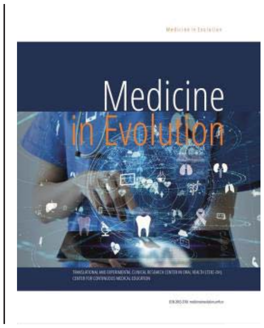
# Quantitative three-dimensional analysis of dental diagnostic models obtained by two additive manufacturing techniques

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## Abstract

Aim and objectives: Due to the low tensile strength of gypsum that causes susceptibility to fracture of dental diagnostic plaster casts, long-term storage of these models may become problematic and inconvenient for dental healthcare practitioners. The purpose of this study is to investigate the possibility of 3D printing these models, by testing the accuracy of dental diagnostic models produced by two additive manufacturing techniques. Material and methods: For this purpose, 20 conventional plaster models from randomly chosen subjects were selected and served as reference. The casts were digitized using a 3D scanner and virtual models were adjusted for 3D printing. The virtual models were reconstructed by using a material jetting (MJ) and reversed-stereolithography (SLA) 3D printer. The reconstructed models were digitized using a laboratory 3D scanner and the resulting mesh datasets were compared with the virtual models by using dedicated inspection software. Results: The trueness of printed models was 67.8 µm for the MJ printer and 86.7 µm for SLA printer, even though this difference was statistically significant ($p > 0.05$), all of the 3D printed models were clinically acceptable.

**Keywords:** 3D printing, SLA, material jetting, dental model

## INTRODUCTION

In the field of dental medicine, plaster study- and working casts are used to provide a three-dimensional perspective of patients' dental arches and to allow the dental healthcare providers to analyze, diagnose, monitor and treat possible abnormalities.1 The necessity of long-term preservation of this type of patient related information is mandatory in many countries and regulated by legislative authority through the means of clinical practice guidelines and ethics codes.

Nonetheless, due to the low tensile strength of gypsum that causes susceptibility to fracture of plaster casts, along with the reduced abrasion resistance of the gypsum1,2 and the relatively large space required for archival of plaster models3, long-term storage of dental models may become problematic and inconvenient for dental healthcare practitioners4. A solution to solve these inconveniences is to digitalize the plaster models, store them in a virtual environment, and obtain physical copies of these models, if needed, through additive manufacturing systems.5–7 Through this state-of-the-art technology, dental models can be obtained without the use of conventional material by means of direct intraoral data capturing via an optical device.8 Digital dental models provide accuracy similar to conventional dental casts9 and can be successfully used for manufacturing dental restorations10 and orthodontic measurements.11 Through this method of production, models can be obtained via subtractive manufacturing in the form of CAD/CAM milling, which is relatively time consuming and wasteful, and additive manufacturing which tends to be main choice, due to the diversity of 3D printing techniques which exist and the low initial cost of such machines.12

Although digital models can be successfully used,13,14 conventional casts are still preferred when dealing with complex cases, when multiple materials are combined to create a restoration such as porcelain fused to metal, over-press crowns or bridges, or implant-based restorations. Furthermore, the production cost of printed models is prohibitively expensive when compared with plaster models, because of the high initial price of the printer and materials and also operating costs. 15 Low cost alternatives to professional 3D printers may represent an approach for the implementation of additive manufactured models, given the fact that numerous companies are creating dedicated materials for this application.

### *Aim and objectives*

Studies which validate the accuracy of 3D models generated with low-cost 3D printers are sparse and mainly focus on a single additive manufacturing process,16 henceforth the purpose of this study is to investigate the accuracy of dental models produced by two additive manufacturing techniques using a professional 3D printer and entry-level alternative. The null hypothesis for this study was that there are no statistically significant differences between the reconstructed models manufactured with the two 3D printers included in this study.

## MATERIALS AND METHODS

A monocentric study was designed and conducted on 20 conventional diagnostic casts belonging to 10 randomly chosen pseudo-anonymized patients. The exclusion criteria for the selection of the conventional casts were: (1) models which represented edentulous or partially edentulous ridges, (2) casts which contained fissures, fractures or air bubbles on the surface of the model, (3) casts with removable dies. The chosen models replicated dental arches with different dental pathologies, including dental anomalies with or without loss of substance and a variety of malocclusions (Figure 1). The conventional casts were digitized with a laboratory 3D optical scanner (In-Eos, Sirona Gmbh, Bensheim, Germany), which scans the surfaces of a single arch at a time, by using blue light optical scanning.

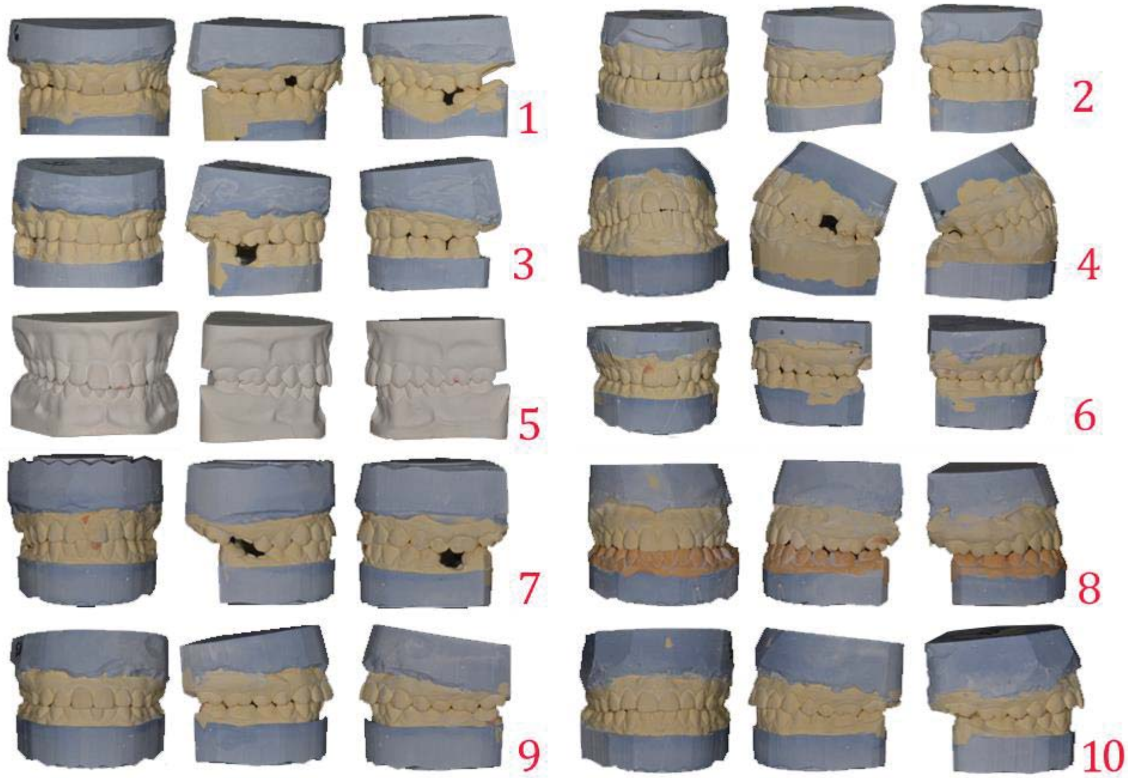


Figure 1. The 10 pairs of dental models used as a reference in this study

The resulting high-resolution point-cloud models were converted to standard tessellation library (.STL) models through the use of the Inlab SW15 (Sirona Gmbh, Bensheim, Germany) computer-aided design software and the resulting mesh models were adjusted further for additive manufacturing reconstruction by using the same dedicated software. In order to ensure a similar configuration, the virtual models were generated as solid models with a flat base.

These digital models will be used to manufacture the 3D printed models and will also serve as reference (REF dataset) when performing the 3D accuracy evaluation by digital superimposition.

The digital reference models were 3D printed by using a reversed-stereolithography printer (Form 3B+, Formlabs Gmbh, Berlin, Germany) and a material jetting printer (Objet 30 Dental Prime, Stratasys LTD, Rehovot, Israel).

In order to manufacture the models through reversed-stereolithography (SLA), the proprietary printing software called PreForm was used to import and orient the digital models flat on the printer platform, as well as to generate the printing strategy. Model V3 resin (Formlabs Gmbh, Berlin, Germany) was used to print the models at a layer thickness of 50 µm. Due to the relatively small size of the build plate, the models were printed flat on the build plate in 3 different batches, by using the same batch of resin, in order to avoid any dimensional error induced by the orientation of the models or by the required support. After printing was completed, post processing was performed by removing the supports, cleaning the excess resin with isopropyl alcohol by using a FormWash automated washing station (Formlabs Gmbh, Berlin, Germany) and a 30-minute exposure per model to UV in a FormCure automated post-curing chamber (Formlabs Gmbh, Berlin, Germany).

The models produced via material jetting (MJ) were manufactured by using a Objet 30 Dental Prime (Stratasys LTD, Rehovot, Israel) 3D printer. This printer has a resolution of 600 dpi on the X and Y axis dpi and 1600 dpi on the Z axis, combined with a layer thickness of 16 µm. We used the Draft mode to manufacture the models, using the Objet Studio software (Objet Geometries Ltd, Rehovot, Israel) to prepare the digital models for printing. This printing mode was chosen because the 36 µm resolution is the most similar setting to the layer height of the reversed-SLA printer. The VeroGlaze MED620 resin (Stratasys LTD, Rehovot, Israel) in combination with the FullCure SUP705 support resin (Stratasys LTD, Rehovot, Israel) were chosen for the production of the models. After printing, the support material was removed by water-jet washing.

After the production of the models, one experienced operator digitized the printed models with the same optical 3D scanner (InEos X5, Sirona Gmbh, Bensheim, Germany) and the 40 resulting mesh datasets (N=40: 20 SLA; 20 MJ) were reference digital models, by using a dedicated inspection software (Geomagic Qualify 13, Geomagic, Morrisville, USA), in order to evaluate three-dimensional accuracy by superimposition. For the purpose of obtaining equal evaluation boundaries for all of the models, the datasets were reduced to the field of interest (1-3 mm below the cervical line of the teeth).

As a result of the performed superimpositions, we analyzed the dimensional discrepancies between the REF dataset and 3D printed models (Figure 2). Thus, the root mean square (RMS) error was used to evaluate the congruence of the superimposed datasets. Color-coded maps were generated from this process to highlight the areas of deviation.

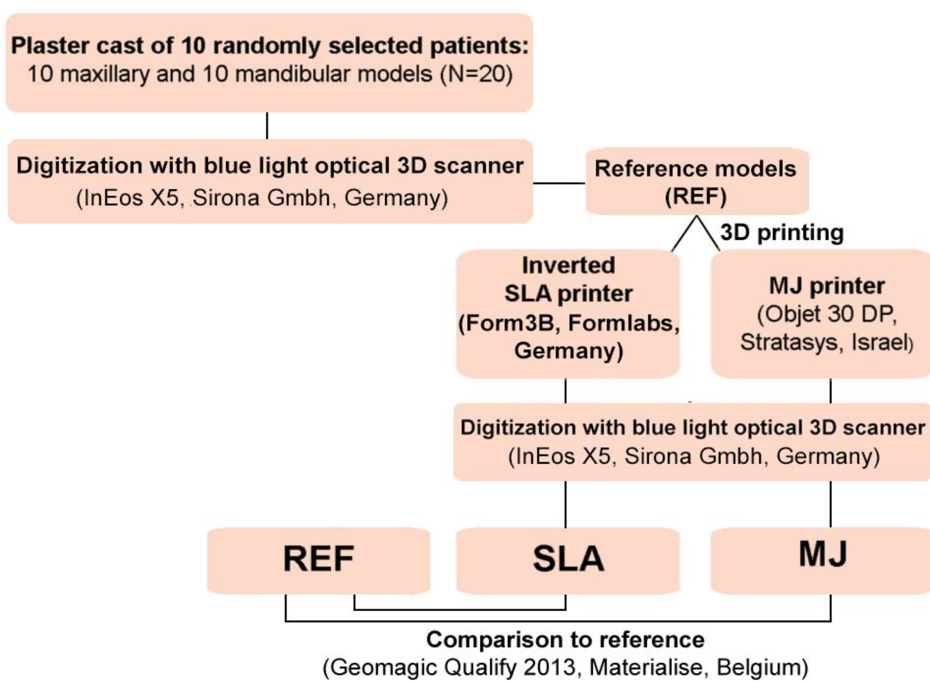


Figure 2. Overview on the general study workflow and methods of data creation

The statistical analysis was performed using the SPSS Statistics 20.0 statistical processing software (IBM SPSS Inc., Chicago, USA). Descriptive statistics and the Shapiro-Wilk test were used to assess normal distribution of the data. Paired t-tests were performed to evaluate statistically significant differences between the additive manufacturing systems (□=0.05). An a priori test of statistical power determination was performed to identify the minimum number of samples required (GPower 3.1.9.2, Kiel, Germany).

## RESULTS

In order to compare the differences in accuracy between the two groups, the results of the a priori power test showed that 20 models per group are sufficient for an effect size of 0.5, an estimate of statistical power of 0.95 and an error level of α = 0.05.

The Shapiro-Wilk test demonstrated a normal distribution of data (p> 0.05). The mean values of the differences between the digital reference models and the digital models of the printed casts, the standard deviation and the descriptive statistics are presented in Table 1.

Table 1. Descriptive statistics of the mean three-dimensional deviations recorded between the CAD models and the printed models- RMS (µm)

| Manufacturing method | Mean+SD | Min. | Max. | Range | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| **SLA** | 86.7 ±5.44 | 79.85 | 99.86 | 20.1 | 84.4 | 89.2 |
| **MJ** | 67.8±5.67 | 59.84 | 78.71 | 18.86 | 65.3 | 70.3 |

Results of the paired-t test indicated that there is a significant medium difference between MJ (M = 67.8, SD = 5.7) and SLA (M = 86.8, SD = 5.4), t (19) = 37.1, p < .001. Thus, the inverted stereolithography printer was associated with a statistically significant smaller degree of accuracy in comparison with the material jetting printer included in this study. Cohen's d was estimated at 8.29, which indicates that the magnitude of the difference between the average of the differences and the expected average of the differences is large according to Cohen's guidelines. By evaluating the color-coded maps of comparisons between the digital models and the printed models, we can see that the deviations are predominantly horizontal for both additive manufacturing methods, as can be seen in Figure 3.

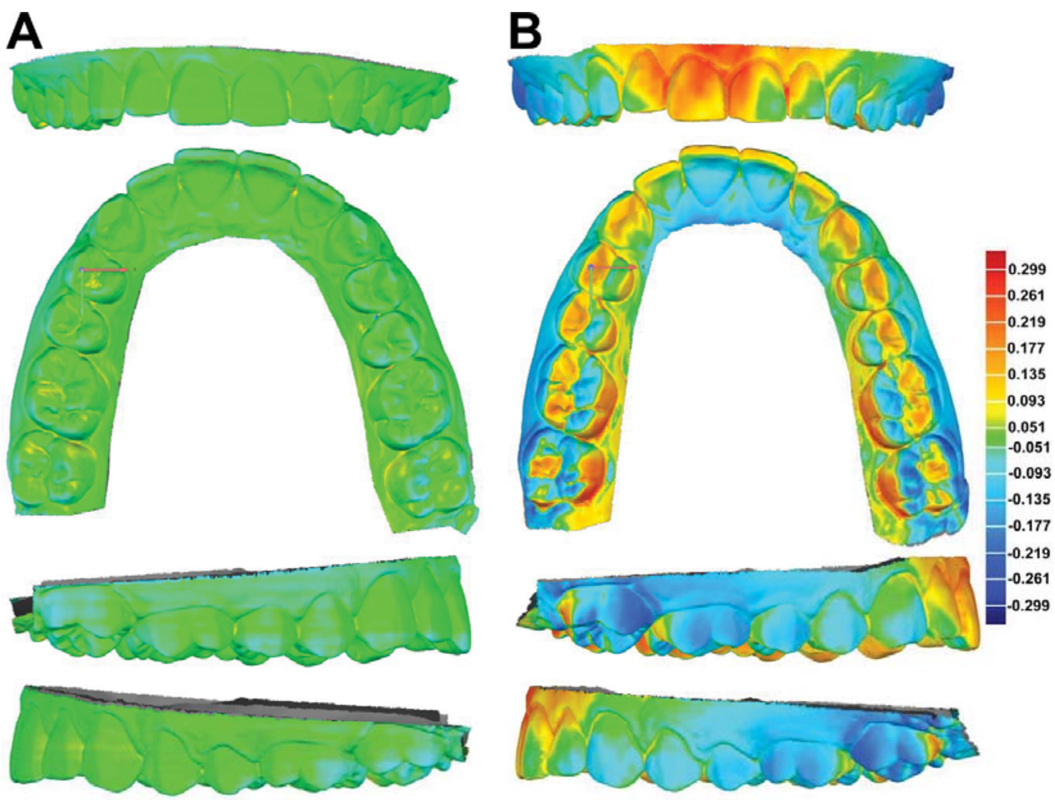


Figure 3. Qualitative analysis of the deviations recorded between the digital models and the printed models; A- model printed with MJ printer; B- model printed with SLA printer

The SLA group records the most horizontal contraction in the lateral area, as well as higher vertical distortion in the posterior area and a slight tendency of horizontal contraction on the oral surfaces of front teeth. Consistent with the information provided by the applied statistical analysis, the smallest deviations in the vertical and horizontal plane can be observed in the models obtained with the MJ printer.

## DISCUSSIONS

The results of this study lead to the rejection of both null hypotheses, as the printed models had different levels of accuracy compared to the reference data sets and there are also statistically significant differences between the reversed-stereolithography and material jetting 3D printers.

In order to achieve the reconstruction of a digital model that was acquired through intraoral scanning, it is necessary to go through several production steps: intraoral data acquisition, digital data processing, actual manufacturing and post-processing.17 Each of these clinical and technical steps can induce a degree of deviation in the accuracy of the reconstructed model mainly through four types of error: (a) operator-induced error; (b) error induced by the printer; (c) material-induced error; and (d) environmental errors.

While subtractive manufacturing is an accurate production method for short-span models18, this method is relatively time-consuming and has a high rate of material consumption. It has been demonstrated that, in general, by using subtractive manufacturing, up to 90% of the material block is removed, depending on the type of restoration produced.19 As an alternative to milling, some additive manufacturing processes, such as material jetting, do not produce material waste because there is no need for supporting structures. In addition, the operator can modify the internal structure of the manufactured object by changing the in-filling degree and the type of filling structure.

In our study, the material jetting printer had the smallest dimensional deviation of the printed models. When selecting the in-fill level, the role of the model should be considered in order to optimize the print speed. For example, documentation models do not require the same mechanical properties as working models, which means that the in-fill volume can be lowered or the model could be printed hollow.

While printers based on material jetting can print patterns directly on the work platform without the need for placement of supports or a particular orientation on the platform, SLA-printed models require tilting on the work platform to prevent delamination caused by the surface tension of the resin. Tilting changes the orientation of the layers, which can change the roughness of the printed part.20

According to the result of the present study, SLA printed models had a smoother surface appearance, but the models exhibited horizontal and vertical contraction. This problem can be caused by the low layer thickness, polymerization shrinkage or post-processing inefficiency. Distortions and contraction can also be caused by defects existing in the polygon network of virtual models, which should be “water-tight”, without overlapping or incorrect orientation of the vertices.

## CONCLUSIONS

Within the limitations of this in vitro study, we conclude that diagnostics models manufactured with MJ and SLA technologies are adequate for use in orthodontics or treatment planning. Although the differences between the diagnostic and reference models manufactured with SLA and MJ technologies were statistically significant, the dimensional error of all printed models was found below 100 µm and therefore they are considered to be acceptable for clinical use.

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