and Almira Ada Diken Türksayar [1]

[1]Biruni University, Faculty of Dentistry, Department of Prosthodontics, Istanbul, Türkiye and [2]Health Sciences University, Gülhane Faculty of Dentistry, Department of Prosthodontics, Ankara, Türkiye and [3]Istanbul Medipol University, School of Dentistry, Department of Prosthodontics, Istanbul, Türkiye

*Corresponding Author; munirdemirel@biruni.edu.tr

Abstract

Objective: This in vitro study aimed to evaluate the scan accuracy of 6 intraoral scanners (IOSs) by using a dentate model.
Methods: A maxillary dentate reference model was digitized with an industrial-grade blue light optical scanner to generate a reference standard tessellation language (STL) file. The same model was digitized by using 6 IOSs (TRIOS 4, TRIOS 3, Primescan, Omnicam, Emerald S, and Medit i700) (n=10) to generate test scan STLs. All STL files were imported into a 3-dimensional analysis software program (Geomagic Control X). Test scan STLs were superimposed over the reference STL by using the initial and best-fit alignments of the software program, and the deviations of the scans of IOS from that of the optical scanner were calculated with the root mean square (RMS) method. The average deviation method was used to define the precision of the scans. Kruskal-Wallis and Bonferroni tests were used to statistically evaluate the data (α=0.05).
Results: A significant difference was observed between groups in terms of RMS values (p<0.001). The Medit i700 and Primescan IOS systems had the lowest RMS values, respectively, indicating the highest trueness. No significant difference was observed between the groups in terms of precision. (p=0.055)
Conclusions: While differences were observed among the six intraoral scanners, the accuracy of the selected IOSs remained within the clinically acceptable ranges. The Medit i700 and Primescan IOS exhibited a higher level of precision in comparison to the other devices. The accuracy of the scanner should be assessed, taking into account clinician, patient, and IOS dependent variables.

Keywords: Digital impression; Intraoral scanner; 3D analysis

Introduction

An exact replication of the intraoral environment, represented in a precise definitive cast, is a crucial precondition for ensuring the sustained success of prosthodontic treatment.[1,2] The factors influencing the accuracy of definitive casts have been extensively researched.[3–5]

Numerous studies have examined the impact of factors such as impression materials, impression techniques, tray selection, die materials, and removable die systems on cast accuracy. It's been observed that nearly every material and method used in the production process of definitive casts can be linked to some form of dimensional alteration.[5] The digital workflow mitigates the need for impression procedures, disinfection, and definitive cast fabrication, which are conventional methods often leading to dimensional changes in the definitive casts.[6,7]

The digital workflow comprises three primary stages: the collection of data (either directly or indirectly), restoration design, and the manufacturing process.[8,9] The data acquisition phase uses two varieties of scanners: intraoral and extraoral. Intraoral scanners are specifically utilized for digitizing patient arches chairside.[10,11]

Using an intraoral scanner (IOS) over traditional impression methods offers numerous benefits. These include a decrease in patient discomfort, particularly for those with a pronounced gag reflex, and the elimination of casting and storage processes. Furthermore, IOS promotes more straightforward patient communication and facilitates speedier, cost-effective interaction between the dental clinic and laboratory technician.[12–16]

At present, various intraoral scanners have been launched and are being utilized in clinical conditions.[2,17] So far, intraoral scanners have been used for creating study models, detecting impressions required for designing and producing a range of restorations

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Figure 1. The master model

(including single crowns, fixed partial dentures, and in certain cases, complete fixed arches), and for surgical applications (incorporated into acquisition procedures for guided surgery). They are also used in orthodontics for fabricating aligners and various customized orthodontic devices.[12]

Indeed, the accuracy of an intraoral scanner, as a blend of trueness and precision, is a critical feature. As defined by the International Standard Organization (ISO) 5725:1[18], trueness refers to the 'degree of alignment between the arithmetic mean of a large number of test outcomes and the true or acknowledged reference value.' Meanwhile, precision is understood as 'the degree of concurrence between varied test results.' Both accuracy and precision are vital for achieving a satisfactory digital scan, leading to an exceptional final product.[19]

Currently, advanced scanning technologies are in use, encompassing methodologies such as the triangulation technique, active wavefront sampling, and confocal scanning technique.[20,21]

Different scanning settings are recommended by the manufacturers, and the choice of scanning technique can often depend on the operator's preferences. With the evolving advancements in intraoral 3D scanning technology, assessing the scanning accuracy of different IOSs available in the market becomes a matter of importance. Consequently, this in vitro study sets out to explore the accuracy of six such scanners. The null hypothesis was that IOS type would not affect the accuracy (trueness and precision) of dentate maxillary arch scans.

Material and Methods

This study does not contain human participants or animals by any authors. Therefore, this type of study does not require ethics committee and consent form information. To assess the accuracy of complete arch measurements across six different intraoral scanners, a standard full-dentate maxillary model (KaVo Dental, Biberach, Germany) was selected as the master model. The master model was produced by using a 3-dimensional (3D) printer using SLA technology (Form 3; Formlabs) and Model V2 Resin (Formlabs) material (Figure 1). All 3D printing procedures were performed following the manufacturer's instructions. After production, the 3D-printed master model was stored in a light-impermeable container for 24 hours before the scanning procedures commenced.

After a thin layer of (2 μm) antireflective spray was applied, the model was scanned by using an industrial-grade blue light optical scanner (RS) (ATOS Core 80 5MP; GOM GmbH, Braunschweig, Germany), a device that leverages stereo camera-based triangulation (1 μm probing error form, 3 μm probing error size, 5 μm sphere spacing error, and 7 μm length measurement error). Prior to the study, RS was calibrated using a calibration panel (GOM Inspect; GOM, Braunschweig, Germany GOM Tip/SN CP40/200/100846). It was then scanned by using the RS (RS-STL).

In this study, six intraoral scanners, listed in Table 1 for models and characteristics, were scanned from the reference model using a dark environment with no direct light to replicate the intraoral region. The IOSs were calibrated according to the respective manufacturer's instructions before the measurements and then repeated 10 times for each IOS according to the manufacturer's instructions. Ten scans of data from each scanner were exported and saved in standard tessellation language (STL) file format (IOS-STLs). All scanning procedures were performed by an experienced operator (M.D.) in the field.

All STL files (RS-STL and IOS STLs) were imported into a 3D analysis software program (Geomagic Control X; 3D Systems). The reference STL was imported as the reference data and the "auto segment" feature of the "region tool" of the software program was used to automatically segment the entire dental arch. Automatically segmented regions on the dental arch were then merged by using the "merge" feature of the "region tool". Then, IOS scan STLs (IOS-STLs) were superimposed over the reference STL (RS-STLs) with initial alignment and local best-fit alignment tools of the software program to evaluate the trueness. After superimpositions, the "3D Compare" tool of the software program was used to generate color maps for qualitative evaluation (maximum-minimum deviations: ± 100 μm, tolerance range: ± 10 μm), and the deviations of were automatically calculated by using the root-mean-square method. The software program (Geomagic Control X; 3D Systems) was used to generate color maps with red representing overcontoured surfaces, blue representing undercontoured surfaces, and green representing acceptable deviations. Figure 2

Statistical analysis

An a priori power analysis was carried out to determine the number of specimens in each group and found that 3 specimens were sufficient ($f=1.23$, $1-\beta=95\%$, $\alpha=.05$)[22]. However, 10 scans per group were performed to increase statistical power. The normality was assessed by using the Shapiro-Wilks test. Given that normality was refuted, Kruskal-Wallis and Bonferroni tests were used to evaluate RMS values. Precision was defined as the average deviation and further analyzed by using the same analyzes. All analyzes were conducted by using a statistical analysis software program (SPSS v20, IBM Corp., Chicago, IL, USA) with a confidence level of 95%.

Results

The trueness of different scanning technologies is reflected in Table 2. The Medit i700 and Primescan IOS systems had the highest trueness and lowest RMS, respectively. However, there was no significant difference found between the trueness of the Medit i700 and Primescan ($p=0.854$). TRIOS 4 had similar results to TRIOS 3 ($p=0.186$), Omnicam ($p=0.997$) and Emerald S ($p=1.000$).

Table 3 provides a comparison of precision values across different scanning technologies. The Omnicam IOS system exhibited the lowest precision value, although this difference was statistically insignificant when compared to other systems ($p=0.055$). The only exception to this observation was the difference between the TRIOS 4 and Omnicam systems, where the difference in precision was significant. ($p=0.046$).

Discussion

As a result of this study, significant differences were observed in both trueness and precision among the different IOSs. Therefore,

Table 1. Models and features of intraoral scanners used in the study

IOS	Version	Manufacturer	Scanning Technology	Source of Light	Working Principle
Emerald S	**Romexis 6.4**	Planmeca	Partial Triangulation	Red Green Blue Laser	Multi-imaging, Video
Medit i700	**Medit Link 3.3.2**	Medit	Optical Triangulation	Visible Light	Quick video viewing
Omnicam	**CEREC 5.2.7**	Dentsply Sirona	Active Triangulation	Visible Light	Multi-imaging, Video
Primescan	**CEREC 5.2.7**	Dentsply Sirona	Active Triangulation	Blue Led Technology	Multi Image
TRIOS 4	**TRIOS 23.1**	3Shape	Confocal Microscopy	Light Laser and Led Reference	Multi Image
TRIOS 3	**TRIOS 23.1**	3Shape	Confocal Microscopy	Light Laser and Led Reference	Multi Image

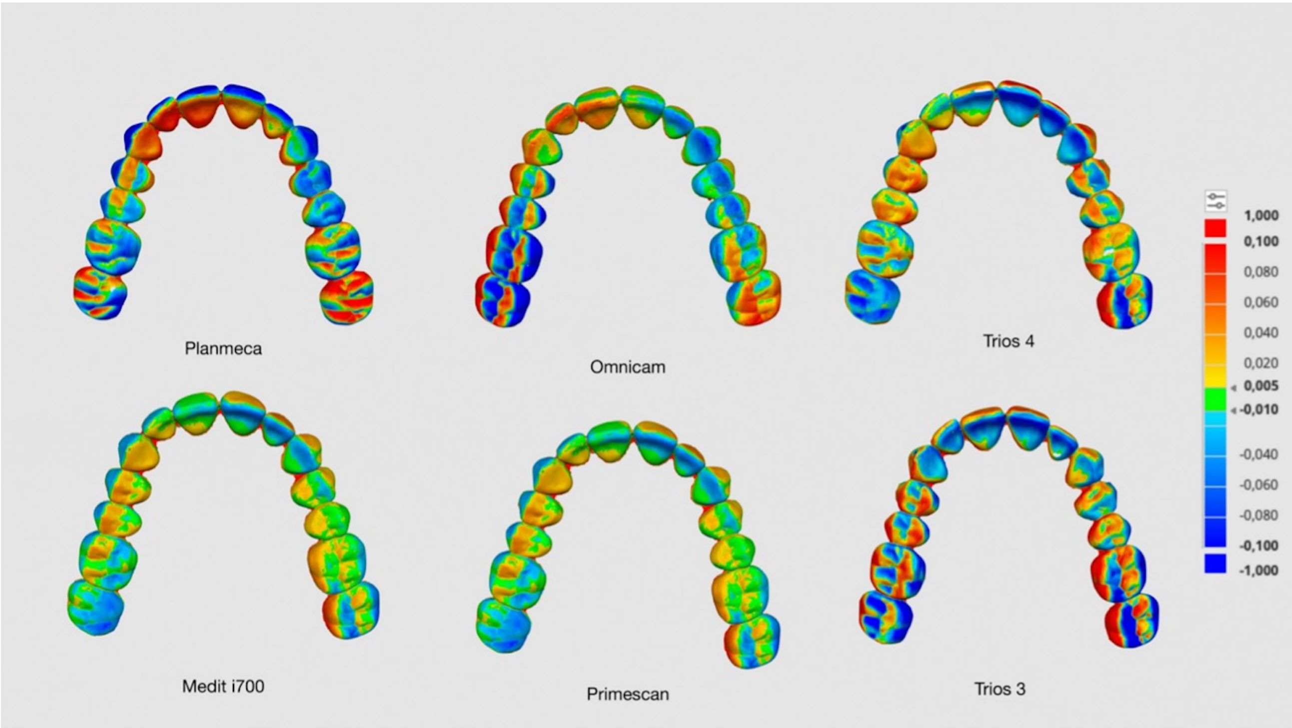

Figure 2. Color-coded maps obtained with different IOSs. Yellow-red colors show expansions, while light blue-dark blue areas show contractions.

Table 2. Trueness findings of the measurements obtained with different intraoral scanners

IOS	Median^X	Std. Deviation	Minimum	Maximum
TRIOS 4	74.00^b	14.32	68.00	105.00
TRIOS 3	92.00^b	7.98	83.00	106.00
Primescan	58.00^a	4.96	50.00	63.00
Omnicam	74.00^a	4.68	69.00	81.00
Emerald S	76.00^b	8.90	73.00	95.00
Medit i700	55.00^a	6.42	43.00	61.00

*Different superscript uppercase letters indicate significant differences among study groups(**P<.05**).

Table 3. Precision findings of the measurements obtained with different intraoral scanners

IOS	Median	Std. Deviation	Minimum	Maximum
TRIOS4	10.00	7.82	1.00	24.00
TRIOS3	3.00	4.59	2.00	12.00
Primescan	4.00	2.25	1.00	7.00
Omnicam	4.00	2.10	1.00	7.00
Emerald S	8.00	3.30	5.00	14.00
Medit i700	3.00	3.36	2.00	10.00

*Absence of different letters on the median values indicates that there is no significant difference between the groups ($P \geq .05$).

the study's null hypothesis, presuming no significant differences among the IOSs, was rejected. The intraoral scanners evaluated in this study are not only extensively employed within the dental field, but they also represent the pinnacle of standards achievable with the current generation of intraoral scanner technology. Evaluating the accuracy of complete arch scans is critical, as situations requiring the fabrication of longer-span or full-arch fixed partial dentures are a common occurrence in dental practice.[23]

This study utilized a reference dataset derived from an industrial high-accuracy scanner and implemented a best-fit alignment method to evaluate and interpret the spatial discrepancies between different datasets. Trueness was computed via RMS values, while precision was determined through the standard deviation of this superimposition. Notably, all the IOSs tested displayed an accuracy within the clinically acceptable limits (below 120 µm), with values ranging from 55.0 µm to 92.0 µm.[23,24] Given the differences in the (trueness) variables tested and the IOSs used across various studies, making a direct comparison can prove to be challenging. Variations in the accuracy of different intraoral scanners (IOSs) have been well-documented in prior research.[25,26] Most studies that have evaluated the accuracy of optical impression systems were performed in vitro.[27–29]

Schmalzl et al.[23] utilized TRIOS 3 and TRIOS 4, which have 2 different software from 2 different years, for complete arch scans. The study revealed that the trueness values varied substantially. For TRIOS 3, the range between years was found to be 47.44±9.17 µm up to 90.24±15.35 µm. As for TRIOS 4, the trueness values were somewhat lower, ranging between years from 31.06±5.24 µm to 52.91±7.44 µm. Importantly, these variations were linked to the different software versions of the intraoral scanners.[23] The values obtained from this research aligned closely with the findings of the aforementioned study.

In the research conducted by Medina-Sotomayor et al.[24], the observed accuracy values in the complete arch model varied notably. They found these values to range from 32.1±13.7 µm to as high as 98.3±14 µm. Meanwhile, the precision values in the same model also exhibited a substantial range, from 98.8±40.4 µm to 261.8±32.6 µm.[24]

In a similar research, Malik et al.[30] conducted a study using a maxillary model, during which they compared two IOSs. Their research findings indicated a variation in the trueness values: for Omnicam, the trueness value was 80.3±12.1 µm, whereas, for the TRIOS 3, it was slightly higher at 87.1±7.9 µm.[30]

Atieh et al.[27] used a mandibular complete arch master model in their study and determined the trueness of the Omnicam to be 46.2±11.4 µm. However, their selection of two molar, premolar, and two incisor teeth for deviation analysis may explain the relatively lower trueness values reported in their research.[27] In a study by Luthardt et al.[31], the researchers identified a mean deviation, or trueness, of 27.9 µm for three teeth, a figure derived through root mean square (RMS) error computation.[31] Another investigation by Mehl et al. reported trueness of 14.3 µm for Bluecam.[32]

In further research, Ender et al.[33] evaluated the trueness of seven different intraoral scanners (IOSs) on a quadrant arch. They discovered that the Lava True Definition scanner had a trueness value of 21.7±7.4 µm, the Lava COS was at 47.7±16.1µm, and the Cadent iTero exhibited 49.0±12.4 µm. For the TRIOS and TRIOS Color scanners, the trueness values were 25.7±4.9 µm and 26.1±3.8 µm, respectively. The CEREC Bluecam, depending on the software version, showed 34.2±10.5 µm for Software 4.0, and 43.3±19.6 µm for Software 4.2. Lastly, the CEREC Omnicam demonstrated a trueness value of 37.4±8.1 µm.[33]

The color-coded maps provide a revealing picture of the performance of different scanners. Emerald primarily exhibits contractions on the buccal sides of the teeth. In contrast, Omnicam demonstrates contraction on the occlusal and lingual surfaces of molars and premolars, while a slight expansion is observed on the buccal sides of these same teeth. TRIOS 3 reveals a deviation pattern similar to that of Emerald S. TRIOS 4, on the other hand, performs slightly better than both Emerald S and TRIOS 3. Primescan and Medit i700 stand out with their lower contraction and expansion levels compared to the other scanners. It's also important to note that the green surfaces on the maps indicate deviations ranging ±10 µm.

In this study, no significant difference was found between the precisions of different IOS. In a similar recent study, six different IOS were evaluated, among them TRIOS 3, Omnicam, Primescan, and Emerald S, similar to the presented study. Researchers have reported that there is no difference between the precision values of different scanners, which is consistent with our study. However, in another study, it was reported that the sensitivity of TRIOS 3 was higher when comparing IOSs, including TRIOS 3 and Emerald S. This may be due to the fact that scans are performed under different conditions, operator-related factors, and differences in dental models. Furthermore, the use of IOSs was found to be more susceptible to errors when measuring longer distances compared to shorter ones.[30,34] Notably, these disparities are often statistically significant, making their underlying causes difficult to pinpoint. Factors potentially impacting accuracy can include the inherent measurement sensitivity of the IOS, image construction techniques, the software algorithm used in the 3D rendering process, the selected scanning protocol, and any bias introduced by the operator.[26]

In this study, the manufacturer-recommended scanning paths were adhered to for each respective IOS, with no alternative scanning paths being evaluated. Previous in vitro research has suggested that the scanning path does not significantly affect the accuracy of quadrant scans. However, it has been observed that the accuracy of complete-arch scans can be dependent on the scanning path. Furthermore, manufacturer guidelines have been found to produce better outcomes than individualized scanning protocols.[35,36]

Different factors can influence the accuracy of IOSs, including intraoral conditions (such as temperature, relative humidity, and lighting), the skill and scanning pattern of the operator, characteristics of the scanner unit (scanning head, light source, and receiver), the speed/up-to-date of the computer software, and the specifics of the scanning area (anterior/posterior, scan length, area, and surface characteristics).[18,35]

Our in vitro study to evaluate IOS accuracy has some limitations. These restrictions include the inability to fully imitate intraoral conditions such as saliva, limited mouth opening, intraoral light environment, patient's jaw mobility, and contrast color difference due to teeth and gums.

Future research should explore the exact location of the prepared teeth or implant being scanned, with a focus on developing a standardized method for the evaluation and comparison of various digital scanning systems. In addition, performance under in vivo conditions should be assessed for a more comprehensive understanding.

Conclusion

While trueness varied across all the scanners studied, precision displayed pleasing consistency. Notably, the Medit i700 and Primescan IOS outperformed others in terms of trueness, a difference that was statistically significant ($p<0.05$). Despite the observed differences among the six IOSs, the trueness of the selected scanners was within clinically acceptable limits. However, the choice of scanner extends beyond accuracy and should take into account factors like scanning time, scan head size, and user learning curve. Lastly, it's important to consider that while accuracy is important, it's not the only factor that determines the utility of an intraoral scanner. Ease of use, patient comfort, integration with other dental software, and cost are also significant considerations.

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Author Contributions

Concept : M.D. , F.E.
Design : M.D.
Resources : M.D. , G.C.
Data Collection : M.D.
Analysis : F.E. , G.C. , A.A.D.T.
Literature Search : G.C. , F.E.
Writing of the manuscript : F.E. , G.C.
Critival Review : A.A.D.T.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' ORCID(s)

M.D. 0000-0002-1487-6834
F.E. 0000-0003-3538-2582
G.C. 0000-0003-0768-8779
A.A.D.T. 0000-0003-3558-3202

References

1. Chandran DT, Jagger DC, Jagger RG, Barbour ME. Two- and three-dimensional accuracy of dental impression materials: effects of storage time and moisture contamination. Biomed Mater Eng. 2010;20(5):243–249. doi:10.3233/bme-2010-0638.
2. Seo K, Kim S. A new method to evaluate trueness and precision of digital and conventional impression techniques for complete dental arch. Appl Sci. 2021;11(10):4612. doi:10.3390/app11104612.
3. Damodara EK, Litaker MS, Rahemtulla F, McCracken MS. A randomized clinical trial to compare diagnostic casts made using plastic and metal trays. J Prosthet Dent. 2010;104(6):364–371. doi:10.1016/s0022-3913(10)60167-9.
4. DeLong R, Heinzen M, Hodges JS, Ko CC, Douglas WH. Accuracy of a system for creating 3D computer models of dental arches. J Dent Res. 2003;82(6):438–442. doi:10.1177/154405910308200607.
5. Emir F, Piskin B, Sipahi C. Effect of dental technician disparities on the 3-dimensional accuracy of definitive casts. J Prosthet Dent. 2017;117(3):410–418. doi:10.1016/j.prosdent.2016.06.008.
6. Mandelli F, Gherlone E, Gastaldi G, Ferrari M. Evaluation of the accuracy of extraoral laboratory scanners with a single-tooth abutment model: A 3D analysis. JPR. 2017;61(4):363–370. doi:10.1016/j.jpor.2016.09.002.
7. Ting-shu S, Jian S. Intraoral digital impression technique: a review. J Prosthodont. 2015;24(4):313–321. doi:10.1111/jopr.12218.
8. Shimizu S, Shinya A, Kuroda S, Gomi H. The accuracy of the CAD system using intraoral and extraoral scanners for designing of fixed dental prostheses. Dent Mater J. 2017;36(4):402–407. doi:10.4012/dmj.2016-326.
9. Vandeweghe S, Vervack V, Vanhove C, Dierens M, Jimbo R, De Bruyn H. Accuracy of optical dental digitizers: an in vitro study. IJPRD. 2015;35(1):115–121. doi:10.11607/prd.2185.
10. Bohner LOL, Canto GDL, Marció BS, Laganá DC, Sesma N, Neto PT. Computer-aided analysis of digital dental impressions obtained from intraoral and extraoral scanners. J Prosthet Dent. 2017;118(5):617–623. doi:10.1016/j.prosdent.2016.11.018.
11. de Villaumbrosia PG, Martínez-Rus F, García-Orejas A, Salido MP, Pradíes G. In vitro comparison of the accuracy (trueness and precision) of six extraoral dental scanners with different scanning technologies. J Prosthet Dent. 2016;116(4):543–550. e1. doi:10.1016/j.prosdent.2016.01.025.
12. Imburgia M, Logozzo S, Hauschild U, Veronesi G, Mangano C, Mangano FG. Accuracy of four intraoral scanners in oral implantology: a comparative in vitro study. BMC oral health. 2017;17:1–13. doi:10.1186/s12903-017-0383-4.
13. 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. doi:10.1016/j.jdent.2016.10.002.
14. Park HR, Park JM, Chun YS, Lee KN, Kim M. Changes in views on digital intraoral scanners among dental hygienists after training in digital impression taking. BMC oral health. 2015;15:1–7. doi:10.1186/s12903-015-0140-5.
15. Rutkūnas V, Gečiauskaitė A, Jegelevičius D, Vaitiekūnas M. Accuracy of digital implant impressions with intraoral scanners. A systematic review. Eur J Oral Implantol. 2017;10(Suppl 1):101–120.
16. Stefanelli LV, Franchina A, Pranno A, Pellegrino G, Ferri A, Pranno N, et al. Use of intraoral scanners for full dental arches: could different strategies or overlapping software affect accuracy? IJERPH. 2021;18(19):9946. doi:10.3390/ijerph18199946.
17. Amornvit P, Rokaya D, Sanohkan S. Comparison of accuracy of current ten intraoral scanners. Biomed Res Int. 2021;2021(1):2673040. doi:10.1155/2021/2673040.
18. ISO. Accuracy (trueness and precision) of measurement methods and results—part 1: General principles and definitions. ISO. 1994.
19. Giuliodori G, Rappelli G, Aquilanti L. Intraoral scans of full dental arches: An in vitro measurement study of the accuracy of different intraoral scanners. IJERPH. 2023;20(6):4776. doi:10.3390/ijerph20064776.
20. Mangano F, Gandolfi A, Luongo G, Logozzo S. Intraoral scanners in dentistry: a review of the current literature. BMC oral health. 2017;17:1–11. doi:10.1186/s12903-017-0442-x.
21. Renne W, Ludlow M, Fryml J, Schurch Z, Mennito A, 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(1):36–42. doi:10.1016/j.prosdent.2016.09.024.
22. Wang X, Zhang F, Ma D, Ye X, Zheng X, Ren R, et al. Evaluation of the accuracy of seven intraoral scanners for the full dentate and partially edentulous complete-arch mandibular casts: An in vitro comparison. Heliyon. 2024;10(10):e31063. doi:10.1016/j.heliyon.2024.e31063.
23. Schmalzl J, Róth I, Borbély J, Hermann P, Vecsei B. The impact of software updates on accuracy of intraoral scanners. BMC Oral Health. 2023;23(1):219. doi:10.1186/s12903-023-02926-y.
24. Medina-Sotomayor P, Pascual-Moscardo A, Camps I. Accuracy of 4 digital scanning systems on prepared teeth digitally isolated from a complete dental arch. J Prosthet Dent. 2019;121(5):811–820. doi:10.1016/j.prosdent.2018.08.020.
25. Nedelcu R, Olsson P, Nyström I, Rydén J, Thor A. Accuracy and precision of 3 intraoral scanners and accuracy of conventional impressions: A novel in vivo analysis method. J Dent. 2018;69:110–118. doi:10.1016/j.jdent.2017.12.006.
26. Winkler J, Gkantidis N. Trueness and precision of intraoral scanners in the maxillary dental arch: an in vivo analysis. Sci Rep. 2020;10(1):1172. doi:10.1038/s41598-020-58075-7.
27. Atieh MA, Ritter AV, Ko CC, Duqum I. Accuracy evaluation of intraoral optical impressions: a clinical study using a reference appliance. J Prosthet Dent. 2017;118(3):400–405. doi:10.1016/j.prosdent.2016.10.022.
28. Ender A, Mehl A. In-vitro evaluation of the accuracy of conventional and digital methods of obtaining full-arch dental impressions. Quintessence Int. 2015;46(1):9–17. doi:10.3290/j.qi.a32244.
29. Güth JF, Keul C, Stimmelmayr M, Beuer F, Edelhoff D. Accuracy of digital models obtained by direct and indirect data capturing. Clin Oral Investig. 2013;17:1201–1208. doi:10.1007/s00784-012-0795-0.
30. Malik J, Rodriguez J, Weisbloom M, Petridis H. Comparison of accuracy between a conventional and two digital intraoral impression techniques. Int J Prosthodont. 2018;31(3):107–113. doi:10.11607/ijp.5643.
31. Luthardt R, Loos R, Quaas S. Accuracy of intraoral data acquisition in comparison to the conventional impression. Int J Comput Dent. 2005;8(4):283–294.
32. Mehl A, Ender A, Mörmann W, Attin T. Accuracy testing of a new intraoral 3D camera. Int J Comput Dent. 2009;12(1):11–28. doi:10.5167/uzh-18814.
33. 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;20:1495–1504. doi:10.1007/s00784-015-1641-y.

34. Kaewbuasa N, Ongthiemsak C. Effect of different arch widths on the accuracy of three intraoral scanners. J Adv Prosthodont. 2021;13(4):205. doi:10.4047/jap.2021.13.4.205.

35. Kernen F, Schlager S, Alvarez VS, Mehrhof J, Vach K, Kohal R, et al. Accuracy of intraoral scans: An in vivo study of different scanning devices. J Prosthet Dent. 2022;128(6):1303–1309. doi:10.1016/j.prosdent.2021.03.007.

36. Latham J, Ludlow M, Mennito A, Kelly A, Evans Z, Renne W. Effect of scan pattern on complete-arch scans with 4 digital scanners. J Prosthet Dent. 2020;123(1):85–95. doi:10.1016/j.prosdent.2019.02.008.