

Three-dimensional printed models versus conventional stone models: an accuracy analysis

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Received: June 05, 2020

Accepted: August 28, 2020

Conflicts of interest: none to disclosure.

Aim: To compare the accuracy (trueness and precision) of cost-accessible three-dimensional (3D) printed models.

Methods: A maxillary typodont (MM) was scanned and printed 10 times in polylactic acid, resulting in 10 digital models (DMs). Polyvinylsiloxane impressions were made to obtain 10 conventional stone models (SMs). All models were scanned and imported to CloudCompare software. The total area and three locations of interest were evaluated (zenith to incisal [Z-I], canine to canine [C-C], and first molar to canine [1M-C] distances). Total area evaluations were performed by aligning the MM and experimental models using the best-fit algorithm and were compared using the Hausdorff distance. The distances between points of interest were measured using the point-picking tool at the same 3D coordinates. The mean volumetric deviations were considered for trueness analysis. Precision was set as the standard deviation. Statistical differences were evaluated using the Student's t-test. **Results:** Total area volumetric comparisons showed that DMs showed superior trueness and precision (-0.02 ± 0.03) compared to the SMs (0.37 ± 0.29) ($P < 0.001$). No differences between the models were observed for Z-I ($P = .155$); however, SMs showed fewer deviations for C-C ($P = .035$) and 1M-C ($P = .001$) than DMs. **Conclusions:** The DMs presented superior trueness and precision for total area compared to the SMs; however, the SMs were more accurate when points of interest were evaluated.

Keywords: Data accuracy. Dental impression technique. Dental models. Esthetics, Dental. Printing, three-dimensional. Technology, dental.



Introduction

Accurate impressions and working models are key factors for the execution of dental procedures. Conventional techniques for dental impressions and models have been successfully performed with elastomeric materials and casted with gypsum for decades. Nevertheless, disadvantages related to the volumetric change of these materials^{1,2}, risk of contamination with oral fluids¹, and requirement of storage space² have been described. With the trend towards digital dentistry, conventional techniques are being progressively replaced by fully digital production processes¹.

Among these, computer-aided design/computer-aided manufacturing (CAD/CAM) allows the fabrication of three-dimensional (3D) digital impressions and models^{1,3}. Advantages of these 3D impressions and models are reduced treatment time, lower probability of human errors, and less discomfort to patients. Additionally, digital models (DMs) not only are easy to replicate, but also allow printing of the model and fabrication of restorations in office^{2,4,5}. Nonetheless, their applicability has been limited because of the cost of related equipment, recurring updates, and the clinicians' learning curve for devices and software^{5,6}. Furthermore, although full digital workflow could be the gold standard in the future, currently it can only be used for CAD/CAM monolithic prosthesis. Physical stone models (SMs) are still imperative for heat press ceramic injection techniques and ceramic adjustments,¹ as well as mock up purposes and fabrication of surgical guide⁷.

Although intraoral scanning accuracy is well established, the resulting 3D printed model has been a major topic of investigation^{2,8}. Different additive manufacturing technologies (AMT), such as fused deposition modeling (FDM), stereolithography apparatus, and selective laser sintering, are available for printing dental models. The major advantages related to material availability and diversity, compact size, and cost-accessibility make FDM the most widely used technology⁹. Additionally, the mean FDM value for layer thickness is approximately 0.254 mm, which is considerably thicker than other AMTs and which favors printing speed⁹. Nevertheless, 3D printed models have applications restricted to study models because of accuracy outcomes and surface properties¹⁰. Hence, studies have been performed to overcome the limitations of FDM and for optimization of its process parameters⁹.

Improvements in FDM printers may increase the application of their printed models for dental purposes. In addition, the possibility of fast-printing cost-accessible models in office could benefit rehabilitations and decrease treatment time. However, the accuracy of FDM models needs to be further explored, even though different levels of accuracies could be required for different dental procedures. The objective of this study was to compare the accuracy (trueness and precision) of cost-accessible DMs and SMs. The null hypothesis tested was that there would be no statistical difference in accuracy between DMs and SMs.

Materials and Methods

The experimental design of this study compared the accuracy (trueness and precision) of DMs and SMs: models' total area analysis and three specified distances of

interest analysis. A two-dimensional digital smile design protocol was performed on PowerPoint (14.0, Microsoft, Redmond, WA, USA) using the photographs of a maxillary typodont model (Pronew, São Gonçalo, Rio de Janeiro, RJ, Brazil) (Figure 1A and 1B). A diagnostic wax-up was fabricated based on the digital smile design measurements (Figure 1C) and the resulting model was considered as the master model (MM).

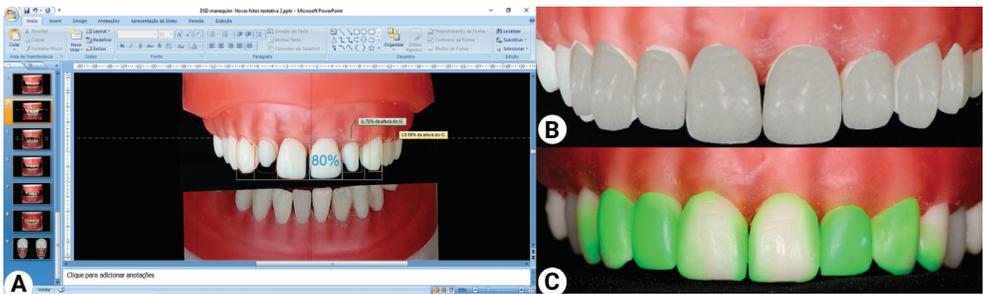


Figure 1. (A) Panoramic view of the PowerPoint software; (B) Digital smile planning; (C) Conventional wax-up based on the DSD (master model)

To obtain the 3D printed models, the MM was scanned (S600 ARTI, Zirkozahn, Gais, Italy), creating a standard tessellation (STL) file. All models were scanned with the same calibrated high-precision scanner ($\leq 10 \mu\text{m}$, S600 ARTI) in this study. The MM STL file was printed 10 times in polylactic acid using an FDM printer (i3 MK3, Prusa, Prague, Czech Republic) (Figure 2A). Initially, the layer height and filament heating temperature of the printing pattern were tested. Layers thinner than 0.3 mm caused strain in the previous layer because of temperature of the material. This effect was minor and deformation was not detected when a 0.3 mm layer was used. Once the layer height was defined, the file was prepared using Fusion 360 (Autodesk, San Rafael, CA, USA) and sliced using MatterControl (version 2.0, MatterHackers, Lake Forest, CA, USA). The slicer software was set at 60 mm/s deposit speed and 185°C filament heat temperature ($\pm 10^\circ\text{C}$ according to room temperature). To promote adequate adhesion and avoid warping, the bed was heated to 50°C. The extruder nozzle diameter was set to 0.4 mm to optimize the printing speed. Polylactic acid was chosen as the material of choice because of its good adhesion with little warp, quality of print, flexural strength, and biodegradability¹¹.

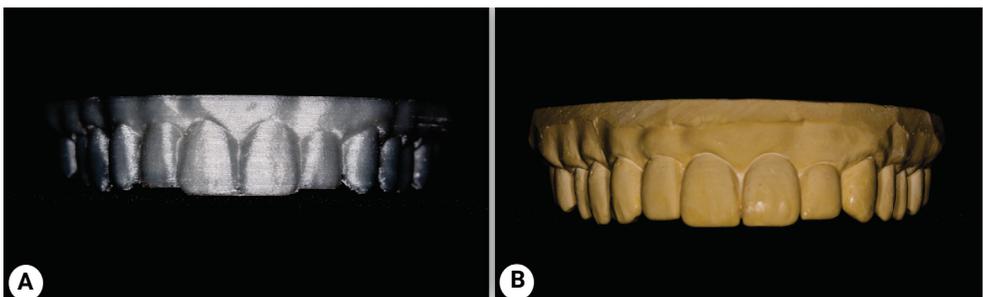


Figure 2. Experimental models. (A) 3D printed model; (B) plaster cast model

Ten single-step light/heavy body polyvinylsiloxane (Adsil, Coltene Vigodent, Rio de Janeiro, RJ, Brazil) impressions were made from the MM and filled with Type IV gypsum (Herostone, Vigodent, Rio de Janeiro, RJ, Brazil) to obtain the SMs models (Figure 2B). The fabrication of SMs followed the polyvinylsiloxane and gypsum manufacturers' recommendations. Neither DMs nor SMs received finishing or polishing.

To evaluate the accuracy of the model, trueness and precision were accessed according to ISO 5725-1:1994¹². Accordingly, trueness was considered as the mean volumetric deviation of the tested models from the MM and precision was set as the standard deviation. The experimental models were scanned using the same dental lab scanner (S600 ARTI), and the STL files were created. These files were then opened and cut using the plane cut tool in MeshMixer software (Autodesk, San Rafael, CA, USA). The parameters of the plane cut at the three axes (x-, y-, and z-axes) were standardized comprising the entire tooth area without the base. Subsequently, the files were exported to the inspection software (CloudCompare, version 2.6.1, GPL software) for analysis. Datasets were obtained from the models' total area and three distances of interest.

The experimental model files were superimposed with the reference MM using the best-fit algorithm (Figure 3) for the total area and compared using the Hausdorff distance. The software computed the distribution parameters and displayed a scalar histogram with a gray curve corresponding to the fit distribution for each comparison. Additionally, the chi-squared test result for fit quality was provided. Fit results were averaged for statistical purposes.

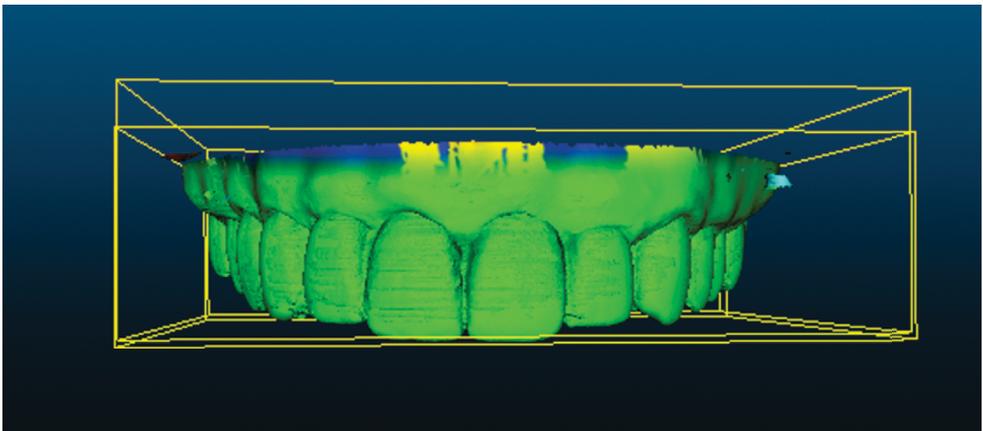


Figure 3. Superimposition of the 3D printed with the master model using best-fit algorithm

All STL datasets were individually imported to CloudCompare for the three specified distances of interest analysis. Each model was aligned at the same coordinate axes and a calibrated operator measured the distances using the software's point-picking tool. The distances evaluated were as follows: zenith to the incisal edge of the maxil-

lary right central incisor (Figure 4A), canine to canine tips (Figure 4B), and distopalatal cusp of right first molar to canine tip (Figure 4C). Divergences in the x-, y-, and z-axes were assessed between each tested model and the reference dataset, and the distances among the values of the three axes were registered for each pair of comparison and then were averaged. Comparisons between the reference and experimental datasets were performed using the Student's t-test at $\alpha = .05$ significance level. The Statistical Package for the Social Sciences 24.0 software (SPSS Inc, Chicago, IL, USA) was used for statistical analysis.

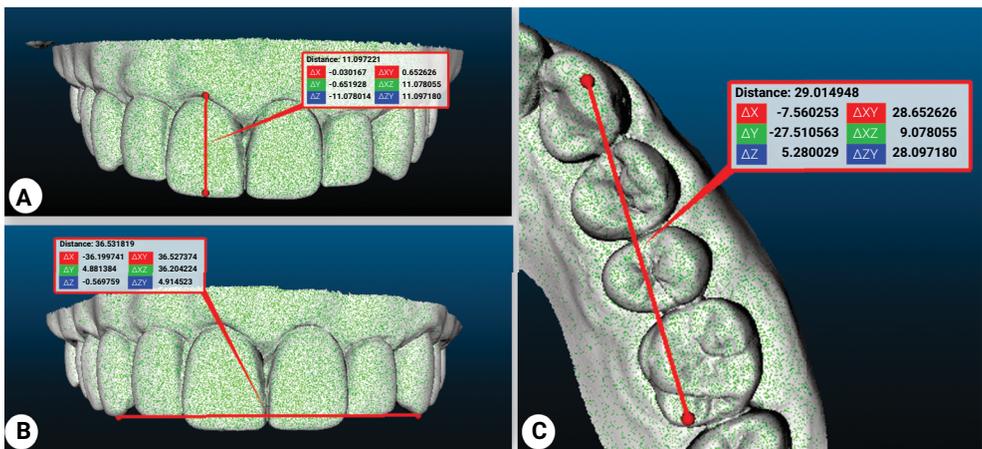


Figure 4. Individual distances of interest. (A) zenith to incisal of the maxillary right central incisor; (B) canine to canine tips; (C) first molar right distopalatal cusp to canine tip

Results

The DMs presented higher trueness and precision for the total area (0.02 ± 0.03 mm) than the SMs (-0.37 ± 0.29 mm) ($P < .001$). Figure 1 shows the fit quality of the experimental models to the reference MM. Hence, the DMs presented a better fit than the SMs (Figure 5).

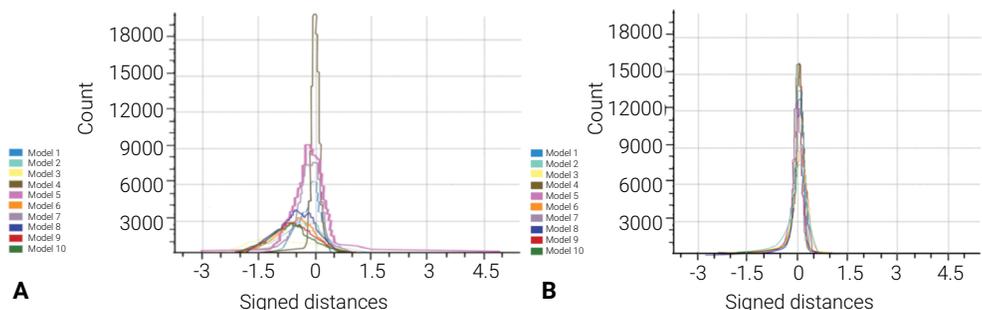


Figure 5. Trueness / Precision of (A) conventional plaster cast and (B) digital printed models compared to the reference dataset (N=10)

Comparisons of the three distances of interest showed no statistically significant difference for the zenith to incisal distance ($P = .155$). However, SMs presented fewer deviations when canine-to-canine ($P = .001$) and distopalatal cusp of right first molar-to-canine tip distances ($P = .035$) were evaluated (Table 1).

Table 1. Mean \pm standard deviation (mm) between the three selected distances of interest (N=10)

Distance of interest	Model			P-value (<0.05)
	Master	3D printed	Stone	
Z-I	11.28	-0.18 \pm 0.10	-0.26 \pm 0.10	0.155
1M-C	29.79	-0.79 \pm 0.46	-0.41 \pm 0.19	0.035
C-C	36.52	-0.79 \pm 0.49	-0.07 \pm 0.16	0.001

Z-I: zenith to the incisal edge of the maxillary right central incisor; 1M-C: distopalatal cusp of right first molar to canine tip; C-C: canine to canine tips.

Discussion

The purpose of this study was to compare the trueness and precision of 3D printed and conventional models by performing two independent analyses of deviation: a best-fit alignment software comparison and an individual operator measurement. The points of interest selected for this study were chosen, taking into consideration their clinical significance and correlation of possible deviations with the printing axis, as follows: zenith to incisal (Z), first molar to canine tip (Y), and canine-to-canine tips (X). Because the total area trueness and precision were higher in the 3D printed models, the null hypothesis was rejected. The literature on the outcomes of 3D printed models is limited, with a trend to attribute them to reasonable accuracy^{1,4,8}. This corroborates our findings with a cost-accessible and user-friendly FDM printer.

Every measurement may include a component of error. In the digital workflow, the error could be attributed to the software, or scanning or printing processes¹³. Scanning precision was not evaluated in this study; however, the same high-precision scanner was used for all data acquisitions. Additionally, digital models are more precise than printouts, regardless of the technology used^{1,4,13}. Based on five previous studies, Brown et al.⁸ (2018) reported a clinically acceptable range of error between 0.2 and 0.5 mm. Therefore, both the groups tested in this study may have resulted in clinically acceptable models when the best-fit methodology was used. This was not observed for the selected distance comparisons. Nonetheless, it is important to note that different dental procedures and specialties require different accuracies, for example, 0.1 mm has been suggested as the maximum threshold for fixed and implant prostheses^{1,2}, while up to 0.3 mm has been acceptable for only diagnostic purposes¹. Therefore, although promising, our results should be interpreted carefully, since quality standards must be clearly defined in further studies. If considered reliable for clinical use, FDM printers may be a relevant alternative because of their user-friendly and low-cost accessibility^{9,14}.

FDM is the most commonly used additive manufacturing technology^{9,10,14}. It calculates each point using analytical geometry and rounds numbers differently for each case. The differences from other printing technologies comprise the level of accuracy and thickness of single layers¹⁵. In this methodology, we printed 0.3-mm layers and all groups presented clinically acceptable accuracy. The total area accuracy was even higher than that of the SMs. This considerably thick layer allowed models to be printed at a considerably higher speed (approximately 2 hours per model). This finding indicates that the FDM tested is a reliable low-cost and fast-printing option that could be incorporated into dental workflows until technologies with better outcomes become more accessible.

Of most concern was that the additive layer deposition pattern of printers affects accuracy and surface finish is limited to layer height¹⁰. Thicker layers may result in discrepancies, especially in the vertical axis. In this study, crown height (zenith to incisal distance) was statistically similar in all the groups. Nevertheless, irregularity on the surface was visible to the naked eye in the printed models, which could have impaired the selection of points of interest, leading to unequal measurements by the operator. In fact, the stair-step effect was seen on the model's surface¹, which could have compromised its smoothness. The discrepancies found in this study could be attributed to the unevenness of the occlusal area², where cusps, tips, and grooves may compromise the pattern of the FDM printer, as shown previously in digital light processing. The created point cloud tag for FDM printouts could bypass the place of deviation so that the final distortion obtained could be lower than the real distortion¹⁵. In addition, the reproducibility of convex shapes seemed to be better in conventional SMs than in the 3D printed models¹.

Reproducibility decreases as the span increases in case of 3D printed models¹. In fact, our results showed higher discrepancies in larger curvature areas, such as intercanine or canine tips to molar cusps, similar to the findings of Koch et al.¹³ (2016). In addition, all experimental models were printed with a regular base since it has been described as accurate, regardless of the printing technology¹⁶. Additionally, contraction of the materials during the construction of layers and further contraction due to residual stress accumulated during the post-curing process may result in distortions¹. Volumetric changes in the impression materials and the resulting models are well established in the literature¹. The volumetric change exhibited by the impression and 3D-printing materials could result in smaller models compared to the MM, corroborating our findings.

The mean error related to the printer considered in this study was up to 0.2 mm. However, other characteristics of FDM printing, such as the calibration of motors and platform inclination, could have hampered the results and should thus be evaluated. Additionally, the influence of the variables surrounding the different 3D printing techniques, such as printer resolution, surface finishing, machine reproducibility⁷, necessity of post-processing¹⁰, and surface smoothness, should be investigated in further studies. Studies evaluating finishing surface methods to increase the accuracy of FDM printer technology are required since surface smoothness has been the ultimate attribute for printing excellence.

The superimposition analysis software for 3D comparisons has been increasingly used in dentistry^{1,2,13,17} with repeated best-fit alignment as a key tool. The use of com-

puter-driven inspection software has been demonstrated to reduce significantly the error margin of deviations. Nevertheless, a calibrated operator manually selecting the locations of interest resulted in lower accurate measurements for both the groups. In this regard, the operator could have selected slightly different points in cups and tips areas, which can be considered as a methodological limitation, yet similar methodology has been validated in a previous study⁸. Additionally, horizontal deviations may occur distally because of standard limitations of intraoral scanners¹. The latter assumption is corroborated by the fact that all the groups presented significant differences in individual horizontal measurements. Further studies using intraoral scanners and inspection software programs must be performed to reassess the discrepancies found in this study. Further studies are recommended to support the development and availability of 3D inspection software programs for the exponentially growing tendency of digital dentistry.

Digital dentistry is a long-term reality that requires a learning curve and accessible and reliable tools. Three-D printing should not only be used as a new technique to perform conventional procedures, but also as a technique that offers new tools to increase creativity and predictability and to develop less invasive and cost-effective treatments¹⁰. Hence, predictable outcomes could be favored with more accurate and reproducible tools. Thus, surface finishing must be considered in procedures where esthetics and fit quality are in high demand. Apart from individual applicability, the printed models investigated in this research can be used for dental procedures until more evidence accumulates, and 3D printing becomes more widespread.

Within the methodological limitations, we conclude that the 3D printed models from the tested FDM printer exhibited superior trueness and precision compared to the conventional SMs for total area comparisons. Nevertheless, conventional SMs showed fewer deviations in individual measurements of convex areas and smoother surfaces of the dental arches. Despite differences in trueness and precision, both SMs and DMs were within the clinically acceptable range, allowing low-cost and accessible FDM printouts to be applied in dental procedures depending on their requirements of accuracy.

Acknowledgments

The authors thank Laboratório CRO for its contribution to the scanning procedures of the models used in this research.

References

1. 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. doi:10.1016/j.jpor.2018.02.002.
2. Rungrojwittayakul O, Kan JY, Shiozaki K, Swamidass RS, Goodacre BJ, Goodacre CJ, et al. Accuracy of 3D Printed Models Created by Two Technologies of Printers with Different Designs of Model Base. *J Prosthodont.* 2020 Feb;29(2):124-128. doi: 10.1111/jopr.13107.

3. Morris RS, Hoye LN, Elnagar MH, Atsawasuwan P, Galang-Boquiren MT, Caplin J, et al. Accuracy of Dental Monitoring 3D digital dental models using photograph and video mode. *Am J Orthod Dentofacial Orthop.* 2019 Sep;156(3):420-8. doi: 10.1016/j.ajodo.2019.02.014.
4. 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):184-90.e12. doi:10.1016/j.prosdent.2015.12.017.
5. Cheng CW, Ye SY, Chien CH, Chen CJ, Papaspyridakos P, Ko CC. Randomized clinical trial of a conventional and a digital workflow for the fabrication of interim crowns: an evaluation of treatment efficiency, fit, and the effect of clinician experience. *J Prosthet Dent.* 2020 Feb 11:S0022-3913(18)31031-X. doi: 10.1016/j.prosdent.2019.08.006.
6. Abduo J, Eiseyoufi M. Accuracy of intraoral scanners: a systematic review of influencing factors. *Eur J Prosthodont Restor Dent.* 2018 Aug 30;26(3):101-21. doi: 10.1922/EJPRD_01752Abduo21.
7. Gjolvold B, Mahmood DJH, Wennerberg A. Accuracy of surgical guides from 2 different desktop 3D printers for computed tomography-guided surgery. *J Prosthet Dent.* 2019;121(3):498-503. doi: 10.1016/j.prosdent.2018.08.009.
8. Brown GB, Currier GF, Kadioglu O, Kierl JP. Accuracy of 3-dimensional printed dental models reconstructed from digital intraoral impressions. *Am J Orthod Dentofacial Orthop.* 2018;154(5):733-9. doi: 10.1016/j.ajodo.2018.06.009.
9. Dev S, Srivastava R. Experimental investigation and optimization of FDM process parameters for material and mechanical strength. *Mater Today Proc.* 2020 ;26(2):1995-9. doi :10.1016/j.matpr.2020.02.435.
10. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. *Br Dent J.* 2015;219(11):521-9. doi: 10.1038/sj.bdj.2015.914.
11. Pei E, Shen J, Watling J. Direct 3D printing of polymers onto textiles: experimental studies and applications. *Rapid Prototyp J.* 2015;21(5):556-71. doi :10.1108/RPJ-09-2014-0126.
12. International organization for standardization. ISO-5725-1. Accuracy (trueness and precision) of measurement methods and results. Part 1: general principles and definitions. 1994.
13. Koch GK, Gallucci GO, Lee SJ. Accuracy in the digital workflow: From data acquisition to the digitally milled cast. *J Prosthet Dent.* 2016 Jun;115(6):749-54. doi: 10.1016/j.prosdent.2015.12.004.
14. Rebong RE, Stewart KT, Utreja A, Ghoneima AA. Accuracy of three-dimensional dental resin models created by fused deposition modeling, stereolithography, and Polyjet prototype technologies: A comparative study. *Angle Orthod.* 2018 May;88(3):363-369. doi: 10.2319/071117-460.1.
15. Taczala J, Czepekowska W, Konieczny B, Sokołowski J, Kozakiewicz M, Szymor P. Comparison of 3D printing MJP and FDM technology in dentistry. *Arch Mater Sci Eng.* 2020;101(1):32.40. doi: 10.5604/01.3001.0013.9504.
16. Camardella LT, de Vasconcellos Vilella O, Breuning H. Accuracy of printed dental models made with 2 prototype technologies and different designs of model bases. *Am J Orthod Dentofacial Orthop.* 2017;151(6):1178-87. doi: 10.1016/j.ajodo.2017.03.012.
17. Muric A, Gokcen Röhlig B, Ongul D, Evlioglu G. Comparing the precision of reproducibility of computer-aided occlusal design to conventional methods. *J Prosthodont Res.* 2019;63(1):110-4. doi: 10.1016/j.jprr.2018.10.002.