ASDJ
AINSHAMS DENTAL JOURNAL

Print ISSN 1110-7642
Online ISSN 2735-5039

AIN SHAMS DENTAL JOURNAL
Official Publication of Ain Shams Dental School
March 2024 • Vol. 33

Efficacy of two different layer heights on the accuracy of 3-D printed orthodontic models

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Aim: This study aimed to assess the accuracy of the 3D printed model by DLP technology at 50-µm and 100-µm layer height
Materials and Methods: A desktop scanner, R700 desktop scanner (3Shape, Copenhagen, Denmark) was used to scan an orthodontic typo-dent cast. A total number of (20) models were printed using a Digital Light Processing 3D printer and divided into two separate group. The 1st group (n=10) and the 2nd (n=10) groups were printed at 50-µm and 100-µm layer heights respectively. Assessment was performed using the GOM Inspect suite to register both the reference and 3D printed digital models to detect the deviation in both X, Y, and Z axes.
Results: Data were presented as mean and standard deviation values and were tested for normality using Shapiro-Wilk test. Data were non-parametric and were tested using Wilcoxon signed rank test. The significance level was set at $p \leq 0.05$ within all tests. In the molar area, 50-µm layer thickness showed statistically significant difference in the right side when compared with 100-µm. In the premolar region, there was no statistically significant differences between both groups in the right side except for the z-axis. The canine area demonstrated that the 50-µm layer height was statistically significant lower in deviation than 100-µm group in all directions. There was a strong agreement between both observers (ICC=0.965, 95%CI= (0.958:0.971), $p<0.001$).
Conclusion: the results of our research as a whole show that models printed at 50-µm display lower deviations in X, Y, and Z axes with a more consistent distortion pattern when compared to 100-µm models. Besides, the ideal thickness for high precision requirements is 50 µm, whereas 100-µm could be used in printing diagnostic models.

Keywords: Accuracy, Orthodontics, Dental, Models,3Dprinting.

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Introduction

Computer Aided Design, Computer Aided Manufacturing (CAD/CAM) technology has been changing the dental practice in so many ways from patient education to execution of treatment plan.[1,2] Digital dental manufacturing is one part of these advanced technologies with high levels of productivity and accuracy, among which is the 3D printing that has been adopted in dentistry at an increasing rate. Three-dimensional printing is an additive manufacturing process that converts digital models into physical ones through a layer-by-layer deposition.[3] In comparison with other available technologies, additive manufacturing is more effective due to its ability to use readily available supplies and recycle waste material. It also has no requirements for costly tools, molds, punches, scrap, or milling. In addition, this technology possesses the advantages of manufacturing complex structures while reducing the polymerization shrinkage by the gradual curing.[4]

Fabrication of dental models is mostly used in prosthodontics, orthodontics, implant dentistry, and oral and maxillofacial surgery. Dental casts are an integral part of the diagnostic records. They allow examination of teeth and the occlusion, aid in diagnosis, and monitor the treatment outcomes. Nonetheless, 3D printed models also present some limitations. Among these limitations are the inaccuracies and the errors of the printed models that can be introduced by various parameters incorporated in the manufacturing and post-processing procedures.[5]

Currently, there is a wide available array of 3D printing techniques with varying results and outcomes.[6] Vat polymerization types are typically presented with higher accuracy and more convenience to the users. This technology utilizes a source of light to selectively cure or solidify layers of liquid photopolymer resin within a tank to produce physical parts.[7] Digital light processing technique, which depends on a digital light projector as a light source, stands out among the vat polymerization technologies owing to its superior accuracy and faster manufacturing time.[8] A fundamental factor in the accuracy of 3D printing process is the layer height which is the thickness of each layer of a print material extruded, cured, or sintered by a 3D printer.[5] The additive layering technique creates a stair-step effect of the object surface which might result in dimensional deviations and a rough surface. Depending on the thickness of the layer, the object surface is either more or less smooth or detailed.[9] Moreover, the layer height may have impact on the mechanical properties of the printed object.[5] It is reported by several studies that the smallest layer height exhibited the highest accuracy.[10-11] Meanwhile, other authors found that the differences between the various layer heights are of no statistical significance.[12-13] The present study aimed to assess the accuracy of the 3D printed model by DLP technology at 50-µm and 100-µm layer height in comparison to the scanned reference model demonstrating the pattern of deviation in the X, Y, and Z axes.

Materials and methods

Sample selection and preparation

The study was designed as a comparative in-vitro study between two groups:

- The 50-µm layer height group.
- The 100-µm layer height group.

The outcome was to "*assess the 3-dimensional deviations of the test groups from the master model*" in the three directions X, Y, Z. The study had an exemption from the Research Ethics Committee of the Faculty of Dentistry, Ain shams University (Rec EM022313). Sample size (n) was a total of (20) samples i.e. (10) for each group. Sample size calculation was performed using G power version 3.1.9.2 based on a previous study by Hazeveld et al. 2014[14] and by adopting an alpha of 0.05 (5%) and a beta of 0.95 (95%). The predicted sample size n= (8) for each group.

An orthodontic typo-dent cast was obtained from Orthodontics department, Faculty of Dentistry, Ain Shams university. The typo-dent was selected to have a full permanent dentition with complete intact surfaces (no plaster voids or teeth fractures). It was also free from dental crowding, mal-aligned teeth, or any other anomalies (Figure 1.a).

Using a R700 desktop scanner (3Shape, Copenhagen, Denmark), the typo-dent was 3D scanned to produce a digital representation of the cast in the form of Standard Tessellation Language (STL) format. The file was then optimized for 3D-printing by cropping gingival and typo-dent base areas. After the optimization of typo-dent scan, the STL file was transferred to 3D slicer software Netfabb (Autodesk, California, USA) for adjustment and alignment before printing. Dent2-3D printer (Mogassam, Cairo, Egypt) was used to print all the twenty models. Each model was printed in a separate print job. The ready-to-print files were transferred to the 3D printer and then the tank was filled with peach NextDent Model 2.0 (NextDent, Soesterberg, Netherlands) as dental cast printing resin. The bases of all printed casts were filled to be solid. The occlusal surfaces were adjusted to be facing downward while the bases were facing upward towards the printing platform where print supports were attached to the solid bases (Figure 1.b). The models were tilted to have a 45° angle between the base and the print platform.

After finishing the manufacturing procedure, the specimens were carefully detached from the build platform using a spatula and the supports were removed from the bases of the models. Subsequently, the de

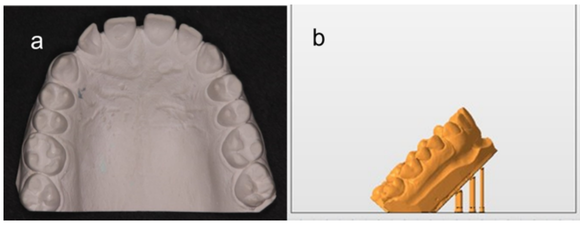
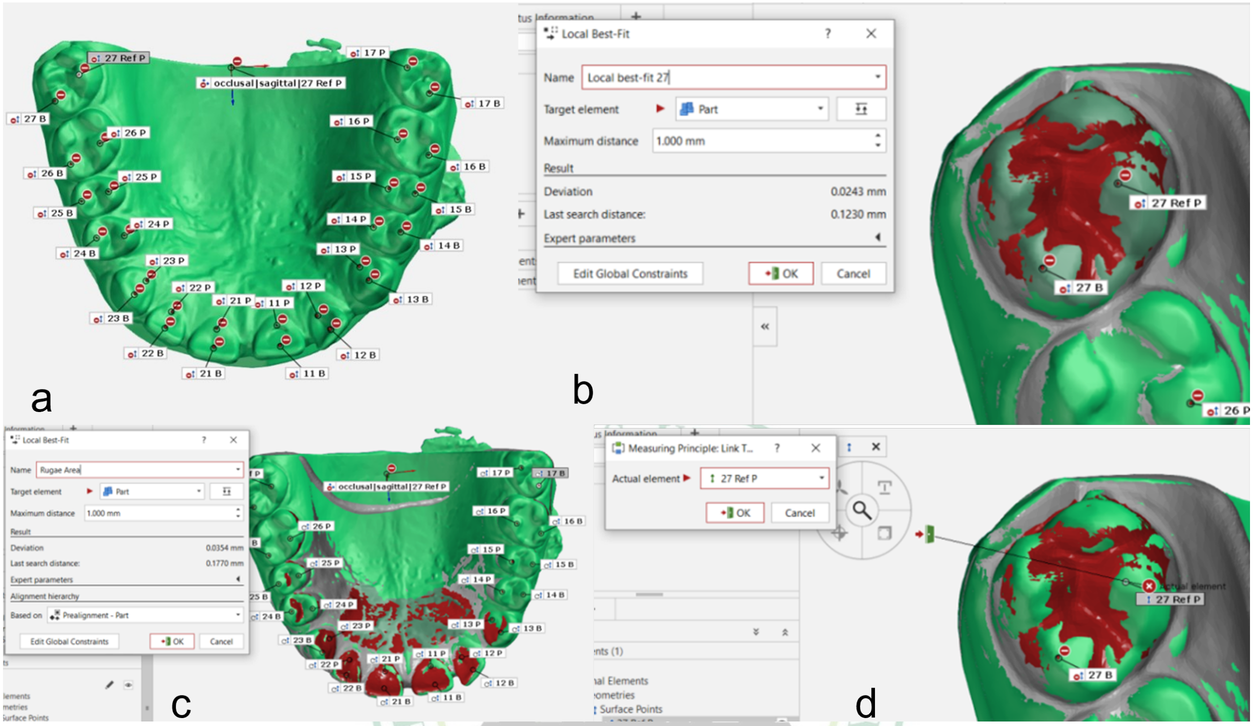


Figure 1: Typodent model. a. Typo-dent cast selected as the reference model for the study. b. The print object showing the print supports attached to the model base.

novo printed specimens were fully submerged in an ultrasonic bath (TriClean Ultrasonic Cleaner U-10LHREC; BrandMax, Alpharetta, GA) with 99% isopropyl alcohol (IPA) (Isopropyl alcohol 99%; Cumberland Swan, Smyrna, TN) for 3 minutes, followed by a second ultrasonic bath with clean 99% IPA solvent for 2 minutes. Afterwards, specimens were rinsed with water and positioned in a paper towel for drying. Specimens were then polymerized in the UV-polymerization machine (PCA-100; Envisiontec) for 2 minutes. All the specimens were numbered from 1 to 10 in each group, and then stored in a black container until scanning for measurements was completed. The samples were blinded and randomized for the operator with the help of an external investigator who was involved in the 3D printing process and was not involved in the assessment procedure. The 20 models were encoded and given alphabetical letters from (A-T) and were known only by the external investigator. After the assessment was performed the outcome assessors came across the alphabetical order of the model. The whole abovementioned procedure was applied for both the 50-µm and the 100-µm groups. Using the same desktop scanner, all the printed models from both groups were scanned at an interval one week after printing. The exported STL files were named after the same letter of the correspondent printed model.

All the STLs were imported into the GOM Inspect suite 2019 software (GOM



GmbH, Braunschweig, Germany) for data evaluation. The master models were imported as CAD bodies and became the nominal elements. Two measurement points were selected as nominal points on the surface of each tooth from the maxillary right second molar up to the maxillary left second molar. The two points were selected to be one on the tip of the mesio-buccal cusp and one on the tip of mesio-palatal cusp on the molars. In the premolars, the two points were selected to be one on the tip of the buccal cusp and one on tip of the palatal cusp. In the anterior teeth, one point was marked on the cingulum ridge, and the other one was selected on the middle of the incisal edge. As a result, a total of 28 points were obtained as nominal points. Then, all the scans of the printed models were imported as actual elements and acting as a mesh model. (Figure 2.a).

After full-surface initial alignment, 15 main alignments were performed by a local best-fit algorithm, where each tooth was selected one by one and drag lines created around it (Figure 2. b). The final best-fit alignment was performed on the rugae area (Figure 2.c). During each local best fit, the two measurement points were copied to the actual element to form the actual points, then the nominal and the actual points were linked together (Figure 2.d). After linking all of the 28 actual points with the nominal points, the best-fit alignment of the rugae area was used as the main and last one.

Deviations of the actual element points from the identical nominal ones were measured in the software in millimeters (mm) in axes X, Y, and Z. The X-axis represented any deviation in left-right; Bucco-palatal direction in the posterior teeth and mesio-distal direction in the anterior teeth. The positive value represents the deviation to the right and vice versa. The Y-axis represented any deviation in the antero-posterior direction; mesio-distal direction in the posterior teeth and bucco-palatal direction in the anterior teeth. The positive value represented the anterior deviation and vice versa. The Z-axis represented any deviation on the sagittal plane perpendicular to the occlusal plane (i.e., apico-coronal direction), where a positive value represented deviation in the coronal directions and a negative value represented a deviation in the apical direction.

Calibration on the method of assessment was done by two observers: an oral and maxillofacial radiologist (more than 5 years' experience) and a prosthodontist (more than 5 years' experience) with a time interval of one week between the two assessments. Intra-examiner reliability was checked by reevaluation 30 % of the scans. A standardized mean of assessment was used throughout the study for all models in the group of 50 µm layer height and 100 µm layer height.

Prior to the initiation of the measurements, the principal investigator underwent calibration sessions together with the supervisor who is experienced with the use of GOM Inspect software (GOM GmbH).

Statistical analysis

Numerical data were presented as mean and standard deviation values and were tested for normality using Shapiro-Wilk test. Data were non-parametric and were tested using Wilcoxon signed rank test. The significance level was set at $p \leq 0.05$ within all tests. Statistical analysis was performed with R statistical analysis software version 4.1.3 for Windows [R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Inter-examiner reliability was measured using intra-class correlation coefficient (ICC).

Results

In the molar area, models printed at 50-µm layer thickness showed less deviation in the right side in the Z axis and in Y axis when compared with 100-µm layer height setting with statistically significant difference between them. Meanwhile, there was no statistically significant difference between both groups in X direction. In the left side, the findings demonstrated that the deviations in the Z axis showed statistically insignificant differences between 50-µm and 100-µm layer heights. Regarding the X and Y axes, the models printed at 100 µm layer height showed statistically significant higher deviations when compared with the 50-µm group (Table 1).

Table 1: Intergroup comparisons of deviations in the molar area

Tooth	Direction	Deviations (mm) (Mean±SD)		p-value
		50µm	100µm	
Right	X	0.03±0.04	0.03±0.01	0.915 ns
	Y	0.01±0.04	0.04±0.03	0.02*
	Z	0.05±0.07	-0.11±0.05	<0.001*
Left	X	0.02±0.04	-0.03±0.01	<0.001*
	Y	0.01±0.04	0.04±0.02	<0.001*
	Z	0.08±0.13	0.07±0.05	0.434ns

***; significant ($p \leq 0.05$) ns; non-significant ($p>0.05$)**

In the premolar region, there was no statistically significant differences between both groups in the right side except for the z-axis where the models in 50-µm group were presented with lower deviation value (0.05±0.06 mm). In the left side, that the deviations in the Z axis showed statistically insignificant differences between 50-µm and 100-µm layer heights. Meanwhile, the models printed at 100 µm layer height showed statistically significant lower deviations in X axis when compared with the

50-µm group. In the Y-axis, models in the 50-µm were presented with statistically significant lower deviations (Table 2).

Table (2): Intergroup comparisons of deviations in the premolar area

Tooth	Direction	Deviations (mm) (Mean±SD)		p-value
		50µm	100µm	
Right	X	0.01±0.04	-0.01±0.03	0.117ns
	Y	0.02±0.04	0.03±0.02	0.460ns
	Z	0.05±0.06	-0.11±0.05	<0.001*
Left	X	0.03±0.03	-0.01±0.03	<0.001*
	Y	0.01±0.04	0.04±0.02	0.002*
	Z	0.04±0.08	0.06±0.05	0.050ns

***; significant (p ≤ 0.05) ns; non-significant (p>0.05)**

The presented results of the canine area demonstrated that the 50-µm layer height was statistically significant lower in deviation than 100-µm group in all directions. Exceptionally, in the Y-axis, the models printed at 100-µm showed lower deviation values (Table 3).

Table (3): Intergroup comparisons of deviations in the canine area

Tooth	Direction	Deviations (mm) (Mean±SD)		p-value
		50µm	100µm	
Right	X	0.01±0.04	-0.02±0.03	0.006*
	Y	0.04±0.03	0.00±0.02	<0.001*
	Z	0.08±0.04	-0.09±0.01	<0.001*
Left	X	0.04±0.03	-0.02±0.03	<0.001*
	Y	0.01±0.04	0.02±0.01	0.172ns
	Z	0.05±0.05	0.08±0.02	0.031*

***; significant (p ≤ 0.05) ns; non-significant (p>0.05)**

In the incisors area, the 50-µm layer height group in the right side tended to show higher deviations in the X and Y axes with statistically significant difference than the models printed with 100 µm layer thicknesses. In contrast, there was no statistically significant difference between both groups in the Z axis. In the left side, the deviation in the X axis tends to be statistically significant lower in the 100 µm group, while in the Y and Z axes; there weren't any statistically significant differences between both groups (Table 4). Inter-examiner reliability was measured using intra-class correlation coefficient (ICC). There was a strong agreement between both observers that was statistically significant (ICC=0.965, 95%CI= (0.958:0.971), p<0.001).

Table (4): Intergroup comparisons of deviations in the incisor area

Tooth	Direction	Deviations (mm) (Mean±SD)		p-value
		50µm	100µm	
Right	X	0.03±0.03	-0.02±0.04	<0.001*
	Y	0.03±0.04	0.00±0.02	<0.001*
	Z	0.04±0.05	0.02±0.05	0.076 ns
Left	X	0.05±0.03	-0.03±0.02	<0.001*
	Y	0.03±0.04	0.03±0.02	0.333ns
	Z	0.06±0.06	0.07±0.02	0.481ns

***; significant (p ≤ 0.05) ns; non-significant (p>0.05)**

Discussion

Three-dimensional printing has been massively introduced in the dental industry.[15] Additionally, differences in printer types depend on specialized engineering, optics, materials chemistry, and design. In 2020, a systematic review by Etemad-Shahidi[5] revealed that several SLA and DLP 3D printers were employed throughout literature. Depending on the commercial kind of the printer independent of the type of technology, variations of the accuracy ranged from 3 µm to 579 µm for SLA and from 16 µm to 446 µm for DLP. In the present study, Dent2-3D printer was investigated as no data is available in the literature regarding its accuracy despite its popular use recently in Egypt. Layer height is only one of several variables that greatly influence how accurate printed models are. The amount of smoothness or detail of an object's surface depends on the layer's thickness which may adversely affect the dimensional stability.[9-16] The study aimed to assess the accuracy of the 3D printed model at 50-µm and 100-µm layer height in comparison with the master model. In the current study, accuracy was defined as accurately reproducing the outside surface of the original digital file. Any additional deviation from this surface was deemed progressively incorrect, taking both positive and negative values into account. The deviations of certain places on the scanned printed models were measured in the X, Y, and Z axes in respect to the scanned master model using 3D meteorology software.

The abovementioned assessment tool provided better level of precision when compared to direct linear measurements on the physical model. This was caused by the small number of measuring points when compared to a whole arch's point estimation for 3D superimposition. Furthermore, there is a significant chance of propensity since physical linear measurements may include human error.[5] Besides, the use of highly accurate desktop scanners in the current study minimizes the risk of bias and produces precise digital representations,[17,18] when used in combination with 3D superimposition. To guarantee uniformity throughout the investigation, the same scanner was used to scan each of the printed models. Moreover, the 3D deviations of numerous places across the arch reflect more information regarding the expansion or contraction of every portion of the model.[20]

The Gom Inspect program uses potent algorithms that are frequently used in the field of industrial production to perform a 3D quantitative evaluation of the agreement between the test and reference file.[9] The use of this software in dentistry is, however, somewhat restricted, and the accuracy of printed dental models is mostly assessed by human linear distance measurements.[20] According to Vág et al in 2019,[21] 3D superimposition analysis utilizing Gom Inspect is more dependable and effective than conventional hand measures. Since then, a number of investigations have been carried out using the Gom Inspect program for point deviation analysis and 3D superimposition. These investigations with a high degree of repeatability have suggested their usage.[22-24]

In the present study, all the parameters that may affect accuracy of the printed models were optimized according to the literature.[(5,25-27)] This optimization and standardization throughout the study allowed meaningful investigation of the effect of the different layer heights on the accuracy of additively manufactured models. Amongst is the use of completely intact model base. The cross-arch stabilizing plate construction and the use of the solid filling pattern is essential for creating a high-accuracy dental model, according to Shin et al.[25] the models were also 45° slanted from the base to the printing platform. According to the state of the research at the time, these printing parameters should result in the most accurate printed models.[26] After the printing process, the models were scanned a week later according to Joda et al.[27] who suggested that the dental models should not be utilized more than 3 weeks after 3D printing.

During the 3D analysis on the meteorology software, caution was taken to negate the minor errors that may arise during the alignment of the scanned printed models and the scanned master one. Therefore, two alignment methods were applied: initial alignment, and local best-fit alignment on the rugae area. Local best-fit of every tooth surface between the printed and the master models was applied to accurately reproduce the intended points for measurements from the nominal cast (master) to the actual cast (3D printed).[28] The local best-fit of the rugae area was selected to be the main one as it is a fixed and prominent anatomical landmark and almost present in the middle of the model.[29] At the same time, it is not included in the areas that were investigated for deviation measurement.

The results of our study indicated the overall superiority of the 50-µm layer thickness over the 100 µm in terms of accuracy that was presented in the z-axis. These results were aligned with the general understanding of 3D printing, where the accuracy of DLP technology increased when layer thickness was reduced from 100 to 50 µm. The DLP technique operates on the premise that resin is light-cured layer by layer. The number of distinct points and triangles creating the STL printable object is determined by the layer thickness. The print will be more precise with reducing layer thickness since a thinner layer will provide more distinct points and triangles, resulting in a smoother, more detailed surface. The overall accuracy is influenced because a thicker layer, which in contrast, has fewer distinct points and greater distances between them, creating a clear stair-stepping effect at the edge.[5]

The deviation of the models printed by 50-µm setting was more consistent throughout all regions in the z axis and they were all in the coronal direction. On the contrary, the 100-µm printed models were less consistent and represented with apical deviation in the right side and coronal deviation the other side. Based on this irregular deviation pattern of the 100-µm, it can be inferred that the higher the layer thickness, the more unpredictable dimensional changes. This form of dimensional changes hasn't been addressed before in the literature even in the studies utilizing 3D superimposition. The assessment approach in the previous studies depended on the overall deviation of the additively manufactured casts without delineating the deviations in the different regions of the models.[5]

Throughout the literature, Z axis is anticipated to be the mostly affected axis when changes are applied to the layer height.[5-10-11-13] However, in the present study, deviations in X and Y directions were also detected while changing the layer height. Similar to the dimensional changes in the Z axis, 50-µm layer thickness was presented with more consistent deviations in X and Y axes.

Regarding the superiority of 50 µm, the findings of our study were consistent with those of Zhang et al. in 2019.[10] However, their results were presented in the form of overall deviation without indicating what is going on in X, Y, and Z axes. Their average absolute deviations at 50µm layer height were 0.023, 0.026, and 0.032mm for the three DLP printers studied, which were smaller than the extent of deviations presented in the current study. Although these outcomes indicate superior performance of the printers used by Zhang et al, the results of the DLP printer utilized in the present study were still within the clinical acceptable range of error. Similarly, the printed models at 100-µm layer height showed better overall accuracy in Zhang et al than the ones in our presented study.

Different results were attained by Sherman et al. in 2020[12] who studied the efficacy and accuracy of a DLP printer for clinical purposes when utilized with various settings and modifications. They found that there was no statistically significant difference between layer thicknesses of 50 µm and 100 µm. Moreover, Sabbah et al. in 2021[13] performed a study using DLP technology. In their study, there was no statistically significant difference between the three distinct layer heights of 25 µm, 50 µm, and 100 µm. Our findings did not match with those of Sabbah et al. in 2021, and this can be ascribed to the different approaches in assessing deviation.

Our findings were consistent with a study by Ko et al. in 2021[11] who examined the interaction between the build angle and the layer thickness. The deviations were ranging from 0.08 to 0.09 mm at 50 µm and were approximately 0.1 µm at 100 µm layer height. These deviation readings at 50-µm layer thickness were slightly greater than ours. This can be due to the fact that 45° was used in our study even though it wasn't one of the analyzed angles in Ko et al study.

Despite using different technology, similar results were obtained by Loflin et al in 2019[29] who investigated the SLA 3D printer. They demonstrated the greater precision of models printed at 50-µm layer height. However, they emphasized how the differences in layer thicknesses used in SLA-3D printing are not clinically significant.

The time spent by the printer to finish the printing job was also reported in the present study. At 50 µm layer height, the printer took 5 hours and 11 minutes to complete the order. On the other side, only 2 hours and 30 minutes were spent to print the model at 100 µm layer thickness. These results are in accordance with Zhang et al in 2019[10] who reported that the printing job of maxillary casts using DLP technology may take between 2 hours and 51 minutes and up to 4 hours when printed at 50-µm layer thickness. In contrast, our 3D printer only took 1 hour and 22 minutes to print the maxillary model by using a layer height of 100 µm. Similarly, Sabbah et al in 2021[13] demonstrated that the printing time is decreased by increasing the layer height.

Regarding the clinically acceptable accuracy of printed models for orthodontic purposes, there is no agreement. The linear distance deviation within 0.2 mm of a study model can be regarded as acceptable in accordance with the American Board of Orthodontics Objective Grading System (ABO OGS) standard, but it might not be accurate enough to produce orthodontic appliances.[10] As a primary application of 3D printed models in orthodontics; clear aligners mandate a minimum 0.1-mm tooth movement in each step. A deviation of 0.05 mm in the printed object is considered adequate in this respect.

Basically, layer thickness should be determined while taking accuracy, cost, time, and other considerations into account, as well as the unique needs of the intended applications. For high efficiency, printing study models with relatively moderate printing accuracy and reasonable printing time could be performed with a layer thickness setting of 100 µm. To achieve high printing accuracy, a layer thickness of 50 µm should be selected. However, some limitations were encountered in the current study including the evaluation of only one printing parameter (Layer Height) and the registration method utilized could only be applied to maxillary models, as the hard palate was used as the main registration area.

Conclusion

Within the limitations of the study and the type and the parameters of the DLP printer used, the findings of the present study indicated that models printed at 50 µm showed lower deviations in X, Y, and Z axes with more consistent pattern of deviation when compared with 100-µm models. However, the use of high-resolution settings increases the 3D printing duration significantly and thus violating the modern trends towards faster treatment protocols.

Competing interests

The authors declare they have no conflict of interest.

Funding

No funding is subjected to the research reported in this manuscript.

Ethics approval

Ethical approval was granted by the local Ethics Committee of Ain-Shams University, Faculty of Dentistry (FDASU-Rec EM022313) in view of the in-vitro nature of the study.

Informed consent

For this type of study, formal consent is not required.

Availability of data and materials

All data included in this study are available from the corresponding author upon request.

Authors' contributions

KS: conceived and performed the experiments, collected the data, interpreted the results, and wrote the manuscript. MA: revised the manuscript and interpreted the results. TA: revised the manuscript. SMA: contributed to collecting the data, involved in the experiment, reviewed and edited the manuscript. SAE: designed the experiments, interpreted the results, and contributed to writing the manuscript.

Acknowledgments

We would like to express our gratitude to Dr. Bassam Abou el Noor (BDS, MSc., DDS) for his assistance with the statistical analysis of this study.

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