# Accuracy of 3-Dimensionally Printed Full-Arch Dental Models

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Accuracy of 3D printed models varied widely between <100 to >500 μm with the majority of models deemed of clinically acceptable accuracy. The smallest (3.3 μm) and largest (579 μm) mean errors were produced by SLA printers. For digital light processing (DLP), majority of investigated printers (n = 6/8) produced models with <100 μm accuracy. Manufacturing parameters, including layer thickness, base design, postprocessing and storage, significantly influenced the model's accuracy.

Keywords: 3-dimensional printing ; additive manufacturing ; dental models ; accuracy

## 1. Introduction

Three-dimensional (3D) printing is an additive manufacturing (AM) process that allows conversion of digital models into physical ones through a layer-by-layer deposition printing process. 3D printing has been adopted in dentistry at an increasing rate and construction of dental models is one of the main applications of this promising technology in prosthodontics, orthodontics, implantology and oral and maxillofacial surgery, amongst others [1]. An essential prerequisite of dental models is creating an accurate replication of teeth and the surrounding tissues to serve their intended purposes as diagnostic and restorative aids for assessment, treatment planning and fabrication of various dental appliances and prostheses. Currently, gypsum casts poured from conventional impressions (e.g., alginates silicones, poly-sulphurs, ethers) are considered the gold standard for constructing dental models [2]. However, these cast models suffer a number of limitations, including a need for expedited processing of impressions, depending on the impression material; storage space for resultant casts; the cost of human and laboratory resources involved in fabrication; poor structural durability; and a propensity to dimensional changes over time [3]. In contrast, 3D printed models could offer a more efficient workflow that can be manufactured on demand and are more resilient, less-labour intensive and potentially time-saving [4]. Nonetheless, 3D printed models also present a unique set of limitations. The accuracy of the resultant models depends on several factors that can introduce errors. This includes the data acquisition and image processing of the oral hard and soft tissues, and the myriad of parameters involved in the manufacturing and postprocessing processes [5]. Moreover, models acquired through vat polymerisation and material jetting are prone to shrinkage during the polymerisation stage as well as having stair-step surfaces due to the layering technique used in construction [6]. In addition, a recent study demonstrated that models exhibit dimensional changes postprocessing as they age with their dimensions reported to be significantly different after three-weeks of manufacturing [7].

At present, there is an array of printing technologies available utilising various techniques, with varying outputs and performances, and consequently confounding the issue of a standardised expectation of accuracy. The most commonly used techniques are stereolithography (SLA), digital light processing (DLP), material jetting (MJ) and fused filament fabrication (FFF). Other processes such as continuous liquid interface production (CLIP) and binder jetting (BJ) have also been utilised but are not as common [8]. The earliest and most widely adopted 3D printing technique is SLA, which utilises ultraviolet (UV) scanning laser to sequentially cure liquid photopolymer resin layers. Each layer is solidified in the x-y direction, and the build platform incrementally drops in the z-direction to be recoated by resin and cured [9]. The photopolymerisation of each new layer connects it to the prior layer resulting in models with good strength. DLP uses a conventional light source to polymerise photosensitive liquid resins. However, unlike SLA, each x-y layer is exposed to the light all at once using a selectively masked light source, resulting in shorter production time [10]. Both SLA and DLP are versatile techniques as they can be used with a wide variety of resin systems [11]. CLIP is an advanced form of DLP technology with the advantage of faster printing time. Additionally, this technique utilises a membrane, which allows oxygen permeation to inhibit radical polymerisation. MJ, similar to vat polymerisation techniques (SLA, DLP and CLIP) employs photopolymerisation. This technique allows for deposition of liquid photosensitive resin through multiple jet heads on a platform, which is then cured by UV light [12]. As opposed to SLA and DLP, this technique requires no post-curing.

Unlike Vat polymerisation and MJ, which use photopolymer material, FFF relies on the melting of thermoplastic materials, extruded through a fine nozzle, to create objects through layering filaments [11]. BJ technology, on the other hand, utilises selectively deposited liquid bonding agents to fuse powdered material.

## 2. Current Insights

Given 3D printing's promising potential and increased use in dentistry, it is essential to evaluate the accuracy of 3D printed dental models. The selection criteria for the included reference standards were high, subsequently the risk of bias and applicability concerns were low according to the QUADAS-2 tool. The findings of this work support the use of 3D printing for the fabrication of dental models and deem them as clinically acceptable with the majority of included studies (*n* = 20/28) establishing a clinically acceptable error range of <100 to 500 μm. 3D printed models were found to be a valid alternative to stone models when taking precision into account. Nonetheless, the study by Wan Hassan (2019) was an outlier which found BJ 3D printed models not clinically acceptable due to their discrepancy of >500 μm. It is, however, worth noting the included studies which used orthodontic models [13][14][15][16][17][18][19][20][21][22][23] had more relaxed thresholds for clinical acceptability (up to 500 μm), compared to those intended for prosthodontic applications (up to 200 μm) [6][24][25]. Indeed, in orthodontics, a measurement difference of <300 μm between orthodontic casts and 3D printed models has been reported to be clinically acceptable [26][27][28]. On the other hand, in prosthodontics, the accuracy needs of dental models for the fabrication of dental prostheses is generally considered higher. A recent study concluded that three-unit fixed partial dentures fabricated using 3D printed models, whilst demonstrating inferior fit when compared to those fabricated using stone casts [29], the detected marginal gaps remained within the clinically accepted threshold of 120 μm reported in the literature [30]. Such clinically relevant thresholds become more critical in complex prosthodontic treatment modalities. Implant-supported complete dental prostheses or hybrid bridges have a maximum acceptable threshold of fit between the prostheses platform and the dental implants ranging between 59–150 μm [31][32][33]. Accordingly, the choice of 3D printing technology must be determined by its intended application. Hence, it is reasonable to conclude that 3D printed models which are clinically acceptable for orthodontic purposes may not necessarily be acceptable for the prosthodontic workflow or other dental applications requiring high accuracy.

The most common 3D printing technology investigated by the included studies was SLA with the findings demonstrating that SLA and DLP achieved the best accuracy for full-arch models. Amongst the SLA printers, Form 2 by Formlabs was investigated the most, and consistently produced clinically acceptable models. Although a wider range of mean errors was observed amongst SLA printed models, the Form 2 SLA desktop printer [34][19][24][23] also consistently produced models more accurate than MJ printers and was more cost-effective [34][35]. Moreover, the SLA printer P30 reported the most accurate models amongst all studies, followed by the DLP Asiga Max UV [7][20]. Additionally, SLA printers produced acceptable results regardless of their layer thickness, and therefore the layer thickness of 100 μm may be considered as an optimal thickness that balances accuracy and printing time when compared to 25 and 50 μm layers [19][23]. Moreover, it was suggested that a hollow or honeycomb infill could be indicated to reduce printing time and material-use with study models. Although no studies assessed the effect of using different resins with the same printer, using the manufacturer recommended resin was advised. In contrast, only one study assessed CLIP technology and used the Carbon M2 printer, which printed 3D models with deviations as small as 48 μm [25]. This study also concluded that the accuracy of 3D printed models was affected by the printing technique regardless of the base design. However, due to the limited studies that assessed the accuracy of BJ [36] and CLIP technologies [25], further investigation of these techniques is required to validate the viability of these printers. It is worth mentioning that some studies did not provide details of the sample size calculation, resin materials and/or post-curing protocols, exposing them to high risk of bias and applicability concerns with regards to sample selection. As a result, no conclusions were drawn based on these parameters, other than those studies that reported using the manufacturer's recommendations.

The two studies which examined the Ultra printer by EnvisionTEC [37][38] reported that the SLA models with horseshoe bases were not accurate nor clinically acceptable due to contraction in the transversal dimension during the post-curing protocol. However, as the horseshoe base is favoured for appliance fabrication and reduces material use, the inclusion of a posterior connection bar was suggested to prevent this significant dimensional reduction in the posterior region of the SLA model [39][37]. Nevertheless, several studies assessing other SLA printers [4][14][39][40][34][20][24] contradicted these findings and concluded that models printed by SLA with a horseshoe base to be clinically acceptable.

When assessing DLP technology, apart from the M-One printer used by Kim et al. (2018), all other printers had accuracies comparable to SLA and MJ. The Asiga Max UV printer produced the lowest mean error (−16 μm) [20]. In addition, Sherman et al. (2020) and Zhang et al. (2019) assessed the accuracy of DLP printed models with various layer thicknesses ranging from 20–100 μm and suggested that all the printed models were clinically acceptable. Thus, similar to SLA printers, it can be inferred that a layer thickness of 100 μm can still produce models with clinically acceptable accuracies for DLP printers.

In addition to layer thicknesses, two studies assessed different filling patterns for DLP printed models [25][22]. Altering the filling pattern from solid to hollow reduced material wastage, build time and cost with no statistically significant difference in mean error.

Most MJ printers could reproduce models with high levels of trueness and precision, regardless of their base design [37]. From those, Objet Eden 260 series [13][15][16][34], was the most commonly investigated printer and consistently produced models with the highest accuracies due to its smaller layer thickness of 16 μm followed by the Projet3500 HDMax [6][41]. These printers were used due to their relatively affordable price and ability to print in smaller layer thicknesses. It is worth mentioning that although the reduction in layer height resulted in smoother surface finish and greater detail, the printing time increased [34].

FFF desktop printers, albeit considered the most affordable printers [17][20], provided models with acceptable accuracy. The most accurate models were created by the Ultimaker 2+ printer (12 μm) [20]. Although the materials used by FFF printers, namely PLA or ABS were inexpensive; the resultant models had inferior surface properties compared to acrylates and epoxides which were used for vat polymerisation technologies (SLA, DLP and CLIP). Similar to SLA and DLP, studies assessing FFF suggested a layer thickness of 100 μm to be clinically acceptable. Moreover, Burde et al. (2017) printed FFF models with a honeycomb pattern to reduce print time, material and cost with the resultant models deemed clinically acceptable.

There were very limited data to compare the results from 3D assessment to linear measurements for the same printers. However, it is worth noting that the highest risk of bias and applicability concerns for index test were recorded for studies that used linear measurements. This was reflective of the limited measuring points provided by those studies in comparison to a full arch deviation measurement by 3D superimposition. Additionally, some of the studies had a high risk of bias as human error may have been introduced by performing physical linear measurements with no information provided on the calibration of the examiners [13][19][20][25]. Furthermore, for 3D superimposition techniques, the risk of bias and applicability concerns were low for most studies as high accuracy desktop scanners were utilised and CAM was the only identified source of error. Nevertheless, studies that used intraoral scanners, made conventional impressions with or without pouring casts had a higher risk of bias due to the additional stages that may have introduced their own set of errors.

The Projet 6000 printed models were assessed using different methods [6][14]. The mean error calculated using full arch 3D superimposition (114.3 μm) was smaller than the intermolar width error measured by a surveying software (190 μm). Similarly, two studies assessed the Juell 3D printer [15][34], and the mean error calculated by full arch superimposition (44 μm) was smaller than the digital calliper measurements for the intermolar width (70 μm). On the other hand, two studies [13][15] assessed the Objet Eden 260VS model, using two different linear measurement methods. The mean errors calculated using surveying software and digital calliper were very similar (74 and 80 μm, respectively). These findings do highlight the need for a standardised measuring protocol to facilitate comparison of results across studies given the noted discrepancy between the different assessment techniques.

## 3. Conclusions

The findings of this work support the use of 3D printed dental models, especially as orthodontic study models. Irrespective of the 3D printing technology, certain printers were able to demonstrate low errors and hence can be recommended for dental applications that require high accuracy models. Other factors such as layer thickness, base design, postprocessing and storage can equally influence the accuracy of the resultant 3D printed models. Nonetheless, the high risk of bias with regards to the lack of standardised testing of accuracy warrants careful interpretation of the findings.

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