Evaluating the accuracy (precision and trueness) of conventional and digital Intraoral Impression Technique

Lana Shwan Jalal [(1)];Dara Hamarashid Saeed [(2)]

Background and Objectives: This study aims to compare and evaluate the accuracy of the conventional and digital intraoral scanner impression approaches of the maxillary dentulous arch with indirect fixed restorations.
Methods: Three prepared teeth were used in a reference model created for an inlay and a 3-unit bridge. From conventional impressions, models of stone were created. An intraoral scanner was utilized to produce digital impressions of the reference model (digital models), and then the stone models were scanned with a laboratory scanner. The stereolithography file format was used to export the files. To determine the trueness of preparations and the accuracy of complete arch, by using 3D analysis software, all datasets were superimposed. To compare the two-model group's accuracy and assess the trueness of the two preparation methods, a test of Mann-Whitney U was utilized.
Results: Significant intergroup precision differences between the two groups (digital and stone) were seen for the complete arch, while the (p) value is smaller than 0.001. Nevertheless, in terms of trueness, there was a significant difference between the models of digital and stone, while the (p) value is smaller than 0.001. Mann-Whitney U test revealed significant differences in trueness among the model groups (stone and digital) ($p < .001$) and types of preparation ($p < .001$).
Conclusions: Compared to stone models, digital models' root means square values of the accuracy of the full arch and its trueness of preparations were lower. Nevertheless, compared to digital models, the trueness of the preparations and the complete arch's accuracy of stone models were inferior.
Keywords: Precision, trueness, accuracy, impression, intraoral scanner.

(1) Department of Department of Basic Science, College of Dentistry, Hawler Medical University, Erbil, Iraq.
(2) Department of Conservative Dentistry, College of Dentistry, Hawler Medical University, Erbil, Iraq.
Correspondent Name: Lana Shwan Jalal
Email: dr.lanaqassab@yahoo.com

Introduction

In restorative dentistry, dental impressions are crucial. They convert the situation intraoral to an extra oral cast, whose accuracy affects the fit of the restorations, which is a critical component in the final restoration's lifetime. [1]

All facets of dentistry, particularly prosthodontics and restorative dentistry, have been significantly impacted as a result of the quick development of Computer Aided Manufacture and Computer Aided Design. [2]

Despite the increased use of intraoral scanners in dental clinics, traditional impressions are still the most popular method and the fundamental standard for taking impressions. Nevertheless, even after the preparation of the tooth and taking an impression, the final restoration nevertheless involves several steps and procedures rife with potential errors, such as the impression itself, casting, and indirect digitization.[3] The accuracy is influenced by the gypsum type, reset time, the transport, the process of disinfection, the impression technique and the impression material, and even the time between individual stages. [4–7]

As a result, optical intraoral digitization appears as obvious means to access the subsequent digital workflows of computer-aided manufacture and design (CAM) and (CAD); due to workflows that require fewer inter-

mediate steps allowing for better control and preventing failures. This concept has been confirmed since various studies have demonstrated that direct digitalization and the associated procedures for single crowns up to one quadrant have a high level of accuracy. [8–10]
There is not enough scientific clarity on the digital procedure for full-arch restorations. On the other hand, a newer study analyzing the most recent software versions and IOS hardware appears to suggest that complete arches should be scanned digitally.[11–14] Clinically acceptable accuracy standards for an IOS should be achieved, generally specified as 100 µm [15–17], Despite the lack of a clear understanding and scientific relationship between global deviation and actual marginal prosthesis mismatch.
Although various research on the accuracy of digitally created dental models has been published, the majority of them are restricted to diagnostic models used in orthodontics.[18,19] Further research regarding the accuracy of prosthodontic models produced digitally is needed since the standards employed to create dental prosthetics that fit perfectly, like inlays and fixed partial dentures, require greater precision and accuracy than those used in orthodontics. Accuracy is comprised of precision and trueness by ISO -5725. The term "trueness" illustrates how closely the experimental result matched the actual value. When an experimental result is highly true, it means that it is either equivalent to or extremely near to the real value. Precision, on the other hand, refers to how well intragroup data agree with one another, which is gained via repeated measurements.[20]

Methods

Fabrication and scanning of reference models:
Three prepared artificial teeth are included in a model of completed arch maxillary for a fixed prosthesis (maxillary left second molar and premolar for 3-unit bridge, and maxillary right first molar for Inlay) model of maxillary Frasaco was used in its construction (standard working model AG-3; Frasaco, Tettnang, Germany). Teeth were prepared with standardized preparations from Frasaco, and the maxillary right first molar was ready to be used in the creation of a ceramic inlay. The cavity wall is 6 degrees of inclination, minimum of 2.5 mm is the width of the occlusal, 5.0 mm is the proximal depth, the proximal depth is 5.0 mm, and rounding was done to the point angles.
To construct a reference model with the photopolymer resin model, the working model's impression (Frasaco model) after preparation of teeth for Bridge and Inlay was made with silicone (vinyl Polysiloxane, 3M ESPE Express™ STD). Then Type IV dental stone was used to pour the impression (SHERAAQUA-Super hard stone, type 4, white). After removing the stone cast from the impression, a laboratory scanner was used to scan it (TRIOS® 3 pod, 3 Shape, Copenhagen, Denmark, E1), and the scanned surface was converted to surface tessellation language (STL). Then the STL file is converted to model builder software, then to the printer's cam program, and printed via a 3D printer (Microlay SLA system, versus 385, Spain).
A photopolymer resin was used to create the printed reference cast (KeyPrint® KeyModel Ultra™ Ivory MSRP) containing acrylate monomer and oligomers, which has a property of high-speed print formulation, smooth surface finish, and two colors optimized for sharp detail, which is used as a reference model. Before scanning the reference model with the laboratory scanner, the reference model was sprayed with Scan spray (non-flammable, NHT, Scan spray), and then the model of sprayed reference via laboratory scanner was scanned. The reference model was exported in a format of surface tessellation language (STL) and imported into Geomagic Control (3D Systems) (Geomagic Control X v2020.1.1).[14,21]
Digital Impressions method:
The reference model's digital impressions were taken utilizing the intra-oral scanner (TRIOS® 3 pod, 3 Shape, Copenhagen, Denmark). The scanners were used by a single operator for calibration, and training, as described by Patzelt et al. (22). The reference model was digitally scanned ten times with an available intraoral scanner (IOS) as demonstrated in Figure 1. The manufacturer's suggested scanning was followed, and scanning was done in restoration mode. The maxillary right third molar's occlusal-palatal sur-

faces were the starting point for the manufacturer's suggested scanning strategy, which also included moving to the other side of the arch while returning from the buccal side whereas always including two surfaces to ensure good data coverage of all surfaces.[23] Changing the scanning angle was about 35-55 degrees during scanning to allow the surfaces to overlap. The scanner head has been kept from the abutments at 0-5mm for gaining optimal capture, with slowly smoothly moving the scanner beside hearing a more radical clicking sound. All the scans were timed from start to finish, and a scan was considered complete once the prepared surfaces were captured entirely, and no major holes in the reference model level presented any deficiency were rescanned. Finally, the export of the scan data into ten STL files for Geomagic Control (3D Systems).

Conventional impression technique:

On the reference model, ten conventional impressions were made using a one-step, two-consistency technique as illustrated in Figure 1, utilizing a vinyl Polysiloxane (3M ESPE Express™ STD) impression material with a plastic impression tray. A single operator took each impression while maintaining standard laboratory temperatures of 23°C and following the instructions of the manufacturer. The impression trays from the reference model were taken after material polymerization and checked for defects. An amount of type IV dental stone that had been pre-weighed was then poured into the models. Before being taken out of the impression, the casts were given 24 hours to set as described by Sim et al.[14] The reference scanner was used to scan each of the ten casts (TRIOS® 3 pod, 3 Shape, Copenhagen, Denmark (E1)) the same procedures as previously described, after which they imported into Geomagic Control (3D Systems) in the STL file format.

Superimposition method (Three-dimensional analysis):

All digital and stone model STL files have been superimposed using (Geomagic Control X v2020.1.1). Using a 3D analysis software (Geomagic Control X; 3D Systems) and a best-fit alignment method, the datasets were superimposed to determine the accuracy (precision and trueness) of the complete arch as well as the trueness among the model groups' preparations. By superimposing the reference model's STL file data with STL file data from conventional stone (n = 10) and digital (n = 10) sources, the accuracy of the complete arch was assessed. Afterward, both groups of (N=10) files were overlaid with the reference model, and the 3D comparison was run to determine the outcome. For each preparation type (Inlay, Bridge), the preparation's trueness was evaluated by superimposing each preparation's STL file utilizing the reference model in the STL files of the two related preparations in the various model groups (each, n = 10).

By combining the scan data for each group (n = 45) and superimposing it, the precision of the entire arch for both groups (Digital, Stone) was evaluated.

The root mean square formula was applied by the 3D analysis program to calculate the quantitative values automatically (RMS).[14] The following formula was used to calculate the average of the negative and positive values using the RMS values:

$$RMS = \frac{1}{\sqrt{n}} * \sqrt{\sum_{i=1}^{n} (x_{1,i} - x_{2,i})^2}$$

Where is the measurement point for i of the reference models, is the measurement point for i of the datasets of the test model, and is the total of the measured points. 20 color segments were chosen for a color map that represents visual deviation.

To check intergroup normality, the Shapiro-Wilk test was utilized, and the Levene test (α=.05) was applied to check for homogeneity of variance. A Mann-Whitney u test was executed to compare how well the two model groups' complete arch accuracy performed. To compare the variations between the two model groups and preparation types, as well as to assess how true the preparation was, a Mann-Whitney u test was also run. For both statistical techniques, 0.05 was chosen as the threshold for statistical significance. Using the SPSS program, all statistical data was examined (IBM SPSS Statistics for Windows, Version 26.0; IBM, Armonk, NY, USA).

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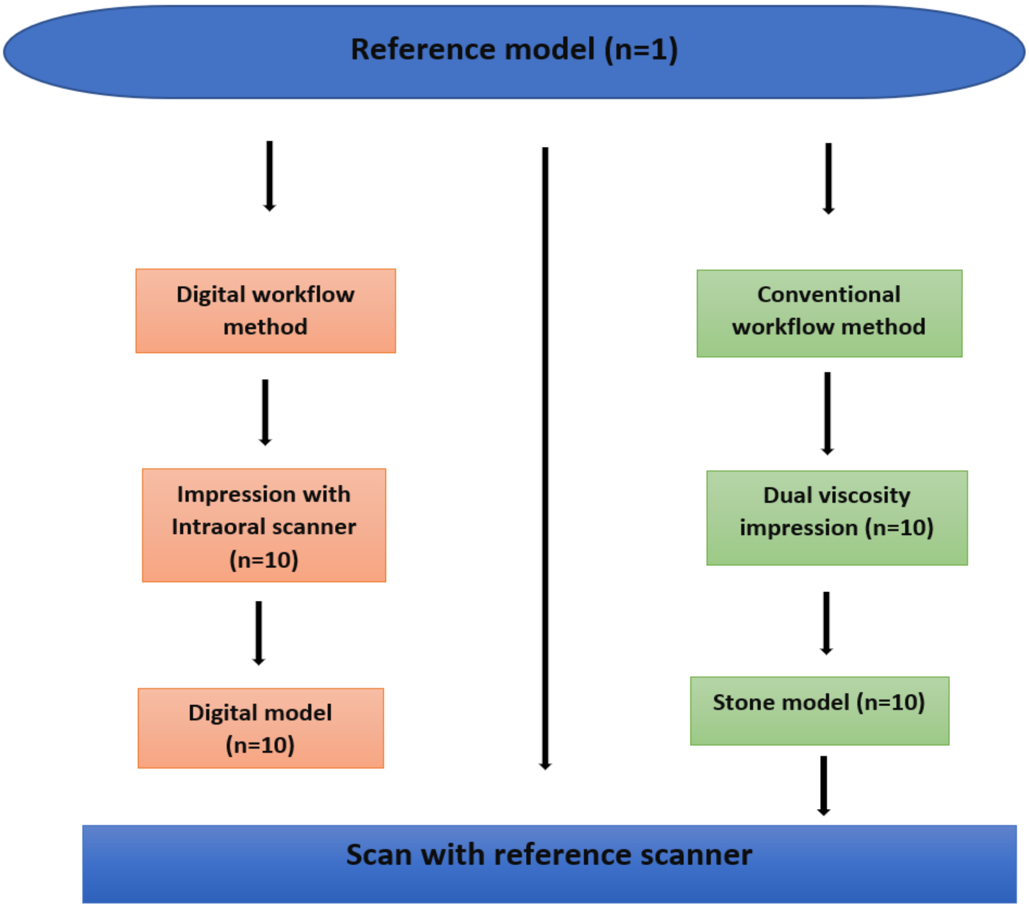

Figure 1: The study design

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Results

Via the Shapiro-Wilk test, the data were evaluated for normal distribution, one of the important tests in statistics for performing either parametric or non-parametric testing. The probability value for each category (Full Arch, Bridge, and Inlay) in (Table 1) is less than the level of significance, while the p-value is less than 0.05, and α=0.05, demonstrating the non-normal distribution of the data. In this study, non-parametric testing should be applied.
Table 2, reports the entire arch accuracy for each of the two model groups. The stone models' precision and trueness for the complete arch were 27.39 ± 8.600 µm and 42.32 ± 10.46 µm, respectively. By using the intraoral scanner precision and trueness of the digital models generated were 10.76 ± 4.00 µm and 35.06 ± 1.76 µm. Consequently, the models' trueness of the digital and stone was significant ($p<0.05$). Significant variations in precision between the two model groups were also discovered while the p-value was less than 0.001.
RMS (mean ± SD) values of the stone and digital for the complete (Bridge, Inlay) are reported in (Table.3). For the Bridge in the stone, and digital models were (12.54 ± 5.78µm), and (6.83 ± 0.72µm) respectively, and the difference of Bridge between stone and digital models were significant because ($p<0.001$). Additionally, significant variations existed between the two model groups in the Inlay of the stone and the digital models ($p < 0.001$), it has been noted that the RMS mean of Inlay equal (14.56 ± 7.49µm), (5.77 ± 0.76µm) for stone and digital models respectively.

Table.1: Test of Normality

type	Shapiro-Wilk	
	Statistic	Sig.
Full Arch	0.799	0.001**
Bridge	0.755	0.000**
Inlay	0.722	0.000**

*p<0.05, **p<0.01

Table.2: The accuracy (precision and trueness) of the digital, stone, model groups for the full arch (precision [n = 45], trueness [n = 10]).

Type	Stone RMS (µm) (mean ± SD)	Digital RMS (µm) (mean ± SD)	Mann-Whitney U test(Z)	p-value
Trueness	42.32 ± 10.46	35.06 ± 1.76	-2.31	0.021*
Precision	27.39 ± 8.600	10.76 ± 4.00	-7.727	0.000**

Table.3: The trueness of the stone and digital for the complete (Full Arch, Bridge, Inlay), n=20

Type	Stone RMS (µm) (mean ± SD)	Digital RMS (µm) (mean ± SD)	Mann-Whitney U test(Z)	p-value
Bridge	12.54 ± 5.78	6.83 ± 0.72	-3.55	0.000**
Inlay	14.56 ± 7.49	5.77 ± 0.76	-3.77	0.000**

Analysis of the color difference map

In Figure 2, color difference maps illustrate the two model groups' precision and trueness for the complete arch. The majority of the arch is shown in green, the stone model, Figure 2(a) and (c), and digital model groups, Figure 2(b) and (d), are within the tolerance range. A map showing the differences in color for each preparation (Inlay, 3-unit Bridge), highlighting the variations between the two model groups, is shown in Figure 3 and Figure 4.

In Figures 3(c) and 3(d), the proximal areas of the preparation are colored yellow; those of the stone model group show positive deviations. Figures 3(a) and (b) are shown to be different from the stone model in that all surfaces appear approximately green.

As shown in Figures 4(c) and (d), Inlay preparation for the stone model appears as yellow in the axial, distal, and facial walls of the preparations, while for digital models, as shown in Figures 4 (a) and (b) only small region of the distal wall appears as a yellow dot.

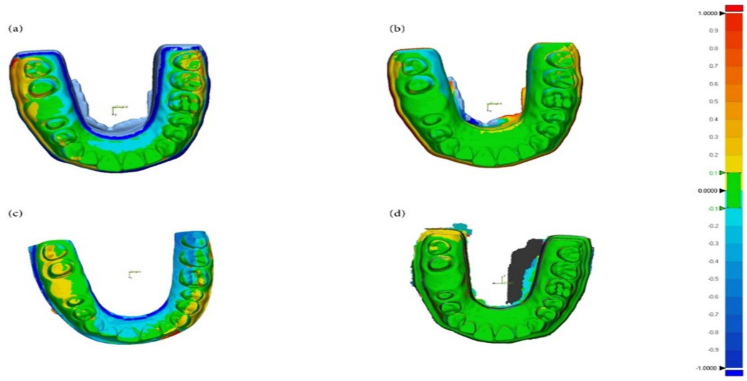

Figure 2: The precision and trueness of the complete arch are displayed on a color difference mapMax/min critical _ 1000 µm (dark red and dark blue). Max/min nominal _ 100 µm (green). The trueness of the (a) stone and (b) digital. The precision of the (c) stone and (d) digital.

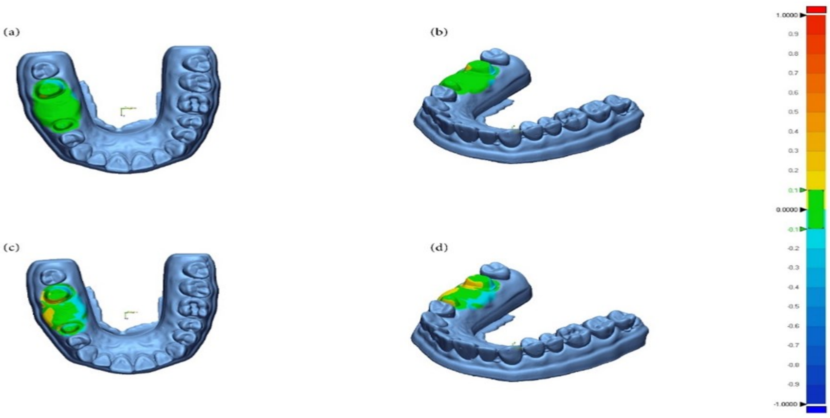

Figure 3: The precision and trueness of the 3-unit bridge preparation are displayed on a color difference map-Max/min critical _ 1000 µm (dark red and dark blue). Max/min nominal _ 100 µm (green). Digital model: (a) 3-unit top view and (b) perspective. stone model: (c) 3-unit top view and (d) perspective.

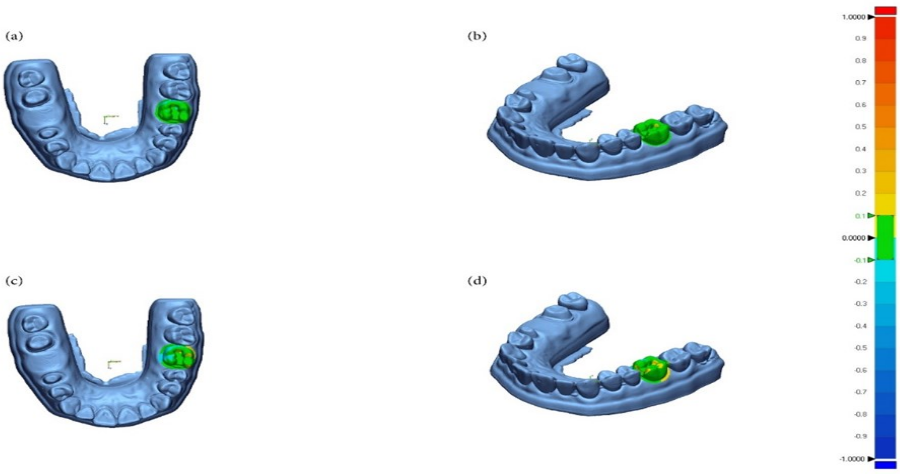

Figure 4: The precision and trueness of the inlay preparation are displayed on a color difference mapMax/min critical _ 1000 µm (dark red and dark blue). Max/min nominal _ 100 µm (green). Digital model: (a) Inlay top view and (b) perspective. Stone model: (c) Inlay top view and (d) perspective.

Discussion

This in vitro study utilized every component of hardware and software for the investigated scanners that are currently on the market. All scanning equipment was calibrated following manufacturer guidelines and updated with the most recent software before being put to use. Impressions were taken by one skilled operator to avoid any user impact. [24] Additionally, data were reported for precision and trueness in line with ISO 5725, as mentioned in earlier research. [25,26]

Results from a few earlier research showed greater accuracy in terms of precision and trueness [27] when full-arch restorations are performed using digital impressions as compared to conventional ones [28–32], which agrees with what was found in the present study. The stone models' precision and trueness for the complete arch were 27.39 ± 8.600 µm and 42.32 ± 10.46 µm, respectively. By using the intraoral scanner, precision and trueness of the digital models generated were 10.76 ± 4.00 µm and 35.06 ± 1.76 µm. Consequently, the models' trueness of the digital and stone was significant ($p<0.05$). Significant variations in precision between the two model groups were also discovered while the p-value was less than 0.001.

Contrary to our findings, research by Sim et al. [14] compared to a model created using a digital approach; the conventional stone model was found to have much better accuracy throughout the entire arch. The impression tray, materials, kind of stone utilized, and process are all factors that affect how accurate (true and precise) a model is when it is created using the conventional procedure. The type of 3D printer, the material that the 3D printer uses, and the type of intraoral scanner, on the other hand, all affect how accurate a model created utilizing a digital process will be. [33]

Individual plastic impression trays were employed in this investigation to provide consistent-thickness impression material, ensuring the accuracy of the impression process. Additionally, compared to previous elastomeric impression materials, the vinyl polysiloxane impression material employed in this study offers higher dimensional stability.[34]

However, Andreas Ender and Mehl. [1] observed that the stone model made using a conventional impression exhibited considerably lower mean values in trueness (20.4±2.2mm) than the digital model made using an intraoral scanner (58.6±15.8mm). These variations might be explained by the use of various intraoral scanners and conventional impression materials.

There are two different types of image recording systems for intraoral scanners (point-and-click and video-based systems) [15,35], and they employ numerous scanning methods, such as triangulation [36], parallel confocal [37], and active wave front. [38]

In this study, an intraoral scanner was used (TRIOS® 3 pod, 3 Shape, Copenhagen, Denmark) employs a triangulation scanning technique and a point-and-click recording system. In earlier research, it was claimed that horizontal deviations in the distal area of the impression data collected using an intraoral scanner were caused by improper software stitching procedures and data matching errors.[15,39]

According to Ender and Mehl [15], a video based-system intraoral scanner had a higher posterior region deviation than one based on a stitching system.

Previous research has discussed that the accuracy of full-arch scans is impacted by the scan path. [23,40,41] As a result, Müller et al. [23], who looked at several scan paths for the IOS Trios3 Pod, advised using a preset scanning protocol. Between the three categories of scan strategies (A, first buccal surfaces, return from occlusal-palatal; B, first occlusal-palatal, return from buccal; C, S-type one–way), the type B scan strategy was applied to this research.

Based on the research by Müller et al. [23], the precision was lowest for scan strategy A (35.0 ± 51.1 µm) and significantly different for B (7.9±5.6 µm) and C (8.5 ± 6.3 µm). The trueness (mean ± standard deviation) was 17.9 ± 16.4 µm for scan strategy A, 17.1 ± 13.7 µm for B, and 26.8 ± 14.7 µm for C without statistically significant difference. Because it provides the highest level of precision and trueness in full-arch scans, scan strategy B was advised, minimizing errors in the final reconstruction. [23]

Additionally, this research discovered substantial variations between the two model groups' preparation types (3-unit bridge and Inlay) (conventional and digital). Digital impressions were shown to produce findings that were more accurate than conventional impressions when the trueness between the two preparations was compared. In comparison to the stone model group, the digital model group's RMS values were lower for all categories of preparations. Regarding our findings that RMS (mean ± SD) for the Bridge in the stone and digital models were (12.54 ± 5.78µm) and (6.83 ± 0.72µm), respectively, and the difference in Bridge between stone and digital models was significant because ($p<0.001$). Additionally, between the two model groups, there were substantial differences in the Inlay of the stone and the digital models($p < 0.001$), it has been noted that the RMS mean of Inlay is equal (14.56 ± 7.49µm), (5.77 ± 0.76µm) for stone and digital models respectively, These results are relative to those that Keul and Güth reported. [26]

In contrast, Ender et al. [42] described the conventional impression technique's maximum accuracy, even across short distances. Even though more accurate results for short-term spans are similar to those of earlier research because they were discovered within shorter distances, more accurate results for transfer accuracy. The conventional impression revealed more accurate findings for precision and trueness for longer distances as well as for those that totally cross the quadrant. These results are comparable to those from earlier research. [25,43] The matching or stitching error may provide an explanation for this that becomes worse as the scan gets longer.[44,45]

As shown in (Figure. 2(c) and figure.3 (c)), positive deviation on the proximal, axial, and occlusal surfaces of the preparations is indicated by the model's expansion, which is indicated in yellow. This may be explained by the setting expansion of type IV dental stones, which counteracts the shrinkage brought on by polymerization in the elastomeric impression material and even increases dimension. This agrees with the findings of Stober et al. [46]

The digital workflow impression technique in dentistry has several benefits, such as time savings and a decrease in patient pain, but it still has drawbacks that prevent it from fully replacing the model of conventional stone. Several investigations on the accuracy of digital impressions created by intraoral scanners are now being conducted [15,35,39], and reports indicate that digital impressions are acceptable for clinical application. [47,48]

Most research used a best-fit method to superimpose models, and datasets of digital scans scanned from a conventional impression. [49,50] However, only a comparison of the two digital data sources is possible in this situation. If the digital dataset corresponds to the actual patient scenario, they fail to provide a solution. Additionally, it is yet unknown when a compensation calculation like the best-fit approach is used, and differences between two datasets are removed. [26]

Consequently, additional study is needed to assess the long-span prosthesis' accuracy like full-arch or half-arch restorations. There are certain restrictions on this in vitro study. A digital impression was made using an intraoral scanner to scan the reference model. Intraoral factors' effect, such as a limited mouth opening and saliva, was not taken into consideration. There is a need for more research that considers the actual clinical environment.

Conclusion

The following conclusions may be drawn given the limitations of this study, despite the fact that the results of the digital model created by an intraoral scanner were comparable to those of a conventional stone model in terms of the preparations and complete arch. Compared to digital models, stone models had a higher root mean square values for the accuracy of the full arch and the trueness of the preparations. Nevertheless, compared to digital models, the trueness of the preparations and the complete arch's accuracy of stone models were inferior.

Acknowledgement

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Conflict of interest

The author reported no conflict of interests.

References

1. Ender A, Mehl A. Accuracy of complete-arch dental impressions: a new method of measuring trueness and precision. J Prosthet Dent. 2013 Feb;109(2):121–8.
2. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. J Prosthodont Res. 2016 Apr;60(2):72–84.
3. Runkel C, Güth JF, Erdelt K, Keul C. Digital impressions in dentistry-accuracy of impression digitalization by desktop scanners. Clin Oral Investig. 2020 Mar;24(3):1249–57.
4. Basapogu S, Pilla A, Pathipaka S. Dimensional Accuracy of Hydrophilic and Hydrophobic VPS Impression Materials Using Different Impression Techniques - An Invitro Study. J Clin Diagn Res. 2016 Feb;10(2):ZC56-59.
5. Schaefer O, Schmidt M, Goebel R, Kuepper H. Qualitative and quantitative three-dimensional accuracy of a single tooth captured by elastomeric impression materials: an in vitro study. J Prosthet Dent. 2012 Sep;108(3):165–72.
6. Kulkarni PR, Kulkarni RS, Shah RJ, Chhajlani R, Saklecha B, Maru K. A Comparative Evaluation of Accuracy of the Dies Affected by Tray Type, Material Viscosity, and Pouring Sequence of Dual and Single Arch Impressions- An In vitro Study. J Clin Diagn Res. 2017 Apr;11(4):ZC128–35.
7. B N, B K. Dimensional Stability and Acuracy of Silicone - Based Impression Materials Using Different Impression Techniques - A Literature Review. Prilozi (Makedonska akademija na naukite i umetnostite Oddelenie za medicinski nauki) [Internet]. 2017 Sep 1 [cited 2021 Dec 10];38(2). Available from: https://pubmed.ncbi.nlm.nih.gov/28991761/
8. Keul C, Stawarczyk B, Erdelt KJ, Beuer F, Edelhoff D, Güth JF. Fit of 4-unit FDPs made of zirconia and CoCr-alloy after chairside and labside digitalization--a laboratory study. Dent Mater. 2014 Apr;30(4):400–7.
9. 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 Sep;20(7):1495–504.
10. 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 May;17(4):1201–8.
11. Ender A, Attin T, Mehl A. In vivo precision of conventional and digital methods of obtaining complete-arch dental impressions. J Prosthet Dent. 2016 Mar;115(3):313–20.
12. Muallah J, Wesemann C, Nowak R, Robben J, Mah J, Pospiech P, et al. accuracy of full-arch scans using intraoral and extraoral scanners: an in vitro study using a new method of evaluation. Int J Comput Dent. 2017 Jan 1;20(2):151–64.
13. Mennito AS, Evans ZP, Nash J, Bocklet C, Lauer Kelly A, Bacro T, et al. Evaluation of the trueness and precision of complete arch digital impressions on a human maxilla using seven different intraoral digital impression systems and a laboratory scanner. J Esthet Restor Dent. 2019 Jul;31 (4):369–77.
14. Sim JY, Jang Y, Kim WC, Kim HY, Lee DH, Kim JH. Comparing the accuracy (trueness and precision) of models of fixed dental prostheses fabricated by digital and conventional workflows. J Prosthodont Res. 2019 Jan;63(1):25–30.
15. Ender A, Mehl A. In-vitro evaluation of the accuracy of conventional and digital methods of obtaining full-arch dental impressions. Quintessence Int. 2015 Jan;46(1):9–17.
16. Fukazawa S, Odaira C, Kondo H. Investigation of Accuracy and reproducibility of abutment position by intraoral scanners. J Prosthodont Res. 2017 Oct;61(4):450–9.
17. Malik J, Rodriguez J, Weisbloom M, Petridis H. Comparison of Accuracy Between a Conventional and Two Digital Intraoral Impression Techniques. Int J Prosthodont. 2018 Mar;31(2):107–13.
18. Hazeveld A, Huddleston Slater JJR, Ren Y. Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques. Am J Orthod Dentofacial Orthop. 2014 Jan;145(1):108–15.

19. Kim JH, Kim KB, Kim WC, Kim JH, Kim HY. Accuracy and precision of polyurethane dental arch models fabricated using a three-dimensional subtractive rapid prototyping method with an intraoral scanning technique. Korean J Orthod. 2014 Mar;44(2):69–76.
20. ISO 5725-1:1994(en), Accuracy (trueness and precision) of measurement methods and results — Part 1: General principles and definitions [Internet]. [cited 2021 Aug 30]. Available from: https://www.iso.org/obp/ui/#iso:std:iso:5725:-1:ed-1:v1:en
21. Treesh JC, Liacouras PC, Taft RM, Brooks DI, Raiciulescu S, Ellert DO, et al. Complete-arch accuracy of intraoral scanners. J Prosthet Dent. 2018 Sep;120(3):382–8.
22. Patzelt SBM, Lamprinos C, Stampf S, Att W. The time efficiency of intraoral scanners: an in vitro comparative study. J Am Dent Assoc. 2014 Jun;145(6):542–51.
23. Müller P, Ender A, Joda T, Katsoulis J. Impact of digital intraoral scan strategies on the impression accuracy using the TRIOS Pod scanner. Quintessence Int. 2016 Apr;47(4):343–9.
24. Kamimura E, Tanaka S, Takaba M, Tachi K, Baba K. In vivo evaluation of inter-operator reproducibility of digital dental and conventional impression techniques. PLoS One. 2017;12 (6):e0179188.
25. Kuhr F, Schmidt A, Rehmann P, Wöstmann B. A new method for assessing the accuracy of full arch impressions in patients. J Dent. 2016 Dec;55:68–74.
26. Keul C, Güth JF. Accuracy of full-arch digital impressions: an in vitro and in vivo comparison. Clin Oral Investig. 2020 Feb;24(2):735–45.
27. Knechtle N, Wiedemeier D, Mehl A, Ender A. Accuracy of digital complete-arch, multi-implant scans made in the edentulous jaw with gingival movement simulation: An in vitro study. J Prosthet Dent. 2021 Feb 18;S0022-3913(21)00019-6.
28. Abdel-Azim T, Zandinejad A, Elathamna E, Lin W, Morton D. The influence of digital fabrication options on the accuracy of dental implant-based single units and complete-arch frameworks. Int J Oral Maxillofac Implants. 2014 Dec;29(6):1281–8.
29. 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 Nov;28 (11):1360–7.
30. Zimmermann M, Koller C, Rumetsch M, Ender A, Mehl A. Precision of guided scanning procedures for full-arch digital impressions in vivo. J Orofac Orthop. 2017 Nov;78(6):466–71.
31. Albdour EA, Shaheen E, Vranckx M, Mangano FG, Politis C, Jacobs R. A novel in vivo method to evaluate trueness of digital impressions. BMC Oral Health. 2018 Jul 3;18(1):117.
32. Alikhasi M, Siadat H, Nasirpour A, Hasanzade M. Three-Dimensional Accuracy of Digital Impression versus Conventional Method: Effect of Implant Angulation and Connection Type. Int J Dent. 2018;2018:3761750.
33. S T, Bk M, Mt B, S H, Dt B, Cj A. Dimensional accuracy of dental casts: influence of tray material, impression material, and time. Journal of prosthodontics : official journal of the American College of Prosthodontists [Internet]. 2002 Jun [cited 2021 Dec 19];11(2). Available from: https://pubmed.ncbi.nlm.nih.gov/12087547/
34. Clancy JM, Scandrett FR, Ettinger RL. Long-term dimensional stability of three current elastomers. J Oral Rehabil. 1983 Jul;10(4):325–33.
35. Nedelcu RG, Persson ASK. Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimensional analysis. J Prosthet Dent. 2014 Dec;112(6):1461–71.
36. Schenk O. The new acquisition unit Cerec AC. Int J Comput Dent. 2009;12(1):41–6.
37. Garg AK. Cadent iTero's digital system for dental impressions: the end of trays and putty? Dent Implantol Update. 2008 Jan;19(1):1–4.
38. Logozzo S, Zanetti E, Franceschini G, Kilpela A, Mäkynen A. Recent advances in dental optics – Part I: 3D intraoral scanners for restorative dentistry. Optics and Lasers in Engineering. 2014 Mar 1;54:203–221.
39. Patzelt SBM, Emmanouilidi A, Stampf S, Strub JR, Att W. Accuracy of full-arch scans using intraoral scanners. Clin Oral Investig. 2014 Jul;18(6):1687–94.
40. Ender A, Mehl A. Influence of scanning strategies on the accuracy of digital intraoral scanning systems. Int J Comput Dent. 2013;16(1):11–21.
41. Passos L, Meiga S, Brigagão V, Street A. Impact of different scanning strategies on the accuracy of two current intraoral scanning systems in complete-arch impressions: an in vitro study. Int J Comput Dent. 2019;22(4):307–19.
42. Ender A, Zimmermann M, Mehl A. Accuracy of complete- and partial-arch impressions of actual intraoral scanning systems in vitro. Int J Comput Dent. 2019;22(1):11–9.
43. Mangano F, Gandolfi A, Luongo G, Logozzo S. Intraoral scanners in dentistry: a review of the current literature. BMC Oral Health. 2017 Dec 12;17(1):149.
44. Flügge TV, Att W, Metzger MC, Nelson K. Precision of Dental Implant Digitization Using Intraoral Scanners. Int J Prosthodont. 2016 Jun;29 (3):277–83.
45. Vandeweghe S, Vervack V, Dierens M, De

46. Stober T, Johnson GH, Schmitter M. Accuracy of the newly formulated vinyl siloxanether elastomeric impression material. The Journal of Prosthetic Dentistry. 2010 Apr 1;103(4):228–39.
47. Ng J, Ruse D, Wyatt C. A comparison of the marginal fit of crowns fabricated with digital and conventional methods. J Prosthet Dent. 2014 Sep;112(3):555–60.
48. Chochlidakis KM, Papaspyridakos P, Geminiani A, Chen CJ, Feng IJ, Ercoli C. Digital versus conventional impressions for fixed prosthodontics: A systematic review and meta-analysis. J Prosthet Dent. 2016 Aug;116(2):184-190.e12.
49. Goracci C, Franchi L, Vichi A, Ferrari M. Accuracy, reliability, and efficiency of intraoral scanners for full-arch impressions: a systematic review of the clinical evidence. Eur J Orthod. 2016 Aug;38 (4):422–8.
50. A E, M Z, A M. Accuracy of complete- and partial -arch impressions of actual intraoral scanning systems in vitro. International journal of computerized dentistry [Internet]. 2019 [cited 2022 Jan 7];22(1). Available from: https://pubmed.ncbi.nlm.nih.gov/30848250/
51. O'Toole S, Osnes C, Bartlett D, Keeling A. Investigation into the accuracy and measurement methods of sequential 3D dental scan alignment. Dent Mater. 2019 Mar;35(3):495–500.