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Comparison of GAP width of thermoformed clear aligners produced by different 3D printers

Comparação da interface modelo-placa em alinhadores transparentes produzidos por diferentes impressoras 3D

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ABSTRACT

Objective: Although clear aligners have been widely used in orthodontics, factors such as thickness and fit are still little studied. In addition, other clinical aspects, such as optical properties, forces and moments and predictability of movement, are fundamental issues for the consolidation of this innovative therapeutic approach. This study aimed to assess how clear aligners manufacturing is impacted by 3D printer techniques and their thermoforming processes through analysis of the model-aligner interface. **Material and Methods:** Models were printed on three different printers with distinct printing technologies, namely FDM (fused deposition material), SLA (stereolithography apparatus), and DLP (digital light processor). In each case, two resolutions were investigated (i.e. 25 μm and 100 μm). Polyethylene terephthalate glycol (PETG) sheets (Track A, Forestadent™, Germany) were made using a thermoforming machine (Plastvac P7, Bio-Art, Brazil) to simulate the orthodontic clear aligner. A universal cutting machine (IsoMet 1000 Precision Cutter, Buehler, UK) was employed to obtain sections of the model-sheet set at the central incisor, canine, first premolar, and first molar regions in the lower arch. The GAP width between models and aligners was obtained through stereomicroscopy (Zeiss, Germany) and measured with Image J/Java software, version 1.46r. Statistical differences were obtained through Analysis of variance (ANOVA) and Tukey's posthoc test at a significance level of 5%. **Results:** Gap differences were smaller for SLA and DLP when compared to FDM 3D printer technologies. It was observed that smaller resolutions (100 μm) displayed higher gap widths, relating precision to higher resolutions (25 μm). The assessment of the dental regions did not reveal any distinction relating to resolution or printer techniques. **Conclusion:** This study showed that SLA and DLP printers produced more precise models than FDM printers used in orthodontics for clear aligners. Factors such as cost, speed and printing capacity may be more important than resolution and GAP for the production of clear aligners in orthodontics.

KEYWORDS

3D printing; Biomechanics; Clear aligners; Digital orthodontics; Orthodontic appliances.

RESUMO

Objetivo: Embora os alinhadores tranparentes venham sendo amplamente utilizados em Ortodontia, fatores como espessura e adaptação aos dentes ainda tem sido pouco estudados. Além disso, outros aspectos clínicos, como suas propriedades ópticas, forças e momentos gerados e previsibilidade da movimentação, são questões fundamentais para a consolidação desta inovadora abordagem terapêutica. Este estudo teve como objetivo avaliar, por meio da análise da interface modelo-placa (GAP), como a produção de alinhadores transparentes é impactada pelas técnicas de impressão 3D e seus processos de termoplastificação. **Material e Métodos:** Modelos de typodont foram impressos em três impressoras diferentes com distintas tecnologias de impressão, a saber: FDM (fused deposition modeling), SLA (stereolithography apparatus) e DLP (digital light processing).

Em cada modelo, foram avaliadas duas resoluções de impressão 3D (25μm e 100μm). Placas de politereftalato de etileno glicol (PETG) (Track A, Forestadent™, Alemanha) foram confeccionadas utilizando uma máquina de termoformagem (Plastvac P7, Bio-Art, Brasil) para simular um alinhador ortodôntico transparente. Uma máquina de corte universal (IsoMet 1000 Precision Cutter, Buehler, Reino Unido) foi empregada para obter as secções do conjunto modelo-placa nas regiões do incisivo central, canino, primeiro pré-molar e primeiro molar, todos do arco inferior. A espessura do espaço presente entre o modelo e o alinhador (GAP) foi obtida por estereomicroscopia (Zeiss, Alemanha) e mensurada com o software Image J/Java, versão 1.46r. Diferenças estatísticas foram analisadas por meio de análise de variância (ANOVA) e teste post hoc de Tukey, com nível de significância de 5%. **Resultados:** As diferenças de GAP foram menores para as tecnologias de impressão SLA e DLP em comparação com a FDM. Foi observado que resoluções menores (100 μm) apresentaram maior GAP, quando comparado com resoluções mais altas (25 μm). A avaliação das diferentes regiões dentárias não revelou diferenças relacionadas à resolução ou às técnicas de impressão. **Conclusão:** Este estudo demonstrou que, embora de maneira discreta, as impressoras de tecnologia SLA e DLP produziram modelos mais precisos do que as impressoras com tecnologia FDM utilizadas em ortodontia para a produção de alinhadores transparentes. Fatores como custo, velocidade e capacidade de impressão podem ser mais importantes que resolução e GAP para a produção de alinhadores transparentes em Ortodontia.

PALAVRAS-CHAVE

Impresssão 3D; Biomecânica; Alinhadores transparentes; Ortodontia digital; Aparelhos ortodônticos.

INTRODUCTION

Clear aligners have become the preferred orthodontic appliances among adults and adolescents, as they value aesthetics, comfort, and hygiene. Unlike conventional orthodontic treatment, these aligners are translucent, and, therefore, have an aesthetical preference. They are employed to correct teeth positioning, mainly in mild to moderate malocclusion cases. When associated with secondary devices (e.g., in skeletal anchorage), clear aligners may treat complex cases, otherwise resourced to orthognathic surgeries. Moreover, these devices are removable and do not interfere with oral hygiene; minimizing enamel demineralization, formation of dental caries, or development of periodontal diseases [1-3].

Thermoforming is a general term that refers to the process of shaping a plastic sheet into a 3-D shape at vacuum or positive pressure. Thermoplastics refers to a type of material made of polymer resins that homogenize when heated. The main materials used in the synthesis of orthodontic aligners are polyurethane (PU), polyethylene terephthalate glycol (PETG), and polycarbonate (PC) due to their excellent mechanical and optical properties, all of which can be provided as sheets with thickness ranging from 0.5–1.0 mm. In addition, particular aspects are of relevance in thermoforming, specifically some process variables (e.g., pressure, heating temperature, and cooling time) may shift between manufacturers, and material selection, which is also critical to avoid force overload on teeth and periodontium to promote retainer adjustment to the dental arch [4-9].

The technology of 3D printing was developed by the 3D System company in 1986. The most commonly used types of 3D printing in orthodontics involve the stereolithography apparatus (SLA) and fused deposition material (FDM) [10]. FDM printing is a more disseminated option in the market, displaying various materials. This method is not only simple to use and maintain, but it also requires minimal space while being widely available; thus making it convenient for in-office use, especially for the manufacture of low-cost prototypes for numerous applications [11]. Digital Light Processor (DLP) printing harbors nanotechnological resources, in which a digital micro-mirror device cures a liquid resin into 3D solid pieces. Although DLP printing is similar to stereolithography, the main difference resides in its light source. Therefore, DLP operates faster, as the projector shapes the material and creates a single layer mirrored from a digital image with tiny voxels [12].

Many studies have reported how aligner's material properties are affected by thermoplastification. In some regions of the teeth, this process reduces the thickness of the aligner, leading to microscopic areas of poor adaptation between the designed model and the sheet. Such changes can directly affect orthodontic biomechanics [6,13-17]. Studies on 3D printing technologies commonly assess technical characteristics such as production time, curing depth, and amount of printing. However, the scientific literature is scarce about how fit of the thermoformed aligner to the printed model compares to these different technologies. This study assesses how clear aligners adapt to different 3D printer mechanisms by analyzing the interface between the model and aligner after thermoforming.

MATERIAL AND METHODS

Scanning

The lower arch of an acrylic model (Typodont) was scanned (3D shape, USA) and then converted into a digital STL file, which allows digital editing through software manipulation and 3D printing (Figure 1A).

3D printing

Thermoplastic sheets were used to print the pieces in each printer in two different resolution qualities. The characteristics of the used 3D printers in the study were: Fusion Depositing Material (FDM), Acrylonitrile butadiene styrene (ABS) supply (Up 3D Mini; Tiertime – Milpitas, CA USA); Stereolithography Apparatus (SLA), Liquid resin supply (3D Anycubic Photon; Anycubic – Shenzhen, China); and Digital Light Processor (DLP), Liquid resin supply (Moonray S100; Sprintray Inc. USA). The plastic sheet type was Track A, from Forestadent, Germany, polyethylene terephthalate glycol (PETG), 0.60 mm.

In order to measure the GAP width, the 3D-printed models were initially sectioned using a hacksaw (Starrett, Itu, SP, Brazil) into four groups based on tooth type: incisors, canines, premolars, and molars. A novel approach was employed in which slices were created on a plane constructed perpendicular to the axis connecting the most mesial and distal points of each examined tooth, intersecting its midpoint. By leveraging the equivalence between the models and the universal cutting machine, this method

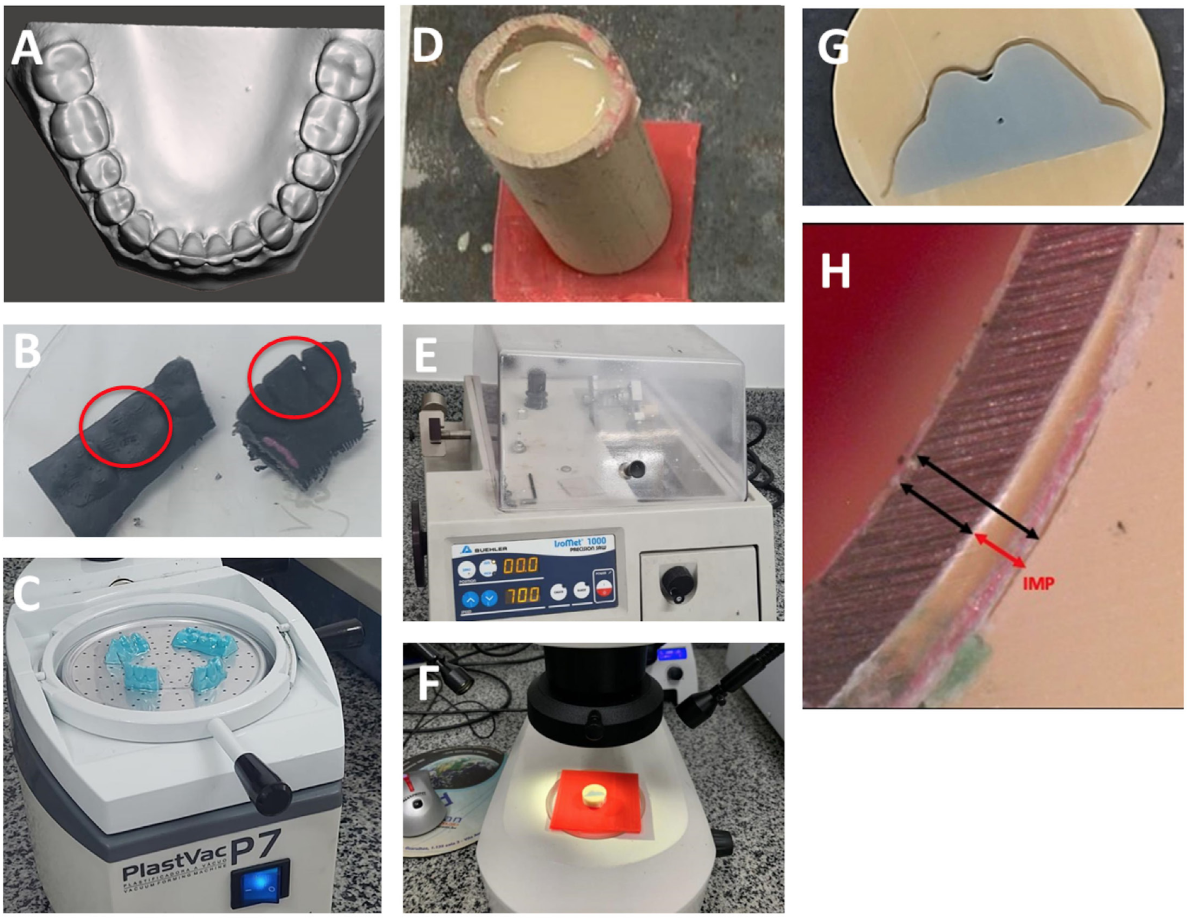

Figure 1 - A: Virtual model (STL file) resulting from 3D digitalization of the acrylic model; B: Segmentation of the printed model into different dental regions (incisors, canines, premolars, and molars); C: Thermoforming machine (Pastvac P7, Bioart); D: Metallic base with polyester resin inside the PVC tube; E: Universal cutting machine (IsoMet 1000); F: Electronic microscope (Zeiss) and images generated by J image software; G: Transversal cut of the sample; H: Scheme of measurement of the model-aligner interface.

ensured consistent and reproducible positioning of all models on an identical plane across samples. For each resolution (25 and 100 μm), two dental arches were used, totaling four dental arches per 3D printer type. Considering the four tooth groups analyzed, a total of 48 samples were generated. This segmentation allowed for optimal model positioning during the sagittal sectioning of the central tooth. (Figure 1B).

Thermoforming

This study introduces a pioneering methodological protocol in which sectioned models, obtained using 0.6-mm-thick sheets (Track A, Forestadent®, Germany), were positioned on a vacuum thermoforming machine (Model P7, Bioart, São Carlos, SP, Brazil) (Figure 1C). All PETG sheets were thermoformed using a heating power of 450 W and a vacuum motor power of 1400 W. As for heating temperature and time, the ideal laminating point was identified by observable changes in the sheet's shape. Typically, this point was recognized by a change in shine or by the sheet sagging 10 to 12 mm. The average heating time was 72 seconds at a voltage of 220 V, reaching an average temperature of 96°C, as recommended by the manufacturer. The cooling time and removal of the plate–model assembly from the thermoforming machine was standardized at 60 seconds, also following the manufacturer's guidelines.

The resulting aligners were meticulously trimmed to ensure the precise preservation of the model–aligner assembly's position—an essential innovation to guarantee procedural accuracy. Uniquely, the assembly was then placed inside a 3-inch polyvinyl chloride (PVC) tube after the application of a demolding agent (Basile Química, RB-596, São Paulo, SP, Brazil), specifically chosen to enable subsequent removal of the set without compromising its integrity. To ensure accurate regional identification, the PVC tubes were carefully labeled according to tooth position prior to resin embedding. For this process, a metallic base and utility wax (Lysanda, São Paulo, Brazil) were used, followed by the addition of 25 mL of polyester resin (Composites Polylite 10316-10, Reinhold do Brasil Ltda, Mogi das Cruzes, SP, Brazil), prepared at a rigorously defined ratio of 12.5 g of calcite to 0.25 mL of catalyst from the same manufacturer (Figure 1D). Notably, resin polymerization was strictly controlled and maintained below 55 °C—an unprecedented refinement intended to preserve the structural and dimensional fidelity of the specimens.

Image capture

In this novel methodological approach, a universal cutting machine (Isomet 1000, Buehler, Illinois, USA) was used to obtain sections of the model–sheet assembly in the regions of the cusp tips of the molars and premolars, as well as the mid-incisal ridges of the central incisors and canines, for subsequent analysis. Uniquely, the quality of the model–aligner interface was verified using a stereomicroscope (Carl Zeiss, model Stemi 508, Microscopy GmbH, Jena, Germany), enabling high-resolution visualization of the interface. The resulting images were systematically recorded and subjected to quantitative analysis using ImageJ software (NIH ImageJ, https://imagej.nih.gov/ij/), an open-source platform widely used for scientific image processing. This integrative methodological approach—combining precise mechanical sectioning, advanced stereomicroscopic evaluation, and digital quantification—represents an accurate and reliable method for assessing the gap between the model and the aligner (Figure 1E–H).

Measurements and data collection

After the models were sectioned and cross-sectional images were obtained using the stereomicroscope, the GAP width was measured in ImageJ software using the linear measurement tool. Prior to measuring each tooth group, the software was calibrated, and the appropriate magnifications were applied to ensure standardization and optimal visualization of the area of interest. The GAP width was calculated using the following formula: GAP width = Total width – Aligner width. The total width was measured at a 90-degree angle from the outer surface of the 3D-printed model to the outer edge of the aligner (Figure 2). All measurements were performed by two examiners (V.H. and L.M.) who had been previously trained in the use of Image J by an experienced professional. After 30 days, 25% of samples were remeasured to evaluate analytical error. The purpose of assessing method error in the linear measurements was to determine the precision and reproducibility of the data, identifying potential variations stemming from the examiners, the software, or the methodology itself, thereby ensuring the reliability and validity of the results.

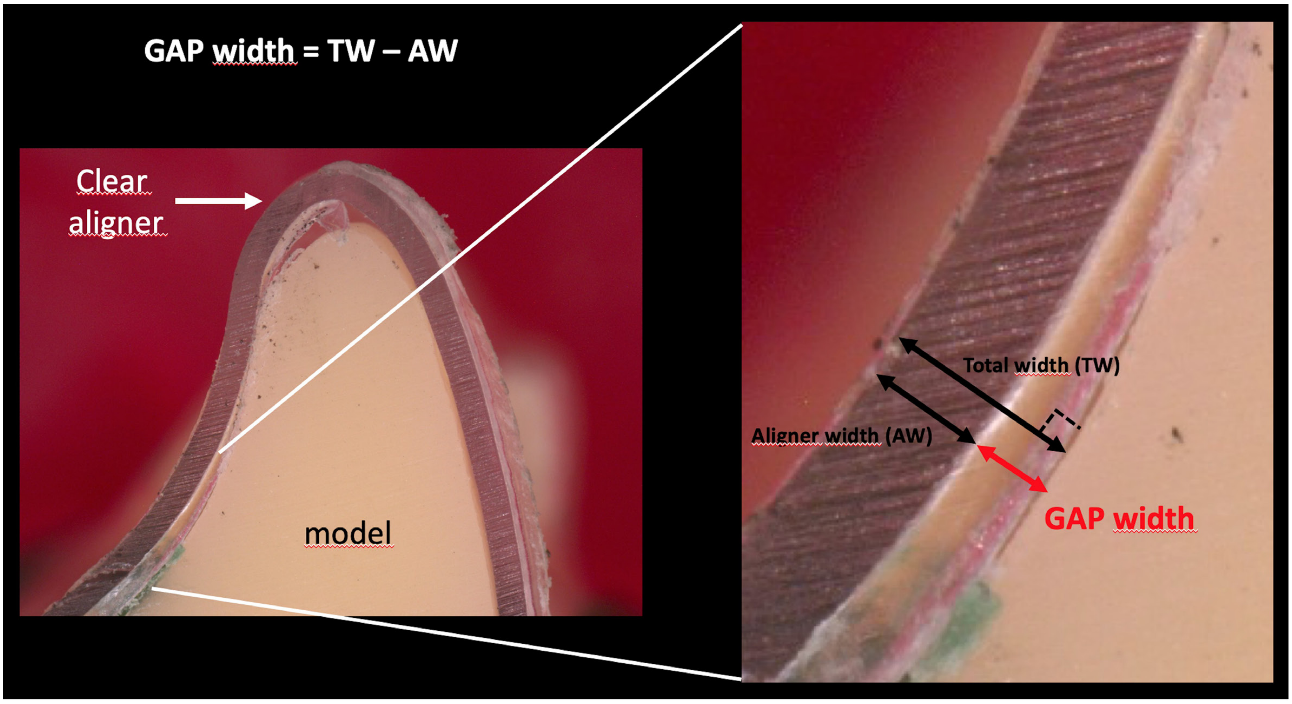

Figure 2 - Measurement scheme for GAP width of thermoformed clear aligners: gap width = total width - aligner width.

Statistical analysis

Sample distribution normality was verified using the Shapiro-Wilk test. Intraclass correlation coefficient (ICC) was used to assess intra- and inter-rater similarity. Descriptive statistics were performed to analyze differences between the 3D printers considering the following variables: resolutions and different regions of the evaluated teeth. Analysis of variance (ANOVA) was used to compare the distinct 3D printers. All tests were performed using GraphPad Prism, version 10.1.2., SPSS, version 22.0, Jamovi® software, version 2.3.21.0, and Microsoft® Excel spreadsheets, version 16.64. Statistically significant values were set at $P < 0.05$. Descriptive analyses were presented in the form of tables and bar graphs with mean ± sem.

RESULTS

Examiner's evaluations (n = 39) were normally distributed ($p < 0.001$) and in between assessments of evaluators or their attempts had excellent correspondence (ICC > 0.9). The analysis of the model-aligner interface gaps for different 3D printers revealed SLA (0.051 ± 0.016 mm), DLP (0.051 ± 0.014 mm), and FDM (0.070 ± 0.022 mm) had different gap widths (Figure 3A). It led to the observation that FDM would produce higher gaps as opposed to SLA or DLP. When further checking for printer resolutions (i.e., 25 μm and 100 μm) for each printer type, a difference between resolutions was observed, in which 25 μm relates to smaller gaps between the sheet and the model (Figure 3B). Considering a regional analysis, no significant results were obtained. (Figure 3C).

A further inferential study was conducted to assess whether there was sufficient distinction between printer type and specific teeth area. This data analysis was performed with Tukey's post-hoc test and revealed no clear effects among compared variables. However, slight trends may be seen in comparisons between SLA vs. FDM ($p = 0.29$) and DLP vs. FDM ($p = 0.28$) in canine regions, where FDM resulted in comparable higher gaps to the model (Table I).

DISCUSSION

The orthodontic treatment underwent an extensive and revolutionary transformation in the past years, changing how patients, of any background, are treated in dental offices. Majorly, this change was enabled through digital processes applied to diagnostics (e.g., intra-oral scanning) and treatments (e.g., planning software for removable aligners). These aligners are developed by certified companies (i.e.

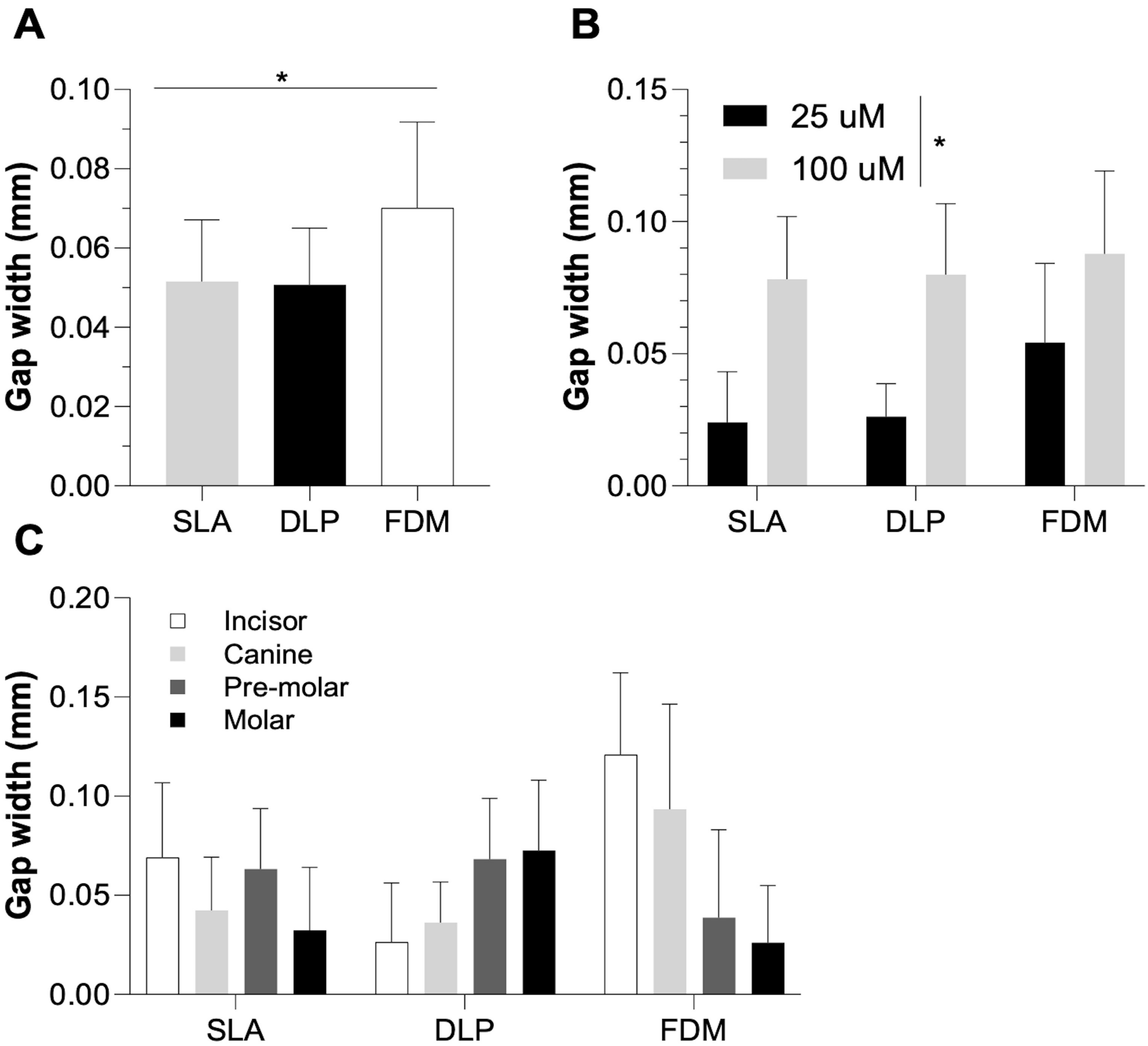

Figure 3 - Comparison of gap width between model and sheets generated from different 3D printer techniques (SLA, DLP, and FDM). A: Analytical comparison between printer techniques. One-way ANOVA, in which n = 48, * p < 0.05. B: Discrimination between resolutions (25 µm and 100 µm) and printer techniques. Two-way ANOVA, in which n = 32, * p < 0.05. C: Assessment of dental region and printer techniques. A statistical test was performed (two-way ANOVA), but no significance was identified. Data is shown as mean ± sem.

Table I - Results of the comparison of GAP width between the 3D printer technologies in different regions of the dental arch

Comparison					
Tooth	3D Printer	3D Printer	Mean difference	t	p
I	SLA	DLP	-0.00	-0.14	0.98
I	SLA	FDM	-0.06	-1.06	0.54
I	DLP	FDM	-0.05	-0.92	0.62
C	SLA	DLP	-0.08	0.00	1.00
C	SLA	FDM	-0.07	-1.52	0.29
C	DLP	FDM	-0.07	-1.53	0.28
P	SLA	DLP	-0.01	-0.26	0.96
P	SLA	FDM	-0.03	-0.68	0.77
P	DLP	FDM	-0.02	-0.42	0.90
M	SLA	DLP	-0.01	-0.30	0.95
M	SLA	FDM	-0.02	-0.66	0.78
M	DLP	FDM	-0.01	-0.35	0.93

Note: ANCOVA followed by Tukey's test (post hoc). Statistically significant values at p < 0.05.

full-service system) or orthodontists using 3D printers as a tool for sequential digital modeling and thermoforming [18]. Through this new context, this study aimed to assess how 3D printer optimizations may lead to novel approaches and efforts to enhance clinical treatment.

After synthesizing sheets using different types of printers (FDM, SLA, and DLP) and resolutions (25 and 100 μm), gap measures between the model and sheet were taken by different examiners for further analyses. Firstly, it was observed that printing resolution is a key factor for the thermoforming process of aligners and their clinical success. Anycubic Photon 3D printer (SLA technology), Up 3D Mini printer (FDM technology), and Moonray S100 printer (DLP technology) had lower values of model-sheet interface gaps when used with better resolution (i.e. 25 μm), thus suggesting an improved adaptation of the sheet to the model.

Higher resolution on axis Z (i.e. layer height) implies a thinner layer, regardless of the used printing technology. Therefore, in this study, one could expect that 3D printing with a layer height of 25 μm had a better resolution than that with a height of 100 μm. Such improvement in resolution can be seen in printed objects with smoother surfaces and more details. Moreover, it is often assumed that a better resolution implies higher precision. A study by Favero et al. (2017) investigated the effect of layer thickness on the accuracy of 3D-printed dental models. Thirty-six typodont models were digitalized before being printed on an SLA printer, in which three distinct layer thicknesses were assessed (i.e., 25, 50, and 100 μm). It was found that models with 25-μm thick layers had lower deviation values, and, therefore, a better fit to the model [19,20]. In agreement with these findings, the present study also demonstrated that all three 3D printers used exhibited differences in printing resolutions (25 μm and 100 μm); however, the mean absolute deviations were very small and are therefore likely to be clinically acceptable for orthodontic applications.

Thus, a difference of 0.02 mm in the GAP may not be clinically significant enough to influence the practitioner's choice. However, other factors—such as acquisition cost, printing speed, and production capacity—should be considered more relevant when selecting a 3D printer for aligner fabrication.

Data also showed clear evidence that the FDM technology displayed higher gaps when compared to either SLA or DLP printers. The reason could be due to FDM's printing technology, which uses the technology of deposition of plastic material by heating (filament), through an extruder nozzle. This is one of the simplest and most popular 3D printing technologies, routinely used in the most diverse areas and not specifically in Dentistry. On the other hand, SLA and DLP are technologies that use a light-curing liquid resin as raw material, either through a point laser source (SLA) or through a layered light projector (DLP). These are the most common and recent technologies used to synthesize orthodontic models in aligners' manufacture [21].

The space between the aligner and the tooth plays a critical role in determining the effectiveness of orthodontic tooth movement. Along with the elasticity of the periodontal tissues, this gap helps absorb part of the force exerted by the orthodontic appliance [22]. Therefore, minimizing the gap between the inner surface of the aligner and the tooth crown is essential for the effective transmission of orthodontic forces. Additionally, a closer adaptation of the aligner to the teeth improves retention and contributes to greater patient comfort. Ideally, the space between the thermoformed material and the tooth surface should be as small as possible.

This study demonstrated that different 3D printers produce distinct patterns of contact on the aligner surface depending on the anatomical contours of various tooth groups. Moreover, clear aligners are designed to maintain intimate contact with tooth surfaces, particularly when teeth are moved using pushing forces rather than pulling. However, the irregular anatomy of tooth surfaces can significantly influence stress distribution [23].

Cervinara et al. [24] showed that stress distribution across the tooth surface is uneven under varying orthodontic forces, largely due to differences in the adhesive properties of the orthodontic film. This finding suggests that the gap between the outer surface of the tooth and the inner surface of the aligner can directly affect the transmission of orthodontic forces through the thermoformed material.

It is currently known that the force delivered by orthodontic films diminishes rapidly, resulting in an average tooth movement of approximately

0.25 to 0.33 mm [25]. In this study, the average gap widths measured for aligners produced by the three types of 3D printers ranged from 0.05 mm (SLA) to 0.07 mm (FDM), across different printing resolutions (25 μm and 100 μm) and tooth groups—all values falling within the typical incremental movement range (0.25 to 0.33 mm) used by most clear aligner systems.

Additional investigation focused on assessing different regions of the dental arch (i.e. incisors, canines, premolars, and molars), whose results do not seem to indicate reasonable differences between these respective areas and interfaces between model and sheet, is warranted. Regarding dental groups, none of the tested 3D printers revealed significant results. The comparison between different tooth groups (incisors, canines, premolars, and molars) was the only analysis that did not show a statistically significant difference across the various 3D printing technologies used. In this study, we compared only tooth groups, not broader dental regions.

It is important to emphasize that in strictly laboratory-based studies, the operator represents a potential source of variability in measurements, even when a standardized calibration protocol is adopted. Factors such as experience, measurement technique, and visual interpretation of image reference points can influence the GAP width values obtained. In this regard, it is essential to consider the impact of the human factor and to adopt strategies—such as repeated measurements and the involvement of more than one evaluator, as conducted in the present study—to minimize this type of variability. Clinically, operational differences (such as the professional's expertise) can indeed influence the quality of the thermoforming process of clear aligners.

This study presents limitations that should be acknowledged. First, as an in vitro investigation, it provides only preliminary insights into the gap width of clear aligners produced using three distinct 3D printing technologies; therefore, additional in vivo research is warranted to enhance the generalizability and clinical applicability of the findings. Second, the analysis was limited to three types of 3D printers commonly used in clinical practice, indicating the need for future studies to explore a broader range of orthodontic materials and manufacturing methods to better understand their influence on aligner fit. Third, the small differences in gap width associated with various thermoforming and printing materials—and their potential impact on orthodontic force delivery—remain largely unexplored, highlighting the importance of further investigation to clarify their mechanical and therapeutic significance.

Since the present research used only PETG material, future studies should aim to evaluate how gap width varies in the context of different malocclusions and alternative materials, such as polyurethane or polycarbonate, when aligners are activated. It is also necessary to determine the role of attachments in modifying aligner fit and force transmission. Additionally, assessing how the observed gap width translates into actual clinical outcomes—particularly in terms of the precision and predictability of tooth movement—will be critical.

CONCLUSIONS

- The Anycubic (SLA) and Moonray S100 (DLP) 3D printers produced more accurate models compared to the UP 3D Mini (FDM) printer. This difference was more pronounced at higher printing resolutions (25 μm), but became negligible at lower resolutions (100 μm);
- No significant differences in model fit were observed along the dental arch for any of the printing technologies evaluated;
- Higher resolutions (i.e., 25 μm) were associated with improved fit between the thermoformed sheet and the printed model. Additionally, printing technologies such as SLA and DLP appear to be more suitable than FDM for the fabrication of clear aligners;
- Nevertheless, factors such as printer cost, printing speed, and production capacity may be more clinically relevant than printing resolution or GAP width when considering the practical application of 3D-printed orthodontic models.

Data availability

I have read the journal's requirements for reporting the data underlying my submission (data policy in BDJ Author instructions) and have included a Data Availability Statement within the manuscript. Data are available upon request to the corresponding author.

Author's Contributions

MM: Conceptualization, Methodology, Writing – Review & Editing. EL: Formal Analysis, Writing – Review & Editing, Supervision. VH: Software, Validation, Resources, Data Curation. ECS: Formal Analysis, Investigation, Resources, Data Curation. CASR: Formal Analysis, Investigation, Resources, Data Curation. JMA: Formal Analysis, Investigation, Resources, Data Curation. LMGP: Formal Analysis, Investigation, Resources, Data Curation. TSF: Formal Analysis, Investigation, Resources, Data Curation. ACRN: Conceptualization, Writing – Original Draft Preparation, Writing – Review & Editing, Supervision.

Conflict of Interest

No conflicts of interest declared concerning the publication of this article.

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Regulatory Statement

I declare that the research entitled "**Comparison of GAP width of thermoformed clear aligners produced by different 3D printers**" was carried out in a laboratory and does not require approval from the Research Ethics Committee because it is an *in vitro* experimental study. All experiments were performed under controlled laboratory conditions, without interaction with living beings.

Disclosure

I am the author responsible for the submission of this article and I accept the conditions of submission.

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