Accuracy of 3D-Printed Full-Arch Dental Models Printed with an LCD-Based 3D Printer

Pimanong Thongsamrith, Chaiyapol Chaweewannakorn,
Supatchai Boonpratham, and Yodhathai Satravaha*

Department of Orthodontics, Faculty of Dentistry, Mahidol University, Bangkok, Thailand
*Corresponding author, E-mail: yodhathai.sat@mahidol.ac.th

Abstract

Additive manufacturing technologies, including LCD printers, have revolutionized dental care by enhancing precision, customization, and efficiency in treatment planning and prosthetic fabrication. However, the accuracy of LCD 3D printers for dental applications requires further evaluation. This study assessed the accuracy of a full-arch dental model produced with an LCD-based 3D printer. A maxillary dental model was generated from a completed non-extraction orthodontic treatment, scanned, and optimized for digital setup and 3D printing. The model was printed on an LCD desktop 3D printer and then analyzed using computer-based digital tools to assess its trueness and precision. The Elegoo Saturn demonstrated a trueness error of 0.157 ± 0.002 mm and a precision error of 0.041 ± 0.004 mm at 100 µm printing resolution. These results indicate that the LCD-based 3D printer produced physical reproductions of digital orthodontic casts suitable for diagnostic, treatment-planning, and demonstration purposes. This study contributes to understanding the accuracy of LCD-based 3D printers in dental applications. RMS values for LCD-based printed models were below 0.20 mm, suggesting their suitability for orthodontic use. Thus, LCD-based 3D printers may be considered appropriate for orthodontic purposes.

Keywords: *3D printing, Orthodontics, Digital dentistry, Accuracy, Dental model*

1. Introduction

In dentistry, 3D printing has revolutionized various aspects of patient care and treatment. Dentists can now produce accurate physical models of a patient's oral anatomy from digital scans, facilitating precise diagnosis and treatment planning. This technology enables the customization and fabrication of dental prosthetics such as crowns, bridges, and dentures with exceptional accuracy and aesthetics. (Dawood, Marti Marti, Sauret-Jackson, & Darwood, 2015) Additionally, 3D printing allows for creating orthodontic appliances, like clear aligners, tailored to individual patient needs. Surgical guides for procedures such as dental implant placement are produced with high precision, improving procedural accuracy and patient outcomes. Moreover, 3D printing facilitates the rapid production of temporary restorations, enhances education and training through anatomically accurate models, and enables the creation of customized tools and instruments. Overall, 3D printing in dentistry has streamlined processes, increased efficiency, and elevated the standard of patient care (Barazanchi et al., 2017).

Additive manufacturing employs several key technologies to address various clinical needs. Stereolithography (SLA) and Digital Light Processing (DLP) utilize UV light to cure liquid resin, enabling the production of high-resolution dental models, surgical guides, and prosthetics with intricate details. Fused Deposition Modeling (FDM) extrudes thermoplastic filament, offering versatility for creating dental models, surgical guides, and temporary crowns at a lower cost. PolyJet printing jets photopolymer resin layer by layer, allowing for the fabrication of detailed dental models, aesthetic prototypes, and multi-material prosthetics with lifelike characteristics. Selective Laser Sintering (SLS) employs a laser to sinter powdered material, providing durability and the option to use biocompatible materials for dental prosthetics and surgical guides. While less common, binder jetting deposits a binding agent onto a powder bed, which is suitable for specific dental applications. These additive manufacturing technologies collectively revolutionize dental care by enhancing precision, customization, and efficiency in treatment planning and prosthetic fabrication (Akyalcin et al., 2021; Barazanchi et al., 2017; Chaudhary, Avinashi, Rao, & Gautam, 2023; Javaid & Haleem, 2019).

LCD printers work by using an LCD panel to selectively cure layers of liquid resin with UV light. This technology allows for relatively fast printing speeds and decent resolution, making it suitable for various dental applications, such as producing surgical guides, dental models, and temporary crowns. The affordability of LCD printers makes them accessible to smaller dental practices and labs that may have budget constraints but still want to leverage the benefits of 3D printing technology for improving patient care and workflow efficiency in dentistry. However, these printers have limitations due to overheating and faster degradation of the LCD screen. Popular dental-specific printers include the Ackuretta SOL, NextDent LCD1, and Sonic 4K 2022, while non-dental printers include the Sonic Mini 8K, Sonic Mighty 12K, Creality Halot, Elegoo Mars, Elegoo Saturn, and Anycubic Photon Mono. These printers are popular due to their lower price, which is 2 to 10 times lower than SLA or DLP printers, partly due to lower manufacturing costs and less optimization for dental use (Caussin et al., 2024).

Accuracy in 3D printing is a crucial aspect determined by both trueness and precision. Trueness pertains to how accurately a printer can replicate an object to closely match its virtual representation. At the same time, precision reflects the printer's consistency in producing the same object repeatedly under identical conditions. The resolution of the x, y, and z axes, dictated by the printer's light source, greatly influences printer precision. XY resolution, in particular, denotes the smallest horizontal feature that can be replicated. Various technologies like SLA, DLP, CLIP, and DPP employ distinct approaches to specify resolution, such as the laser spot diameter or the pixel size of the projector or LCD screen. (Ide et al., 2017; Piedra-Cascón, Krishnamurthy, Att, & Revilla-León, 2021). A number of investigations have assessed the precision of various 3D printing methods. For instance, Venezia et al. examined the accuracy of orthodontic models, fabricated using DLP, LCD, and SLA techniques, featuring both crowded and aligned teeth. Their findings indicated variations in accuracy among the technologies, yet all remained clinically viable. SLA printers demonstrated superior detail in intricate regions but showed potential limitations in consistency, whereas DLP technology boasted shorter printing durations (Venezia et al., 2022). Surprisingly, there has been limited research on the precision of LCD 3D printers in manufacturing dental models (Lo Giudice et al., 2022; Venezia et al., 2022). Therefore, the present study aimed to evaluate the accuracy of the 3D printed full arch dental model printed with an LCD-based 3D printer.

2. Objectives

The present study aimed to evaluate the accuracy of the 3D printed full arch dental model printed with an LCD-based 3D printer in aligned teeth.

3. Materials and Methods

3.1 Preparation of the digital maxillary master model file

An STL (stereolithography) file is a widely used format in 3D printing and computer-aided design (CAD). It represents a 3D model as a collection of triangular facets. This format is commonly used to store information about the geometry of an object, including its shape and surface texture, allowing it to be easily interpreted and processed by 3D printers and CAD software.

A maxillary dental model of a completed non-extraction orthodontic treatment was chosen to generate a master STL that will be used as a master model in the present investigation. The maxillary dental model was scanned using a desktop scanner (3Shape D900L). Next, the acquired STL file underwent optimization for 3D printing and for subsequent digital superimposition procedures. The maxillary model STL file was modified into a horseshoe shape with a hollow base (thickness 2.5 mm), and three half-sphere markers were added as reference points on the model base using Meshmixer software. The model was exported into an STL file and will be used as the maxillary master model.

3.2 Prototyping of a maxillary model

The STL file of the master model was prepared for printing using the company's recommendation. The physical printed model of the digital master was then created using an LCD desktop 3D printer, the Elegoo Saturn 4K. Photosensitive resins designed for dental model production were utilized to fabricate the maxillary models. All models were printed horizontally, aligning the occlusal plane with the build platform, and each printing session resulted in 2-3 models. A layer thickness of 100 µm was chosen for the prototyping process. Ten models were prototyped for the investigation.

Post-printing processes were conducted in accordance with the manufacturer's guidelines.

3.3 Computerized Digital Analysis of Maxillary Models

3.3.1 Digital Model Superimposition:

Each 3D-printed model underwent scanning using the desktop scanner (3Shape D900L), and the resulting STL files were exported to GOM Inspect Pro, a 3D analysis software, for conducting superimposition with the digital master model. A specific procedure was implemented for this purpose. Initially, a point-based registration was executed using three half-sphere markers as reference points, followed by the ultimate registration of the two models utilizing an automated best-fit algorithm. Subsequently, a cutting plane passing through the same landmarks was established to exclude the model's base and eliminate distortion arising from its removal from the print bed. The preliminary point-based superimposition and the best-fit algorithm were performed between the master model and models generated from the LCD printer to analyze trueness. Additionally, ten pairs of STL models acquired from the 3D printer were randomly selected to conduct intra-group combinations for precision analysis.

3.3.2 Deviation analysis (calculation of trueness and precision):

The STL files of the superimposed models were analyzed to determine the distances and deviations between them. These distances, representing the differences in surface points between the two digital models, were converted into root mean square (RMS) values. RMS values provide an assessment of the average errors when comparing two datasets sharing the same coordinate system. Depending on whether the original master model or the 3D-printed models generated from the same printer were used as the reference for deviation analysis, RMS values reflect either trueness or precision.

The results of the deviation analysis will be complemented by 3D colour-coded maps, where yellow-to-red areas indicate distance values exceeding positive limits. In contrast, turquoise-to-dark blue areas indicate values below negative limits. A tolerance range (green color) is set at ±0.05 mm, with differences beyond this range highlighted in the color-coded maps.

The entire computer-based digital analysis workflow will be conducted by one examiner. Two weeks after the final examination, all procedures (excluding prototyping) will be repeated to assess intra-observer variability and method error. A second examiner will also perform the same procedures to evaluate inter-observer reliability.

3.4 ***Statistical analysis***

The data's normal distribution and equality of variance will be assessed with the Shapiro-Wilk Normality Test and Levene's test. Data analysis was carried out by using the software program SPSS version 22, and the data was presented in descriptive statistics with means, percentages, standard deviations, frequencies, and minimum and maximum ranges.

Figure 1: The LCD-based 3D printer used in this study: ELEGOO Saturn 4K Resin 3D Printer

4. Results and Discussion

4.1 Result

4.1.1 Trueness error

Superimpositions of the master model file and ten printed model files were calculated for the distances and deviations for the trueness error. The value of the trueness error of the Elegoo Saturn at 100 µm printing was 0.157 ± 0.002 mm (Table 1, Figure 2).

A color map of superimposed models in GOM Inspect visually represents the deviations between two scanned objects, typically reference and test models. This color map highlights areas of discrepancy, typically displayed using a spectrum of colors ranging from blue (indicating areas where the test model is below the reference model) to red (indicating areas where the test model is above the reference model), with green typically representing areas of minimal deviation. This visualization aids in identifying regions where the test model differs from the reference model, allowing for detailed analysis and adjustments as needed. In the present study, color maps obtained from the registration of the scanned printed aligned models with the digital master model showed more deviation at the molar area (Figure 3).

Table 1: Descriptive data of root-mean-squared (RMS) values of the trueness of LCD 3D-printed dental models, using the digital master model file as a reference

Data		Statistic	Std. error
Mean		.157010	.0022573
95% Confidence	Lower Bound	.151904	
Interval for Mean	Upper Bound	.162116	
5% Trimmed Mean		.156994	
Median		.158700	
Variance		.000	
Std. Deviation		.0071382	
Minimum		.1441	
Maximum		.1702	
Range		.0261	
Interquartile Range		.0090	
Skewness		-.047	.687
Kurtosis		.787	1.334

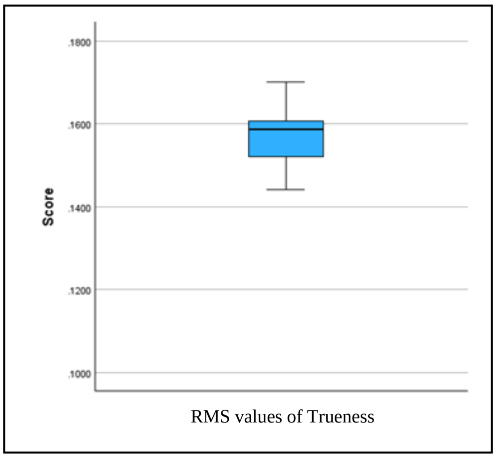

Figure 2: Box plot of root-mean-squared (RMS) values of the trueness of LCD 3D-printed dental models

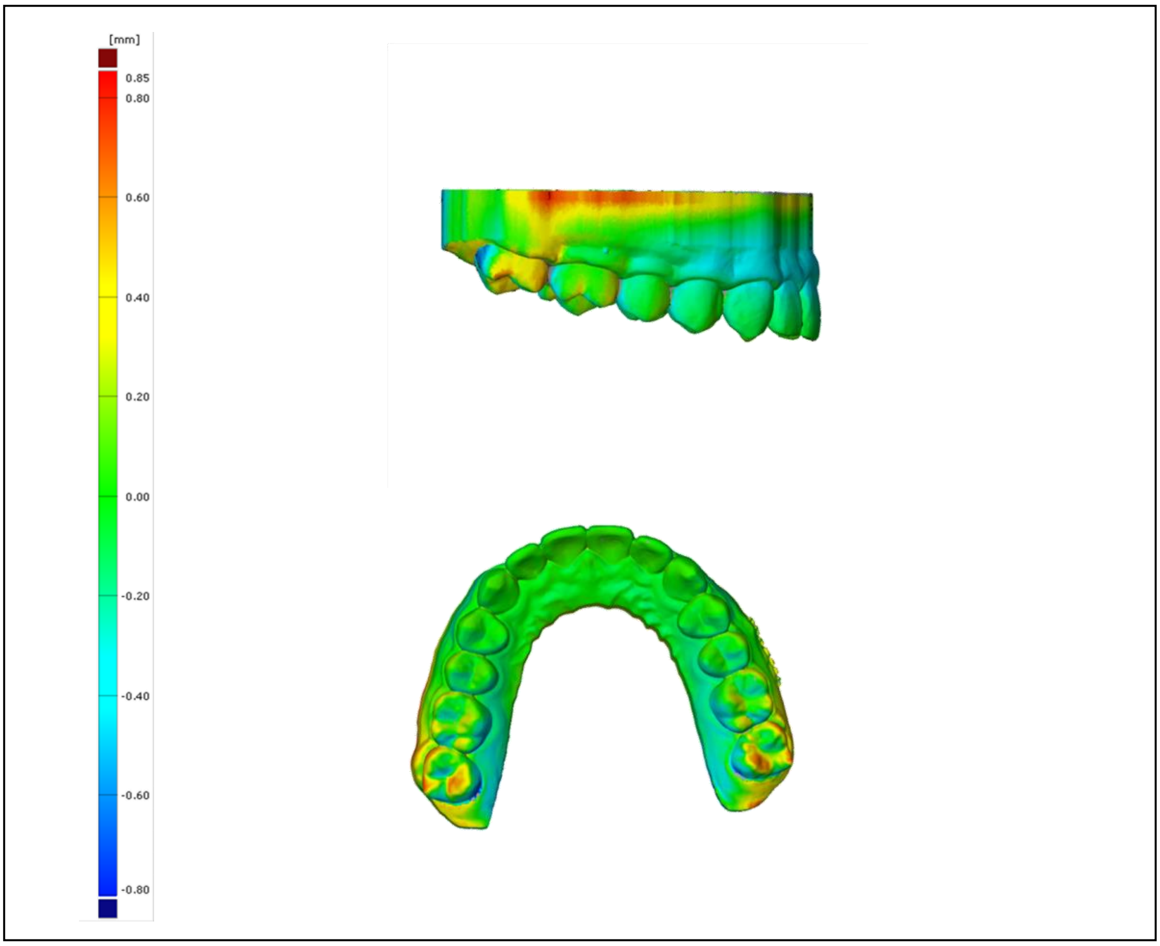

Figure 3: Color maps obtained from the registration of the scanned, printed, and aligned models with the digital master model (analysis of trueness) [Yellow-to-red fields = positive, turquoise-to-dark blue = negative, green = range of tolerance (± 0.20 mm)]

4.1.2 Precision error

Superimpositions between 10 pairs of printed model files were calculated for the distances and deviations for precision error. The value of the precision error of the Elegoo Saturn at 100 µm printing was 0.041 ± 0.004 mm (Table 2, Figure 4). Color-coded maps obtained from the registration of two scanned, printed aligned models showed more deviation at the proximal area and posterior teeth (Figure 5).

Table 2: Descriptive data of root-mean-squared (RMS) values of precision of LCD 3D-printed dental models, using the other printed model as a reference

Data		Statistic	Std. error
Mean		.040880	.0047546
95% Confidence Interval for Mean	Lower Bound	.027679	
	Upper Bound	.054081	
5% Trimmed Mean		.040800	
Median		.036600	
Variance		.000	
Std. Deviation		.0106317	
Minimum		.0282	
Maximum		.0550	
Range		.0268	
Interquartile Range		.0193	
Skewness		.347	.913
Kurtosis		-1.229	2.000

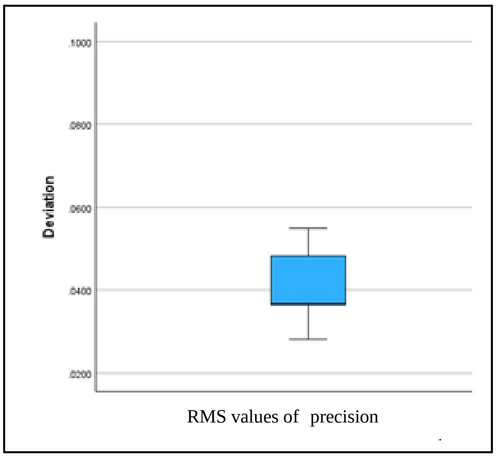

Figure 4: Box plot of root-mean-squared (RMS) values of precision of LCD 3D-printed dental models

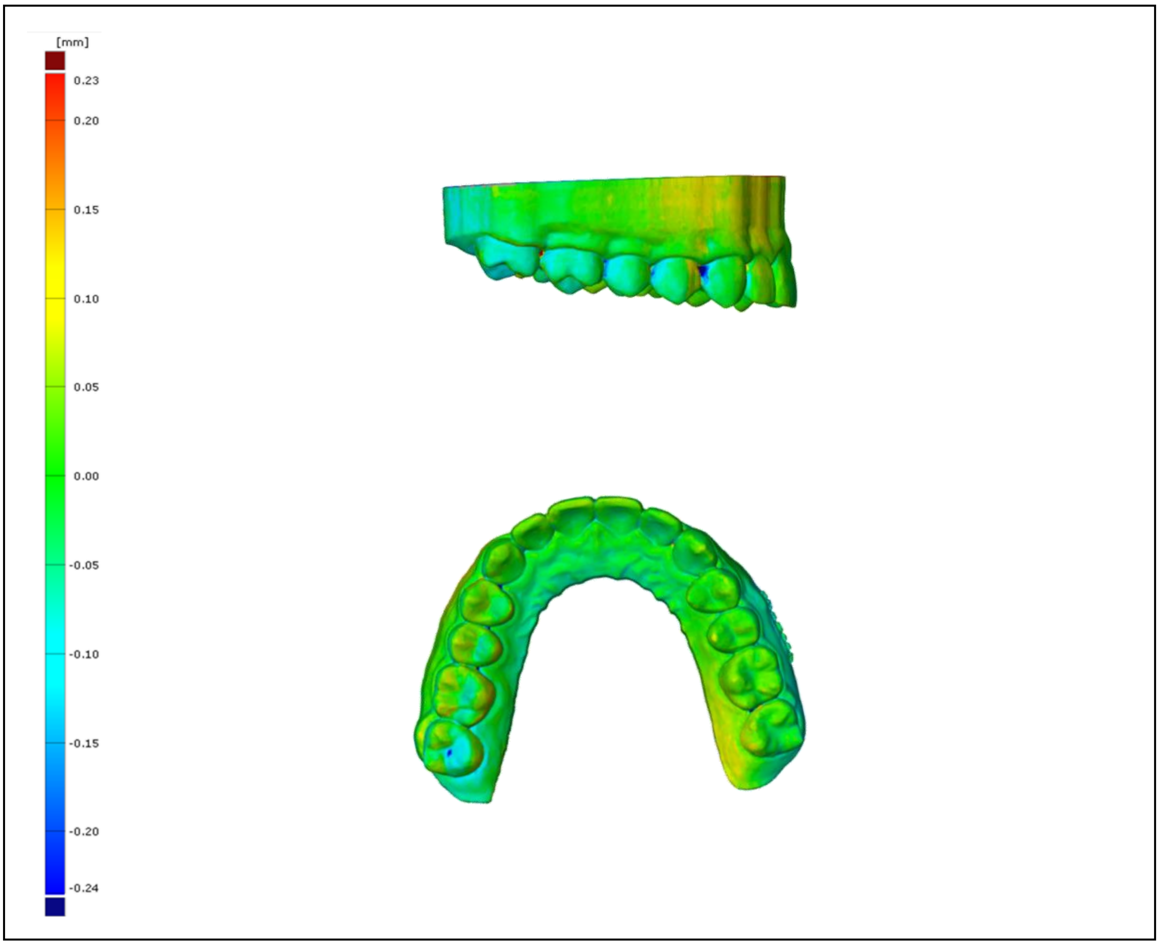

Figure 5: Color maps obtained from the registration of two scanned printed aligned models (analysis of precision) [Yellow-to-red fields = positive, turquoise-to-dark blue = negative, green = range of tolerance (± 0.05 mm)]

4.2 Discussion

Advanced technology has greatly influenced the field of dentistry, including the use of three-dimensional (3D) printing in orthodontics. The predominant 3D printing method examined in the studies was SLA, which showed that SLA and DLP had the highest accuracy for full-arch models. Form 2 by Formlabs was the most studied SLA printer and consistently produced models that met clinical standards. While SLA-printed models had a broader range of mean errors, the Form2 SLA desktop printer was particularly noteworthy (Favero et al., 2017; Loflin et al., 2019). LCD 3D printing technology shares the foundational principles of Laser-SLA and DLP printers, all belonging to the vat polymerization category. Unlike the others, LCD printers utilize a liquid crystal display as their light source. In this process, light travels uniformly through the LCD panels onto the build area without any need for a lens or similar apparatus, eliminating pixel distortion concerns. The primary distinction lies in speed; LCD printers outpace Laser-SLA counterparts, rivalling the swiftness of DLP printers. Furthermore, their affordability is attributed to the economical materials used in their construction, contributing to their rising popularity (Tsolakis et al., 2022).

A systematic review of the literature on 3D printing in orthodontics found that the accuracy of a printed dental cast can be influenced by various factors. These factors include the type of 3D printing technology, the design of the dental cast's base, and the materials used for printing. Additionally, the layer height and position of the model on the building template were found to have minimal impact on the accuracy of the printed dental model. Recent studies have also highlighted the importance of post-processing techniques in improving the accuracy of 3D-printed dental models (Mostafavi et al., 2023; Mostafavi et al., 2021). Factors such as proper cleaning, drying, and finishing of the printed models can significantly contribute to their overall accuracy and quality. In addition to these factors, the expertise of the dental practitioner and the precision of the 3D scanning process also play crucial roles in ensuring the accuracy of the printed dental models (Etemad-Shahidi et al., 2020; Kim et al., 2018).

For optimal print settings, according to Etemad-Shahidi et al. (2020), a layer thickness of 100 µm may be viewed as an optimal setting that strikes a balance between accuracy and printing time, particularly when compared to layers of 25 µm and 50 µm. Building upon these findings, Venezia et al. (2022) suggest that a layer thickness of 50 µm could potentially offer the most suitable and balanced option for printing orthodontic models intended for clear aligner fabrication. They argue that given the increase in printing time associated with higher z resolution, opting for 25 µm layers may not be justifiable, particularly for printers in the medium-professional segment, and is not advisable for low-budget 3D printers. In our study, we opted for 100 µm layers to reduce printing time, and the results were satisfactory.

The reported clinically acceptable range of the printed models varied from 100 to 300 µm (Kim et al., 2018; Park & Shin, 2018). Schirmer and Wiltshire considered a measurement discrepancy of under 0.20 mm to be acceptable in a clinical setting (Schirmer & Wiltshire, 1997), while Hirogaki et al. required an accuracy of approximately 0.30 mm (Hirogaki et al., 2001). Halazonetis, on the other hand, deemed an accuracy of 0.50 mm insufficient for orthodontic study models (Halazonetis, 2001). The current study's root mean square (RMS) value for trueness and precision did not surpass 0.16 mm, indicating that the results fell comfortably within the parameters established by these previous studies. Therefore, the conclusion is that the LCD-based 3D printer evaluated in this study delivered physical reproductions of digital orthodontic casts that were suitable for diagnostic, treatment-planning, and demonstration purposes. The minimum accuracy required depends on the purpose of the dental model. The study was intended to focus solely on the accuracy of an LCD-3D printer in aligned detention without comparing it with other printing methods or considering various malocclusions. Future research should explore the precision of dental models in various types of malalignment models, as well as examine how the ageing of models affects their accuracy. This aspect will be investigated in forthcoming studies.

5. Conclusion

The RMS values (root mean square deviation or error) observed in LCD-based printed models were under 0.20 mm, a clinically acceptable threshold in orthodontics. Hence, employing LCD-based 3D printers in orthodontic practices may be acceptable.

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