RESEARCH AND EDUCATION

Dimensional accuracy of microcomputed tomography-scanned half-arch impressions

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Dimensional accuracy is essential for impression-making techniques as it affects everything from planning to delivering a well-fitting restoration. The recent advent of digital tools in dentistry has begun to change a nearly century-old workflow of preparing an impression and pouring it in gypsum to create a cast upon which a restoration will be fabricated.[1-6]

Elastomeric impression materials used in dentistry undergo polymerization shrinkage from the linkage of monomers to macromolecules.[7] When the impression is poured using a gypsum mixture, the compressive and diametral tensile strength, compressive strength, surface porosity, microhardness, setting time, setting expansion, and the inclusion of air bubbles while mixing the gypsum all affect restoration accuracy.[8] The strength and expansion of gypsum also vary depending on stone type, ratio of powder to water, temperature, and humidity.[8,9]

The accuracy of extraoral scanners to optically scan the cast and intraoral scanners to directly scan the

ABSTRACT

Statement of problem. Accuracy in impression making may be enhanced by digitizing the physical impression directly and thereby be unhampered by errors introduced by gypsum casts.

Purpose. The purpose of this in vitro study was to compare the dimensional accuracy of micro-computed tomography (micro-CT) scans of impressions with that of optical scans of impressions and gypsum casts.

Material and methods. A titanium maxillary cast with 3 metrology-grade ruby spheres in place of 3 teeth was used as a reference. Sphere 1 (S1) to sphere 2 (S2) distance (S1-S2) was 25.036 mm, and sphere 1 (S1) to sphere 3 (S3) distance (S1-S3) was 41.846 mm. Half-arch impressions were made of the titanium cast using polyvinyl siloxane impression material with a 1-step 2-phase technique. The polyvinyl siloxane impressions were then micro-CT scanned and optically scanned, and the resulting stone casts were also optically scanned. Scans from the 3 groups—CT scanning of impressions (CT), optical scanning of impressions (OP), and optical scanning of stone casts (SC)—were used to measure the distances between the 3 ruby spheres and were compared with the reference titanium model. The Wilcoxon signed-rank test for matched pairs was used to compare the groups (α=.01).

Results. For the distance of 25.036 mm, S1-S2 distance, CT scans of impressions (CT) showed an error of 20 ±20 μm, whereas optical scans of stone casts (SC) showed an error of 0 ±20 μm. At a distance of 41.846 mm, S1-S3 distance, CT showed an error of 0 ±40 μm, whereas SC showed an error of −40 ±40 μm. The difference in error between measurements at both distances was statistically significant (*P*<.01). The group of optical scans of impressions (OP) had to be excluded because of missing data and deformed features on the scan.

Conclusions. Although optically scanned stone models are more dimensionally accurate than micro-CT scanned impressions at a 25.036-mm distance, at a distance of 41.846 mm, micro-CT scanned impressions showed less error than optically scanned stone models. Micro-CT scanning of half-arch impressions is a viable method of digitizing a physical impression of dental structures and capturing data about the patient's oral structures. A digital image obtained by micro-CT scanning is more accurate than that obtained by optical scans of stone casts for long-span restorations. (J Prosthet Dent 2019;121:797-802)

patient's teeth has been studied. Malaguti et al[10] compared the fit of zirconia crowns made by traditional and digital techniques. They found that intraoral and stone cast scanners digitized the prepared tooth

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Clinical Implications

Computed tomography scanning of impressions is as accurate as optically scanning stone casts. For long-span restorations, the dimensional accuracy of computed tomography scanning impressions exceeds that of optically scanned stone casts. Time and cost may be saved in scanning an impression compared with scanning a poured cast. There is also the opportunity to eliminate dimensional discrepancies caused by handling and the inherent expansion of the gypsum.

accurately and created well-fitting copings. Recently, microcomputed tomography (micro-CT) scanning has been scrutinized as another way of digitizing the information gathered by an impression. As far as the authors are aware, only 1 study[11] has investigated digitizing dental impressions using a micro-CT scanner. Kim et al[11] made micro-CT scans of polyvinyl siloxane (PVS) impressions of a reference model. One of the teeth was prepared for an inlay and another for a crown. They then milled composite inlays and zirconia crowns from the micro-CT scan data. The fit of these restorations was compared with that of restorations created by the conventional method of optically scanning stone casts poured from the PVS impressions and images made with an intraoral scanner. The accuracy of dental restorations made from micro-CT scans of the impressions was found to be better in terms of dimensional accuracy than digitizing with intraoral scanners.[11]

The present in vitro study was conducted to better understand the accuracy of micro-CT scans of impressions as compared with pouring an impression in dental stone and optically scanning it. The null hypothesis was that the error created while digitizing an impression using a micro-CT scanner would be similar to the error generated while digitizing an impression or a stone cast by optical scanning.

MATERIAL AND METHODS

A titanium master model was created from a digital scan of a typodont maxilla. The maxillary second molar, first premolar, and central incisor of the maxillary right quadrant were replaced with metrology-grade ruby spheres (grade 25). The ruby spheres were designated as S1 (maxillary right second molar), S2 (maxillary right first premolar), and S3 (maxillary right central incisor). The distances between these spheres were measured using a National Institute of Standards and Technology- (NIST)-traceable coordinate measuring machine with an accuracy of 2.8 +L/333 μm and a resolution of 0.000003 (National Institute of Standards and Technology

Traceability 18201690469047). The distance between S1 and S2 was 25.036 mm and that between S1 and S3 was 41.846 mm. These measurements served as a reference for measuring the accuracy of the tested methods.

The titanium model was secured to a flat base, and a custom tray was designed to seat on the right half of the arch the same way each time by engaging 2 metal indexing pegs, 1 in front and the other behind the titanium cast (Fig. 1). The tray was designed with a minimum 2-mm clearance between the cast and the tray to allow for the optimum thickness of impression material. PVS material was used to create the impressions because it is known to register the form of teeth and surrounding tissues correctly.[7,12,13]

Thirty half-arch impressions were made of the titanium model using PVS impression material with a single-step dual-phase technique.[14] A heavy-body PVS impression material (Capture–Heavy body; Glidewell Dental) with a setting time of 3 minutes was used to make the impressions (n=30). A new tray was used for each impression. Light-body PVS (Capture–Light body; Glidewell Dental) was syringed around the ruby spheres (Fig. 2), and the tray was filled with the heavy-body PVS. The tray was placed over the cast and allowed to set for twice the manufacturer's recommended time to ensure complete polymerization at room temperature. All impressions were made by the same clinician (M.K.) with a stopwatch used to measure the polymerization time. Once the impressions had polymerized, they were carefully removed from the model.

To replicate a clinical scenario where impressions are transported to a dental laboratory for fabrication of the casts and restoration, the impressions were left for 24 hours. They were then optically scanned using a desktop scanner (E3 3Shape scanner; Ivoclar Vivadent AG) and micro-CT scanned (Nikon XT H 225; Nikon Corp). They were then poured using preproportioned water and Type IV stone (Ivory Resin stone; ETI Empire Direct) and allowed to set for an hour in a cast dryer (Cast dryer; Glidewell Dental). The poured casts were then carefully separated from the impression and optically scanned with the E3 3Shape scanner.

The raw 3D image model Volume Graphics Info (VGI) file generated from the micro-CT scanner is rendered using hundreds of cross-sectional [radiograph] images made by directing an X-ray beam at an object. The images are taken at multiple positions during a full 360-degree rotation of the object. These data from the VGI file were imported to software which generated polygonal surface data based on a density histogram. The polygonal surfaces generated from the raw data were restricted to the portions of the data that fell within the specified density level. All other raw data that did not fall within that density were not converted to polygonal surface data to eliminate unwanted noise in the definitive
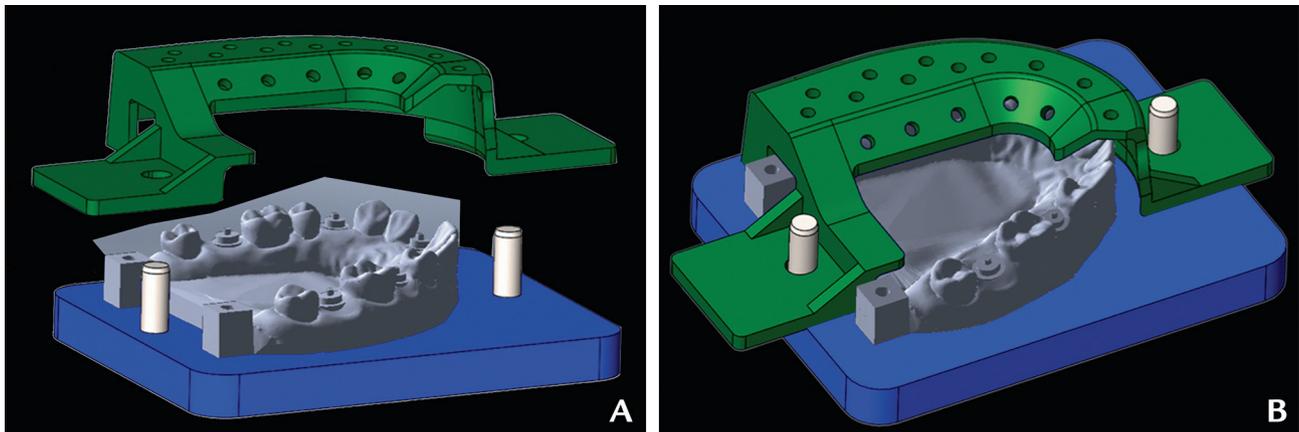
Figure 1. Experimental arrangement. A, Custom tray designed to replicate closed-mouth impression. B, Custom tray designed to seat repeatably by engaging metal pegs in front of and behind titanium cast.

standard tessellation language (STL) model. Scans from the 3 groups—CT scanning of impressions (CT), optical scanning of impressions (OP), and optical scanning of stone casts (SC)—were used to measure the distances between the 3 ruby spheres and compared with the reference titanium cast. STL files from the optical and computed tomography scanner were then compared with 3D inspection and metrology software (Geomagic Qualify; 3D Systems Inc). The spherical area of the rubies was selected in the software. Using the 'Create new feature' tool in the Qualify software, new spheres were fitted to the selected area of the scanned rubies by using the software's Best Fit algorithm. The centers of the fitted spheres were then marked. Distances between the centers of S1 and S2, between centers of S1 and S3 were measured and recorded on each 3D scan. Two observers were trained and standardized to conduct the measurements on the digital casts. They measured distances between the centers of S1-S2 and S1-S3 in all 30 CT specimens, 30 OP specimens, and 30 SC specimens 3 times each, with measurements performed at least 24 hours apart. The average of those 6 measurements from 2 observers for each impression and corresponding cast was calculated giving a total of 30 averages of a total of 180 data points for each kind of scan—CT, OP, and SC.

To improve clinical relevance, the accuracy of processes that attempt to duplicate an original one are best evaluated by looking at the error between known and obtained measures rather than simply reporting the obtained measurements. The error was measured by subtracting the measured distance from the known distance on the reference titanium model.

The G*Power 3.1 software was used to calculate the sample size a priori for a Wilcoxon signed-rank test for matched pairs.[15] For an effect size (dz) of 1, an α error probability of .01, and a power (1-β error probability) of .99, the software suggested a sample size of 29. This
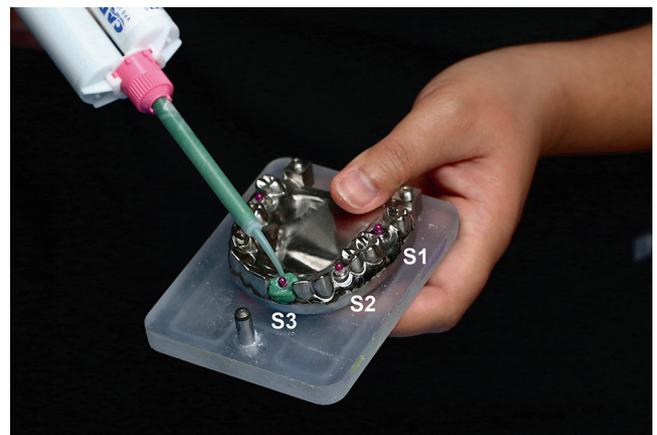

Figure 2. Metrology grade ruby spheres (S1, S2, and S3) on titanium cast. Light-body polyvinyl siloxane impression material syringed around sphere 3.

number was rounded to 30 specimens in each group (CT, OP, and SC). The data were analyzed using a statistical software program (XLSTAT v19.7.48771; Addinsoft). The observations were not expected to pass the Shapiro-Wilk test for normality because they were all based on impressions of the same titanium model. The nonparametric Wilcoxon signed-rank test for matched pairs was used to compare the 2 groups.

RESULTS

Thirty specimens in group CT and 30 specimens in group SC captured all the features between S1 and S2 and between S1 and S3. The distances between the centers of the spheres were measured and recorded. The 30 specimens in group OP, however, did not consistently capture S3, and a few of the scans did not capture the sphere at all. This may be because the spheres presented an undercut area that the optical scanner was unable to scan. The OP scans that did capture S3 did not capture it
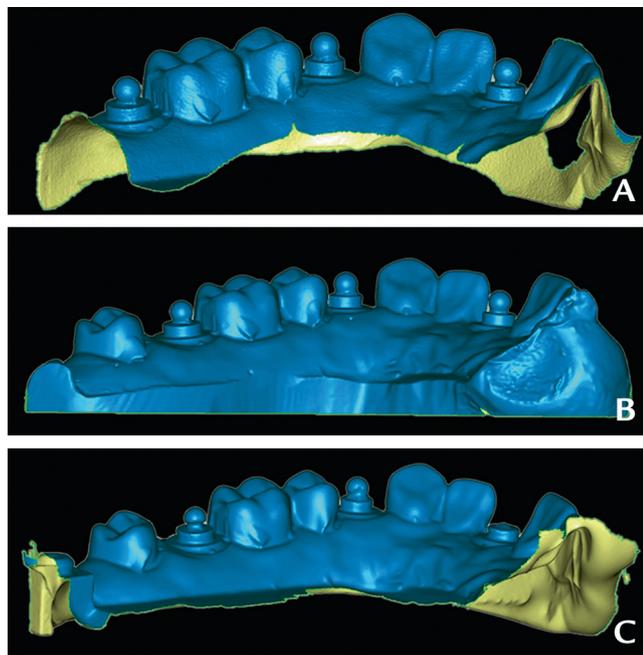
Figure 3. A, Computed tomography scan of impression. B, Optical scan of stone cast poured from same impression. C, Optical scan of impression (note hemispherical S1, deformed S2, and missing S3).

entirely, and the sphere often appears deformed as seen in Figure 3. This study was not designed to look qualitatively at the shape of the spheres; however, the optical scanner did capture elongated shapes or hemispheres instead of spheres from the impression. For these reasons, group OP was excluded from further analysis.

The measured distances S1-S2 and S1-S3 were subtracted from the known measurements obtained by the coordinate measuring machine to give the error or difference in the measures. Significant time savings were found in micro-CT scanning impressions. For computed tomography scans, it took less than 5 minutes to scan and process the image. Stone casts in comparison took between 30 and 40 minutes to be poured, processed, set completely, and then optically scanned. Optical scans of the impressions were also rapid; however, the resulting scans were distorted, and data were missing.

For the distance of 25.036 mm, S1-S2 distance, CT specimens showed a mean error of 20 ±20 μm, whereas SC specimens showed an average error of 0 ±20 μm. At a distance of 41.846 mm, S1-S3 distance, group CT showed an error of 0 ±40 μm, whereas group SC showed an error of −40 ±40 μm.

A statistically significant difference was seen between the S1-S2 distance measurement (*P*<.01) as well as the S1-S3 distance measurement (*P*<.01). As seen in Figure 4, the SC group had a lower error average when the distance S1-S2 was measured. However, SC shows a greater error in the longer distance between S1 and S3 compared with CT. In comparing the processes of

micro-CT scanning of PVS impressions and optically scanning stone casts, a statistically significant difference was found in the measurements obtained compared with the reference model in assessing dimensional accuracy over short spans as well as long spans.

DISCUSSION

The null hypothesis is rejected over short spans of 25.036 mm because CT and SC groups have a statistically significant difference in errors over the short span. On longer spans of 41.846 mm, CT has a lower error and SC has a larger error. At this longer distance, the null hypothesis is rejected as the difference in error is also statistically significant.

This experiment was conducted to quantify the error produced in different processes to digitize oral structures. From the data, it appears that at 25.036 mm, the SC group was more dimensionally accurate than the CT group. However, as the distance increased to 41.846 mm, CT specimens were more accurate than SC specimens. These findings are consistent with those of Luthardt et al,[16] who compared the accuracy of digital and conventional impressions. When considering quadrants, elastomeric impression materials showed deviations of 19 μm, similar to the findings in the present study with micro-CT scanning of PVS impressions over a 25-mm span. Although the setting expansion of modern Type IV die stones is designed to match the inherent volume loss of elastomeric impression materials,[7] gypsum definitive casts are oversized.[12]

Freitas et al[17] looked at the expansion of 15 different gypsum products at 2-hour set and emphasized that their study closely followed the recommendations of the respective manufacturers, both regarding the dosage of the products and the handling process. Failure to follow these instructions changes the properties of the cast, especially regarding the water to powder proportion; excess water increases hygroscopic expansion because it causes greater growth of gypsum crystals. Heshmati et al[18] tested the expansion of 6 brands of dental stone. They reported that all exhibited continued expansion while setting under clinical conditions. The amount of expansion varied significantly among the materials, with 22% to 71% of the expansion occurring after 2 hours.

Michalakis et al[9] placed a control cast at room temperature and approximately 50% humidity and an experimental cast at an elevated 40°C temperature and less than 20% humidity. The experimental casts showed an expansion between 24 and 96 hours after the initial set. The increased temperature and reduced humidity also seemed to cause a contraction in stone casts after 1 week, meaning that in some climatic conditions, restorations must be fabricated on casts immediately to avoid changes that might affect the fit of the definitive
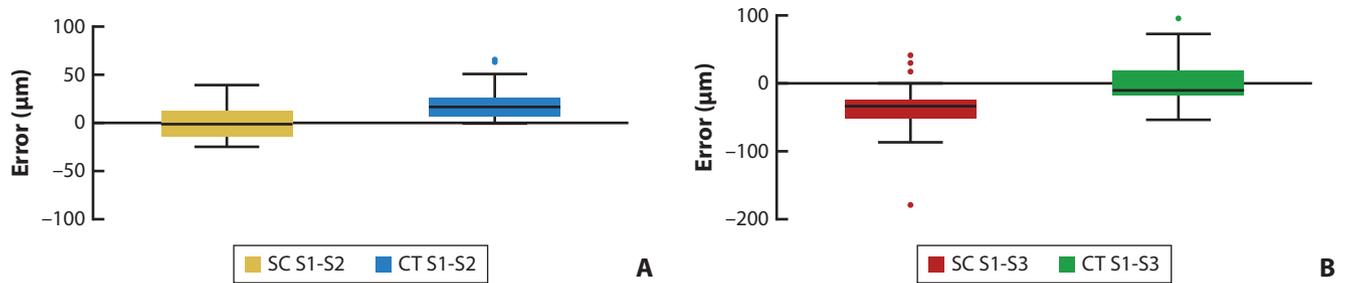
Figure 4. Average error for distance (µm). A, Between S1 and S2. B, Between S1 and S3. CT, computed tomography scanning of impression group; SC, optical scanning of stone cast group.

restoration. Gypsum changes in dimension over time and in varying conditions. This may have a significant impact on the restorations fabricated on gypsum casts.[9,17,18]

Hoffman et al[19] reported similar results when comparing stone casts to 3D-printed casts from intraoral scans of a reference model with a single crown preparation and a 3-unit fixed partial denture preparation. The dimensional errors in optical scans of stone casts in their findings are consistent with those in the present study, over both short and long spans.[19] The conclusion that optical scans of stone have greater dimensional error over a large distance is in agreement with the study by Vecsei et al.[20] Reductions in volume of PVS materials due to polymerization have been reported to be as low as 0.1% to 0.05%. This linear contraction is well matched to the setting expansion of modern Type III and Type IV die stones and results in a slightly larger replication of the preparation.[7] It is anticipated that the contraction of the impression material and expansion of the stone compensate each other to provide an accurate representation of the captured soft and hard tissues. However, depending on the formulation of the specific impression material and the formulation of the stone, there may not be overcompensation or undercompensation of impression material shrinkage.[12]

The impression material is not free from the errors that could be introduced by impression-making materials and techniques such as air bubbles, rupture of impression material, inaccurate impression tray dimensions, too much or too little impression material, insufficient adhesion of the impression to the impression tray, and impression material distortion during removal from the mouth or the disinfection procedure.[21]

As discussed, elastomeric materials contract as they polymerize, and errors can be introduced in an impression; those errors, compounded with errors in gypsum, can result in a flawed replica. PVS impression materials used for making definitive impressions have been reported to exhibit poor wetting characteristics, resulting in voids on the surfaces of the prepared casts. Voids on the cast may also appear due to the use of nonvacuum mixed dental stone and the actual technique of pouring the impression.[22]

This experiment did not quantify the material error alone and includes any errors the imaging processes of micro-CT scanning and optical scanning themselves may bring. We believe that micro-CT scanning an impression simplifies the process because a good impression has little dimensional change, and there are no stone-introduced errors in the process of pouring a gypsum cast.

Optical scanning of impressions yields incomplete data becase of undercuts present in dental impressions. A glossy, shiny, or textured surface can affect the quality of an extraoral optical scan. In contrast, micro-CT scanning does not seem to be affected by any undercuts present in the impression, any liquid remaining on the surface, or any surface texture of the polymerized impression material.

This in vitro study had limitations that are inherent in a study of this nature. Only linear dimensional errors in the 2 methods used for measuring change in distances between 3 points on the titanium model were quantified. Dimensional deviations are inherent to the elastomeric molecular structure and should be described in a 3D manner.[23] Additional studies are required to quantify 3D change in the impression scans and scans of the stone casts. This study did not gather qualitative information or quantify discrepancies in the anatomy captured.

This study did not quantify the completeness of the scans obtained from micro-CT versus optical scanning. There are limitations to this study in that it measured only dimensional accuracy without considering qualitative aspects of the impression and cast. The optical scanner had trouble recording undercuts in dental impressions as seen in Figure 3. This study did not capture this discrepancy, and additional studies will be required to expand on this issue. Because this was an in vitro study, it does not consider the effects of saliva or disinfectant solution on the impression.

This study includes only a quadrant which is representative of closed-mouth impressions. Further studies should include complete-arch measurements to expand on this study and relate findings to a complete-arch impression. The design of the way the experimental

tray was placed and retrieved for repeatability did not replicate the way closed-mouth impressions are used in the patient's mouth. This may have affected the impression during tray removal, and the results may not precisely reflect the clinical setting.

Stone casts were poured using a strict protocol–the water and powder were measured, and care was taken to ensure there were no air bubbles. Four stone casts that had air bubbles affecting the metrology spheres were redone by making new impressions. This may not reflect the reality of what happens in a busy dental laboratory, nor does it shed light on the consequences of the errors introduced by voids, breakage of the cast, and subsequent repair that may lead to substandard casts. Intraoral scanning is an upcoming method of impression making, and studies are needed to compare the accuracy of intraoral scanning with that of micro-CT scanning of impressions.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Over short spans, as for a single crown, optical scans of stone casts seem to be more accurate than micro-CT scans of impressions.
2. Over longer spans, as for a fixed partial denture, micro-CT scans of impressions are more accurate than those of stone casts.
3. Micro-CT scans of an impression are comparable in accuracy to optical scans of stone casts.

REFERENCES

1. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J 2008;204:505-11.
2. 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;47:343-9.
3. Mangano F, Shibli JA, Fortin T. Editorial digital dentistry: new materials and techniques. Int J Dent 2016;2:2-4.
4. Vlaar ST, van der Zel JM. Accuracy of dental digitizers. Int Dent J 2006;56:301-9.
5. Zandinejad A, Lin W, Atarodi M, Abdel-Azim T, Metz M, Morton D. Digital workflow for virtually designing and milling ceramic lithium disilicate veneers: a clinical report. Oper Dent 2015;40:241-6.
6. Sakornwimon N, Leevailoj C. Clinical marginal fit of zirconia crowns and patients' preferences for impression techniques using intraoral digital scanner versus polyvinyl siloxane material. J Prosthet Dent 2017;118:386-91.
7. Mandikos MN. Polyvinyl siloxane impression materials: an update on clinical use. Aust Dent J 1998;43:428-34.
8. Azer SS, Kerby RE, Knobloch LA. Effect of mixing methods on the physical properties of dental stones. J Dent 2008;36:736-44.
9. Michalakis KX, Asar NV, Kapsampeli V, Magkavali-Trikka P, Pissiotis AL, Hirayama H. Delayed linear dimensional changes of five high strength gypsum products used for the fabrication of definitive casts. J Prosthet Dent 2012;108:189-95.
10. Malaguti G, Rossi R, Marziali B, Esposito A, Bruno G, Dariol C, et al. In vitro evaluation of prosthodontic impression on natural dentition: a comparison between traditional and digital techniques. Oral Implantol (Rome) 2016;9:21-7.
11. Kim C, Baek SH, Lee T, Go J, Kim SY, Cho S. Efficient digitalization method for dental restorations using micro-CT data. Nat Sci Reports 2017;7:1-8.
12. Wadhwani CPK, Johnson GH, Lepe X, Raigrodski AJ. Accuracy of newly formulated fast-setting elastomeric impression materials. J Prosthet Dent 2005;93:530-9.
13. Thouati A, Deveaux E, Iost A, Behin P. Dimensional stability of seven elastomeric impression materials immersed in disinfectants. J Prosthet Dent 1996;76:8-14.
14. Luthardt RG, Walter MH, Quaas S, Koch R, Rudolph H. Comparison of the three-dimensional correctness of impression techniques: a randomized controlled trial. Quintessence Int 2010;41:845-53.
15. Conover WJ, Iman RL. Rank transformations as a bridge between parametric and nonparametric statistics. Am Stat 1981;35:124-9.
16. Luthardt RG, Loos R, Quaas S. Accuracy of intraoral data acquisition in comparison to the conventional impression. Int J Comput Dent 2005;8:283-94.
17. de Freitas CA, Zanotti TS, Rizzante FAP, Furuse AY, de Freitas MFA. Linear setting expansion of different gypsum products. South Brazilian Dent J 2015;12:61-7.
18. Heshmati RH, Nagy WW, Wirth CG, Dhuru VB. Delayed linear expansion of improved dental stone. J Prosthet Dent 2002;88:26-31.
19. Hoffman M, Cho SH, Bansal NK. Interproximal distance analysis of stereolithographic casts made by CAD-CAM technology: an in vitro study. J Prosthet Dent 2017;118:624-30.
20. 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.
21. Camardella LT, Breuning H, de Vasconcellos Vilella O. Accuracy and reproducibility of measurements on plaster models and digital models created using an intraoral scanner. J Orofac Orthop 2017;78:211-20.
22. Sherfudhin H, Abdulla MA. Preparation of void-free casts from vinyl polysiloxane impressions. J Dent 1996;24:95-8.
23. Schaefer O, Schmidt M, Kuepper H, Friedrich H. Qualitative and quantitative three- dimensional accuracy of a single tooth captured by elastomeric impression materials: an in vitro study. J Prosthet Dent 2012;108:165-72.

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