

In vitro accuracies of 3D printed models manufactured by two different printing technologies

Purpose

This study aims to compare the accuracies of full-arch models printed by two different 3D printing technologies.

Materials and Methods

A mandibular horseshoe-shaped master model was designed with RapidForm XOR2 software. The master model was printed 10 times with 3D printers using direct light processing (DLP) and PolyJet technology (n=20). The printed models were then scanned with an industrial scanner and saved in STL file. All digital models superimposed with the master model STL file and comparison of the trueness was performed using Geomagic Control 3D analysis software. The precision was calculated by superimposing combinations of the 10 data sets in each group.

Results

The trueness of printed models was 46 µm for the DLP printer and 51 µm for PolyJet printer; however, this difference was not statistically significant (p=0.155). The precision of printed models was 43 µm for the DLP printer and 54 µm for PolyJet printer. DLP printed models were more precise than the PolyJet printed models (p<0.001).

Conclusion

The 3D printing technologies showed significant differences in the trueness of full-arch measurements. Although DLP printed models had better trueness than PolyJet printed models, all of the 3D printed models were clinically acceptable and might be used for the production of fixed restorations.

Keywords: 3D printing, Direct light processing, Polyjet, Trueness, Precision

Introduction

The introduction of dental CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) systems has considerable effects on the fabrication process of dental prostheses. As a result, advanced physical model requirement has been eliminated in most dental applications (1-3). With the recent development of dental scanners, patient's intraoral topography can be transferred to digital environment. There is no need for physical storage, and replication of models is easy and fast (2,4,5).

3D printing has the advantages of fast production, minimum waste of materials, complex geometry production, and multiple product manufacturing (4). 3D printing technology is currently used for the production of fixed prostheses, guides for implant surgery, models for orthodontic as well as maxillofacial surgery planning (2,6-9).

Currently, different techniques and technologies are available for producing dental models with 3D printers. Stereolithography (SLA), direct light processing (DLP), material jetting (PolyJet) 3D printing technologies are commonly used in dentistry (4,10). The DLP technology uses a high power LED,

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a digital projector, and a photopolymer liquid resin to produce objects layer-by-layer. DLP printers can cure the entire surface of the photopolymer resin in a single pass, and this leads to shorter printing times (4,11). The PolyJet technology has a similar mechanism of an inkjet printer, using liquid photopolymers rather than ink. PolyJet printers disperse the photopolymer over the workspace, and cure them with UV light source (6,12).

The accuracy term includes trueness and precision parameters. The deviation of the printed object from its actual dimensions is described as the trueness of a 3D printer (13). Higher trueness means that the dimension of the printed object is similar or equivalent to the reference object (14). On the other hand, the 3D printer's precision defined with the difference between repeated prints (13).

In the field of prosthetics, the accuracy evaluation of 3D printed dental models is limited (12,14,15). Therefore, this study aimed to compare the accuracies of models used for the production of fixed prostheses, printed with DLP and PolyJet printing technologies. The null hypothesis was that there is no statistical difference in the accuracy and trueness of models fabricated with two different 3D printers.

Material and Methods

Study model

An horse-shoe shaped master model simulating the mandibular arch was designed with CAD software (RapidForm XOR2, 3D Systems Inc, USA). Six abutments (10,15 mm height) with a 6° total angle of convergence and 1 mm at circumferential shoulder finish lines, mimicking prepared teeth (right mandibular second molar, right mandibular second premolar, right mandibular canine, left mandibular canine, left mandibular second premolar and left mandibular second molar) were positioned on the arch.

3D printing

The digital master model was then saved in Standard Tessellation Language (STL) file format and was transferred to each of the 3D printers. Ten models were manufactured for each printer by using two different printing technologies; DLP technology (Perfactory Vida, EnvisionTEC Inc., Dearborn, Michigan, US), and PolyJet technology (Objet30 Orthodesk, Stratasys Ltd., Eden Prairie, Minn, and Rehovot, Israel) (Figure 1). DLP printer used E-Model and PolyJet Printer used VeroDentPlus materials while printing. 20 models were printed in total. Corresponding numbers were given to the 10 models in each group. According to the manufacturer's recommendations, printed DLP models were soaked into isopropyl alcohol for post-process and waited 3 minutes for post-cure. The models printed with PolyJet printer were cleaned with a waterjet for 2 minutes and no additional post-cure process was required for PolyJet. The technical data of 3D printers are summarized in Table 1.

Digitization process of the models

An industrial structured blue LED light 3D scanner (ATOS Core 200 5M, GOM GmbH, Braunschweig, Germany), was selected as the reference scanner. According to VDI/VDIE

2634 Part 3 (VDI e.V.; Düsseldorf, Germany) maximum deviations were: 0,002 mm probing error form (Sigma), 0,004 mm probing error (size), 0.007 mm sphere spacing error and 0,008 mm length measurement error. The reference scanner was calibrated and was tested. Then, all printed models were scanned with the reference scanner, and each digital model was saved in STL file format.

3D comparison

Printed models were superimposed over the master model by using the best-fit alignment method of the 3D analysis software (Geomagic Control, 3D Systems, Rock Hill, SC, USA). Same method was used for each sample. A sample size of 15.000 points with a tolerance of 0.001 mm was used in 3D analysis. Root Mean Square (RMS) values were used for the trueness and precision comparisons. Trueness was assessed, in each case, by the superimposition of the master model data over the data sets obtained from the DLP and PolyJet models. Precision was determined by superimposing the combinations of the 10 data sets in each group (45 pairs for each printer technology). Color maps were also used to evaluate the distribution of 3-dimensional deviations which were spread over the complete surface of each printed model. In the color-coded maps, yellow-to-red fields indicated printed models which were larger than master model; and light blue-to-dark blue fields indicated printed models which were smaller than master model (Figure 2).

Statistical analysis

The statistical analysis was done with a significance level of 95% using statistical software (SPSS v20 for Macintosh; IBM Corp., Chicago, IL, USA). According to Kolmogorov–Smirnov test with Lilliefors Significance correction, variances were found to be normally distributed in trueness group ($p=0.194$). Therefore, independent-sample *t*-test was used to analyze trueness values ($p=0.155$). Kolmogorov–Smirnov with Lilliefors adjustment test was conducted for testing normality ($p=0.009$) of the precision group. The normality assumption was not met, therefore, Mann-Whitney U test was used to evaluate the significant differences between groups ($p<0.001$).

Results

Trueness and precision

The mean trueness of DLP printed models was $46\pm 9.86\ \mu\text{m}$, and for PolyJet printed models it was $51\pm 5.11\ \mu\text{m}$ (Figure 3). No significant differences were found between DLP and PolyJet printed models ($p=0.155$) in the comparison of trueness measurements. However, significant differences were found in the precision of the printed models. The mean precision of DLP printed models was $43\pm 13.77\ \mu\text{m}$, and PolyJet printed models was $54\pm 8.65\ \mu\text{m}$ (Figure 3). DLP printed models were significantly more precise than PolyJet printed models. ($p<0.001$).

Color map evaluation

In the color maps, acceptable deviations were set in the range of $\pm 30\ \mu\text{m}$ (green areas) (Figure 3). In the trueness com-

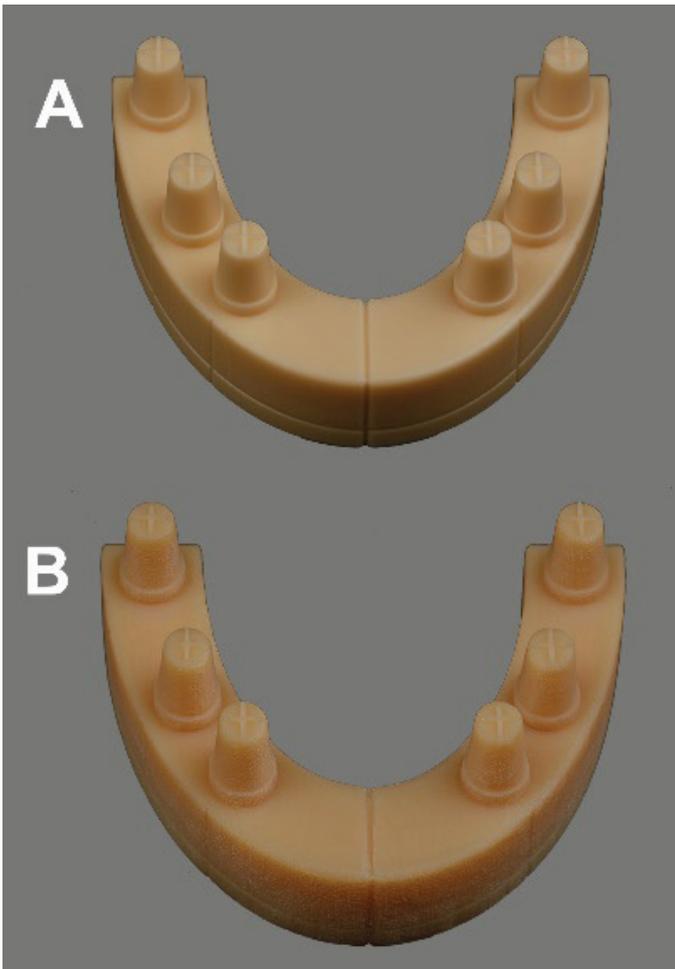


Figure 1. The 3D printed models using DLP technology (A) and PolyJet technology (B).

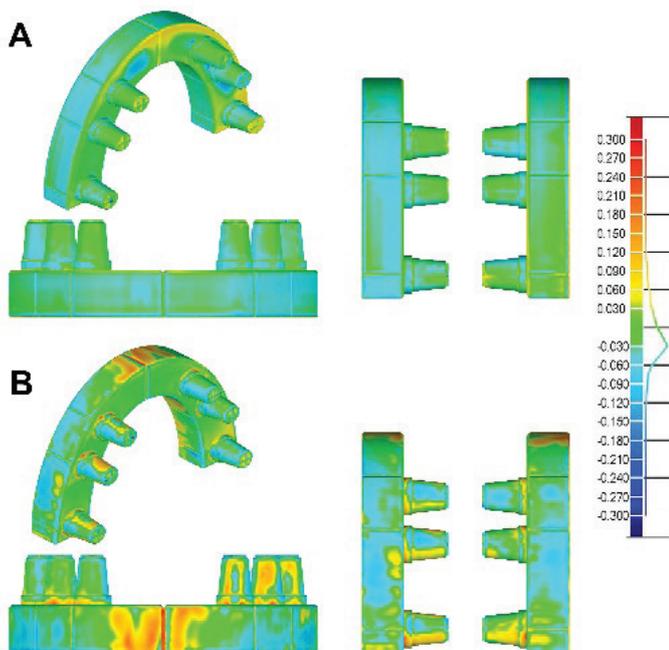


Figure 2. The color maps display the discrepancy between the printed models and the master model. The scale bar ranges from -300 to $300 \mu\text{m}$. Light blue through dark blue color (-30 to $-300 \mu\text{m}$) indicates the printed model is smaller than the master model; green color shows difference $\pm 30 \mu\text{m}$ between printed model and master model; yellow to red color ($+30$ to $+300 \mu\text{m}$) indicates printed model is larger than the master model. A: DLP, B: PolyJet.

parison, DLP printed models displayed a more homogenous pattern of green surfaces than PolyJet printed models. Lingual section of the arch showed a slight contraction. In the posterior region and the buccal of the posterior abutments, a slight expansion was observed on DLP printed models. On the other hand, PolyJet printed models displayed a slight expansion in the midline of the arch. Posterior abutments showed uneven deviations (mostly contraction). In some models, the circumferential expansion was observed in the posterior abutments (Figure 3).

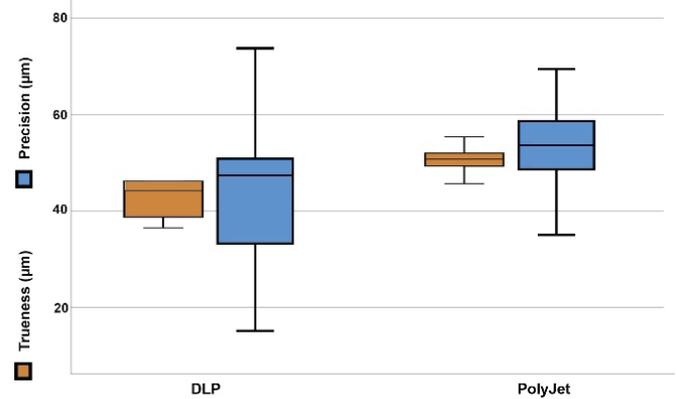


Figure 3. Trueness and precision for DLP and PolyJet models. Orange color presents "trueness" and blue color presents "precision".

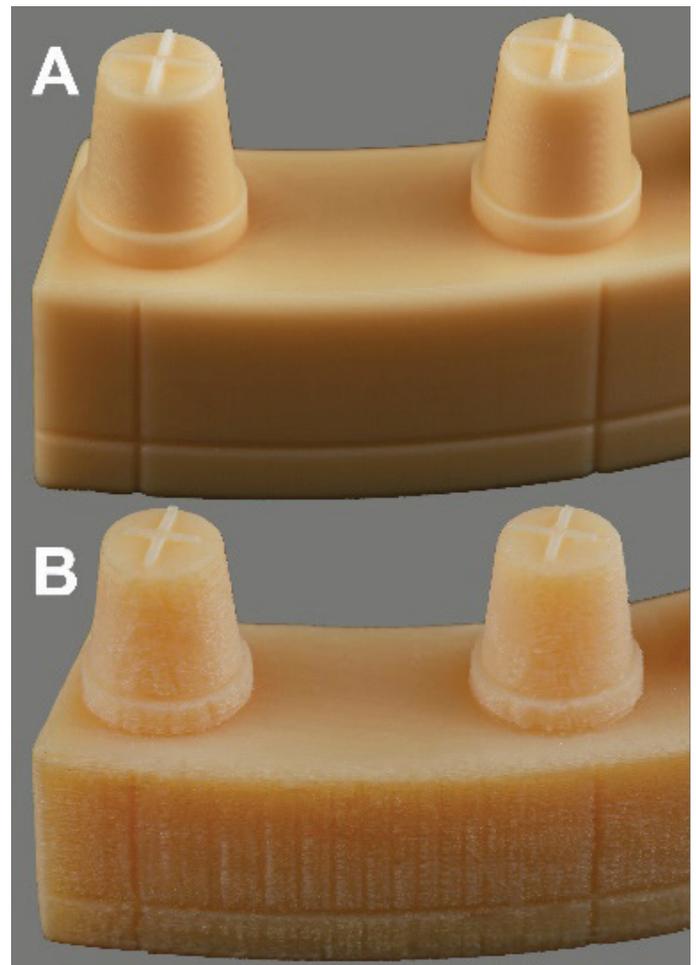


Figure 4. The surface quality of 3D printed models. DLP printer used E-Model material, and PolyJet printer used VeroDentPlus material during the production of the models. DLP model has a smooth surface, and in contrast to DLP, PolyJet model has a rough surface. A: DLP, B: PolyJet.

Table 1. Technical data of tested DLP and PolyJet printers.

Printer	Manufacturer	Technology	Material	Layer Thickness	Resolution (x-,y- and z-axis)
Perfactory Vida	envisionTEC	DLP (Direct light processing)	E-Model	50 µm	X&Y - 73 µm Z - 25 to 150 µm
Objet30 Orthodesk	Stratasys	PolyJet	VeroDentPlus	28 µm	X-axis: 600 dpi Y-axis: 600 dpi Z-axis: 900 dpi

Table 2. Printing time and costs of models manufactured by DLP and PolyJet printers.

Printer	Support Material	Post-cure	Post-process	Printing time	Cost of one model
Perfactory Vida	No need	3 min	2 min (isopropanol alcohol bath)	4 models in 1 hour	\$ 2-9
Objet30 Orthodesk	SUP705	No need	2 min (waterjet)	2 hr, 30 min (one model)	\$ 6,5

Discussion

According to the results of the present study, regarding the trueness and precision of two different printed models, the null hypothesis stating that the DLP printed models had no significant differences than PolyJet printed models was accepted. However, the null hypothesis on the precision variable was rejected.

The accuracy of the physical models might affect the misfit of fixed prostheses, which could lead to larger marginal or internal discrepancies before the prosthesis delivery (3,12). In the literature, the clinically acceptable range for the production of fixed prosthesis varies from 100 to 200 µm (16-18). In this study, the trueness of all printed working models found below 100 µm and therefore they were considered to be acceptable for clinical use.

The layer thickness, building direction, angle, intensity, laser speed, curing process, different printing technologies are influencing factors for the accuracy of printed models (19-23). When compared to previous studies, the present one reveals inconsistencies because the accuracy of reference scanners, printer technology, print materials, the geometry of printed models, printing parameters and analysis methodology used in these studies vary. The accuracy of the scanner also affects the quality of the measurements. The scanner used in this study is an industrial scanner with an accuracy of 2 µm and might not have a significant effect on the results of this study.

In the current study mean RMS trueness values of DLP models were 46 µm and PolyJet models were 51 µm. Precision values were 43 µm for DLP models and 54 µm for PolyJet models. Some authors stated that there was no significant difference between SLA and DLP printers. They used a complete-arch model, and RMS trueness values were 85 µm and 105 µm for SLA and DLP printers, respectively. Furthermore, the precision of SLA printer was 49 µm, and DLP printer was 52 µm (14). The precision of their DLP printer was close to the one used in the present study; however, the trueness of DLP printer in our study was more accurate.

Although the layer thickness was the same as the printer used in this study, photopolymer resin materials and printers' brands were different. These differences might have led to dimensional differences in printed models. According to Jin *et al.*, mean trueness (RMS) of complete-arch SLA models was 114.3 µm, and PolyJet was 124 µm (12). Mean RMS precision values were 59 µm for SLA and 41 µm for PolyJet models. Kim *et al.* found the accuracy of complete-arch models 74 µm for DLP, and 69 µm for PolyJet and 176 µm for SLA printers (24). Besides, PolyJet and DLP models were found to be more precise than SLA. However, the layer thickness and X-Y resolution values of SLA and DLP printers were different from the current study. Dietrich *et al.* found trueness of two complete-arch models for PolyJet as 66 µm and 62 µm, for SLA models as 109 µm and 92 µm (25). Regarding precision, SLA models were found as 20 µm and 23 µm, PolyJet models were found as 46 µm and 38 µm. These values were close to the precision values calculated in this study, and slight differences can occur among different printing materials and technologies. In the current study, DLP models showed better trueness values than the PolyJet models, and the reason for this might be the lower level of photopolymer shrinkage during photocuring. Jin *et al.* stated that more evaporation and contraction may occur on PolyJet models during the printing process (12). According to Rebong *et al.*, expansion and/or shrinking of resin materials may occur during the printing process, and this could explain the trend of dimensional increase and decrease (26).

In our study, the layer thickness of PolyJet models was 28 µm, and DLP models was 50 µm. Although the layer thickness value of PolyJet printer was lower than DLP printer, PolyJet models were not more accurate than DLP models. According to Favero *et al.*, this could be explained by the increased number of layers (20). Higher amounts of layers during the production of objects might increase the potential for errors and artifacts. Besides, Favero *et al.* stated that as the layer thickness decreases, the deviation value increases (20).

Regarding to the color maps, homogeneous green areas were observed in DLP models. The posterior region and the

upper surface of the arch showed a slight expansion. Lingual region of the arch displayed a slight contraction (Figure 2). The lingual region of the arch had a smooth surface, and this causes polymers to contact evenly (4). PolyJet models displayed a localized expansion on the buccal of the arch, especially in the anterior region (Figure 2). The reason for this might be the expansion of the resin material during the printing process. In some models, the contraction was observed in the posterior region and abutments (Figure 2). This shrinkage pattern might be due to the higher photopolymer density in the posterior than the anterior (4).

The cost of one model and printing times varied among different printing technologies (Table 2). Perfactory Vida (DLP) prints four models in 1 hour, and Objet30 Orthodesk (PolyJet) prints one model in 2 hours 30 minutes. DLP printer needs less time to print models because of the high-resolution projector, which cures entire layers at once. Besides, DLP models can be printed with a smooth surface finish. However, the surface quality of PolyJet models was lower than DLP models (Figure 4). PolyJet printer used VeroDentPlus material, and a rougher surface finish was observed. This may be associated with the VeroDentPlus photopolymer material because smooth surface quality can be obtained using other photopolymer resins like VeroClear. In contrast to DLP models, the post-curing process is not necessary for PolyJet models.

In this study, only two different printers and printing materials were compared. Future studies should evaluate different printers, the role of layer thickness, new printing materials, the effect of building angle, and printing parameters to guide clinicians and dental laboratories for selecting appropriate printers.

Conclusion

3D models printed with DLP printer (46 µm) showed better trueness than models printed with Polyjet printer (51 µm), but this difference was not significant. On the other hand, DLP printed models (43 µm) showed better statistical precision of the complete-arch than the PolyJet printed models (54 µm) ($p < .001$). The current study demonstrated that physical working models manufactured with tested 3D printers are within the clinical tolerance, and both DLP and PolyJet printed models are suitable for the production of fixed prostheses.

Türkçe Özet: İki Farklı Baskı Teknolojisi ile Üretilen 3 Boyutlu Modellerin Doğruluğu: In Vitro Üç Boyutlu Değerlendirme. Amaç: Bu çalışma, iki farklı 3 boyutlu baskı teknolojisi ile üretilen tam ark modellerin doğruluğunu karşılaştırmayı amaçlamaktadır. Gereç ve Yöntem: Mandibuler at nalı şeklindeki ana modeller RapidForm XOR2 yazılımı ile tasarlanmış ve tasarlanan ana modeller doğrudan ışık işleme (DLP) ve PolyJet teknolojisi kullanılarak 3 boyutlu yazıcılarla üretilmiştir ($n=20$). Üretilen modeller daha sonra endüstriyel bir tarayıcı ile taranarak STL dosyası şeklinde kaydedilmiştir. Elde edilen tüm dijital modeller, ana model STL dosyası ile üst üste karşılaştırılmış ve doğruluğunun karşılaştırması Geomagic Control 3D analiz yazılımı kullanılarak gerçekleştirilmiştir. Doğruluk, her gruptaki 10 veri seti kombinasyonunun üst üste karşılaştırılması ile hesaplanmıştır. Bulgular: Üretilen modellerin doğruluğu DLP yazıcı için 46 µm ve PolyJet yazıcı için 51 µm olarak bulunmuştur; fakat bu fark istatistiksel olarak anlamlı değildir ($p=0.155$). Üretilen modellerin hassasiyeti DLP yazıcı için 43 µm ve PolyJet yazıcı için 54 µm'dir. DLP yazıcı ile üretilen modeller PolyJet ile üretilen modellere göre daha hassastır ($p < 0.001$). Sonuç: 3

boyutlu baskı teknolojileri, tam ark ölçümlerinin doğruluğunda önemli farklılıklar göstermiştir. DLP ile üretilmiş modellerin PolyJet ile üretilmiş modellere göre doğruluğu daha yüksek olmasına rağmen, tüm 3 boyutlu üretilmiş modeller klinik olarak kabul edilebilirdir ve sabit restorasyonların üretimi için kullanılabilir. Anahtar Kelimeler: 3 Boyutlu baskı, Direkt ışık işleme, Polyjet, Doğruluk, hassasiyet

Ethics Committee Approval: Not required.

Informed Consent: Not required.

Peer-review: Externally peer-reviewed.

Author contributions: FA and SA participated in designing the study. FA and SA participated in generating the data for the study. FA, SA, and GC participated in gathering the data for the study. FA, SA, and GC participated in the analysis of the data. FA and GC wrote the majority of the original draft of the paper. SA participated in writing the paper. All authors have had access to all of the raw data of the study. All authors have reviewed the pertinent raw data on which the results and conclusions of this study are based. All authors approved the final version of this paper. All authors guarantee that all individuals who meet the Journal's authorship criteria are included as authors of this paper.

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