Original Article

Effects of printing layer thickness and build orientation on the mechanical properties and color stability of 3D-printed clear aligners

Chengzan Wu[a]; Utkarsh Mangal[b]; Na Bai[c]; Hoon Kim[d]; Geelsu Hwang[e]; Jung-Yul Cha[f]; Kee-Joon Lee[f]; Jae-Sung Kwon[g]; Sung-Hwan Choi[h]

ABSTRACT

Objectives: To determine effects of printing layer thickness and build orientation on mechanical properties and color stability of direct 3D-printed clear aligner resin.

Materials and Methods: Specimens were printed using 3D printed clear aligner resin with two printing layer thicknesses (50 μm, 100 μm) and three build orientations (90°, 60°, and 45°). Mechanical properties (tensile stress, tensile strain, and elastic modulus), color stability in coffee and artificial saliva, and roughness were then evaluated.

Results: Specimens printed with a 50 μm layer thickness and orientation at 90° demonstrated superior color stability in artificial saliva. However, all specimens showed high susceptibility to coffee staining regardless of layer thickness or orientation. Mechanical properties were improved in the order of 90° < 60° < 45° build orientation, showing statistically significant differences ($P < .05$). Surface roughness was increased in the order of 90° < 60° < 45° build orientation, showing statistically significant differences ($P < .05$).

Conclusions: Printing layer thickness and orientation exerted significant effects on mechanical properties, color stability, and surface roughness of 3D-printed clear aligner resin. (*Angle Orthod*. 2025;95:355–361.)

KEY WORDS: 3D printing clear aligner resin; Layer thickness; Build orientation; Color stability; Surface roughness

INTRODUCTION

Malocclusion can adversely affect dental esthetics, self-confidence, oral hygiene, and periodontal health. Patients pursue orthodontic treatment not only for health benefits but also to enhance their appearance and boost self-esteem.[1] The preference for clear aligners over traditional braces is growing among

[a] Graduate Student, Department of Orthodontics, Institute of Craniofacial Deformity, Yonsei University College of Dentistry, Seoul, Republic of Korea.

[b] Assistant Research Professor, BK21 FOUR Project, Yonsei University College of Dentistry, Seoul, Republic of Korea.

[c] Associate Professor, Department of Prosthodontics, The Affiliated Hospital of Qingdao University, Qingdao University, School of Stomatology of Qingdao University, Qingdao, Shandong, China.

[d] Staff Scientist, Research Institute of Agriculture and Life Sciences, College of Agriculture and Life Sciences, Seoul National University, Seoul, Republic of Korea.

[e] Professor, Department of Preventive and Restorative Sciences, School of Dental Medicine, Center for Innovation & Precision Dentistry, School of Engineering and Applied Sciences, University of Pennsylvania, Philadelphia, PA, USA.

[f] Professor, Department of Orthodontics, Institute of Craniofacial Deformity, Yonsei University College of Dentistry, Seoul, Republic of Korea.

[g] Assistant Professor, Department and Research Institute of Dental Biomaterials and Bioengineering, BK21 FOUR Project, Yonsei University College of Dentistry, Seoul, Republic of Korea.

[h] Associate Professor, Department of Orthodontics, Institute of Craniofacial Deformity, Yonsei University College of Dentistry, Republic of Korea.

Corresponding author: Sung-Hwan Choi, DDS, MSD, PhD, Department of Orthodontics, Institute of Craniofacial Deformity, Yonsei University College of Dentistry, 50-1 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea
(e-mail: selfexam@yuhs.ac)

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patients and doctors, as aligners offer greater comfort by reducing lip irritation and enhancing overall quality of life.[2]

The conventional method for producing clear aligners relies on thermoplastic materials and vacuum thermoforming, in which aligners are molded to a predesigned dentition model. This process is time-consuming, labor-intensive, and leads to significant material waste.[3] Additionally, the thermoforming process generates heat, which can affect material performance.[4] A more innovative approach is direct 3D printing of aligners, which eliminates the need for resin-based setup models. This method enhances precision, shortens production timelines, reduces costs, and minimizes supply chain complexity.[5]

Outcomes of 3D printing, an additive manufacturing method, can be influenced by various parameters, with layer thickness being a key factor that affects printing time and resolution.[6] However, faster printing could also introduce discrepancies between layers, which might impact mechanical properties.[7] A co-factor of layer thickness is build orientation, as the polymerization process in 3D printing creates anisotropic structures where strength and behavior vary with the direction of the printed layers.[8] Research has also suggested that build orientation can significantly influence color stability and stainability properties of 3D-printed products.[9] However, limited data exist on how these factors impact 3D-printed clear aligners. Therefore, it is essential to investigate how these parameters influence the printing workflow and outcomes to enhance clinical applicability.

This study aimed to investigate the impact of layer thickness and build orientation on properties of 3D-printed clear aligner resin, with a specific focus on mechanical properties and color stability. The null hypothesis was that neither the layer thickness nor the build orientation would affect mechanical properties and color stability of a 3D-printed clear aligner resin material.

MATERIALS AND METHODS

Experimental Design and Specimen Preparation

In this experiment, Tera Harz TC-85 DAC resin (Graphy, Seoul, South Korea) was used. Resin specimens were designed using the TinkerCAD computer-aided design software (Autodesk, Montreal, Quebec). The slicing software Uniz (Uniz, CA, USA) facilitated the orientation and support structure design for the samples at three distinct angles to the build platform: 45°, 60°, and 90°.

Samples were sliced with layer thicknesses of 50 μm and 100 μm, exported as ZSLR files, and printed using a Uniz NBEE printer (Uniz, CA, USA). After printing, the postcuring and postprocessing procedures were conducted according to the manufacturer's specifications.

Printed samples were grouped based on varying printing layer thicknesses and build orientations: 50 μm/45°, 50 μm/60°, 50 μm/90°, 100 μm/45°, 100 μm/60°, and 100 μm/90°.

Tensile Test

Dumbbell-shaped specimens (3.2 × 9.5 mm) were prepared in accordance with ASTM D638-5 standards for tensile testing.[3] Tensile tests were conducted under controlled conditions at 25°C and 55% humidity using a universal testing machine (Instron 5942, Instron, Norwood, MA, USA) with a crosshead speed of 5 mm/min. Each specimen was elongated at a constant rate until complete fracture occurred.

Staining of Aligners

Disc-shaped specimens (32 × 0.5 mm) were prepared for conducting color change evaluations, as clear aligners commonly used in clinical practice were typically 0.5 mm thick. A coffee (Maxim KANU Ice Blend Americano, Dongsuh, Seoul, Korea) solution was prepared with 3 g of distilled water. Artificial saliva (TMABIO, Goyang-si, Korea) was used as purchased without any additional processing. Specimens were then immersed individually in coffee or artificial saliva and stored at 37°C.

Color Change Evaluations

Color changes were characterized using a $L^*a^*b^*$ color system established by the Commission Internationale de l'Eclairage (CIE $L^*a^*b^*$).[10] The L^*, a^*, and b^* values of specimens were measured using a spectrophotometer before staining and after staining for 12 hours, 24 hours, and 7 days. Before each measurement, samples were cleaned ultrasonically for 5 minutes and dried with tissue paper. Total color change (ΔE^*) value was calculated using the equation: $\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$, quantifying the color difference over time.[10] ΔL^*, Δa^*, and Δb^* represented differences in L^*, a^*, and b^* values between 12 hours, 24 hours, or 7 days and the initial (0 hours) measurements.

Color Change Rating

The National Bureau of Standards (NBS) system was utilized to quantify visually discernible levels of color alteration (Table 1).[11] ΔE^* values were converted into NBS units using the following equation: NBS $= \Delta E^* \times 0.92$. This conversion established a

Table 1. National Bureau of Standards Ratings

National Bureau of Standards Units	Descriptions of Color Changes
0.0–0.5	Trace: extremely slight change
0.5–1.5	Slight: slight change
1.5–3.0	Noticeable: perceivable
3.0–6.0	Appreciable: marked change
6.0–12.0	Much: extremely marked change
12.0 or more	Very much: change to other color

correlation between observed color changes and a clinical standard.[12]

Surface Roughness Measurement

Surface roughness was measured using a Stylus surface profiler (DektakXT, Bruker, Billerica, MA, USA) and Bruker Software (Bruker, Billerica, MA, USA). Five disc-shaped specimens (10 × 2 mm) were tested per experimental group, with two measurements taken per specimen to determine the average roughness (Ra) value. The stylus with a 524 μm range, measured across 4,500 μm at an applied force of 1 mg, and a speed of 100 μm/s.

Statistical Analysis

Data were presented as mean ± standard deviation. Statistical differences in results were assessed using two-way analysis of variance (ANOVA) with printing layer thickness and build orientation, and Tukey's post-hoc test for multiple comparisons. The statistical analysis was conducted using Past v.4.03 software (Oyvind Hammer, 2022) with a significance level set at $P < .05$.

RESULTS

Tensile Test

A significant interaction between layer thickness and build orientation was observed in two-way ANOVA ($P < .05$), affecting mechanical properties in tensile tests, except for fracture strain. Both tensile stress at yield and elastic modulus decreased as build orientation increased (Figure 1A,B). Fracture strain also decreased with increasing build orientation for the same layer thickness (Figure 1C). In the 50 μm group, the 90° build orientation showed the highest tensile strain at yield (Figure 1D). However, no statistically significant difference in tensile strain at yield was found in the 100 μm group.

Color Change Evaluations

Color measurements were analyzed quantitatively, revealing a significant interaction between layer thickness and build orientation after 12 hours of coffee staining ($P < .05$, two-way ANOVA). Build orientation significantly influenced color change in coffee (Figure 2A). However, after 24 hours and 7 days of staining, neither build orientation nor layer thickness had a significant effect on color change (Figure 2B,C). After 12 hours of coffee staining, a high ΔE^* value was noted, with the 50 μm/90° group showing significantly

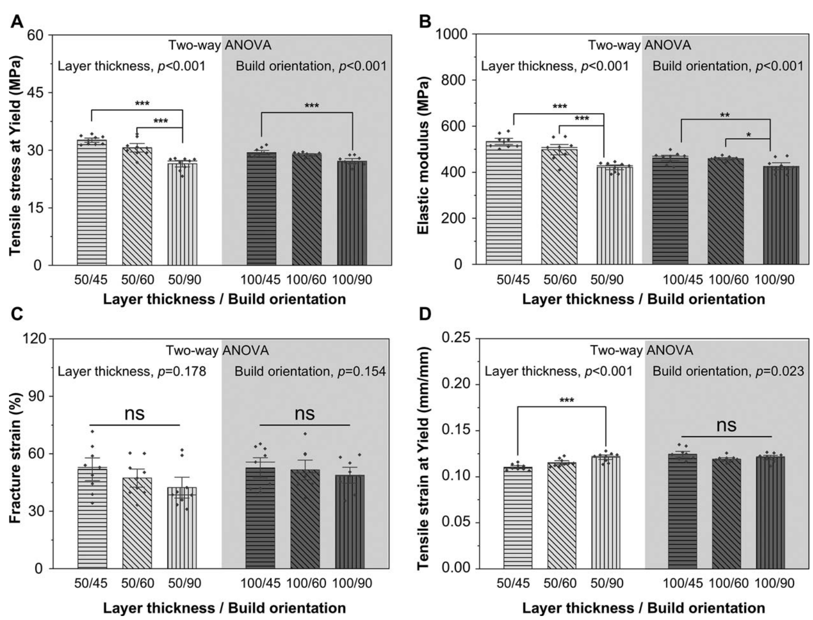

Figure 1. Results of tensile test. Comparison of (A) tensile stress at yield, (B) elastic modulus, (C) fracture strain, and (D) tensile strain at yield. A post-hoc Tukey's honestly significant difference (HSD) test was performed for multiple comparisons. (n = 9; * $P < .05$; ** $P < .01$; *** $P < .001$; ns indicates not significant).

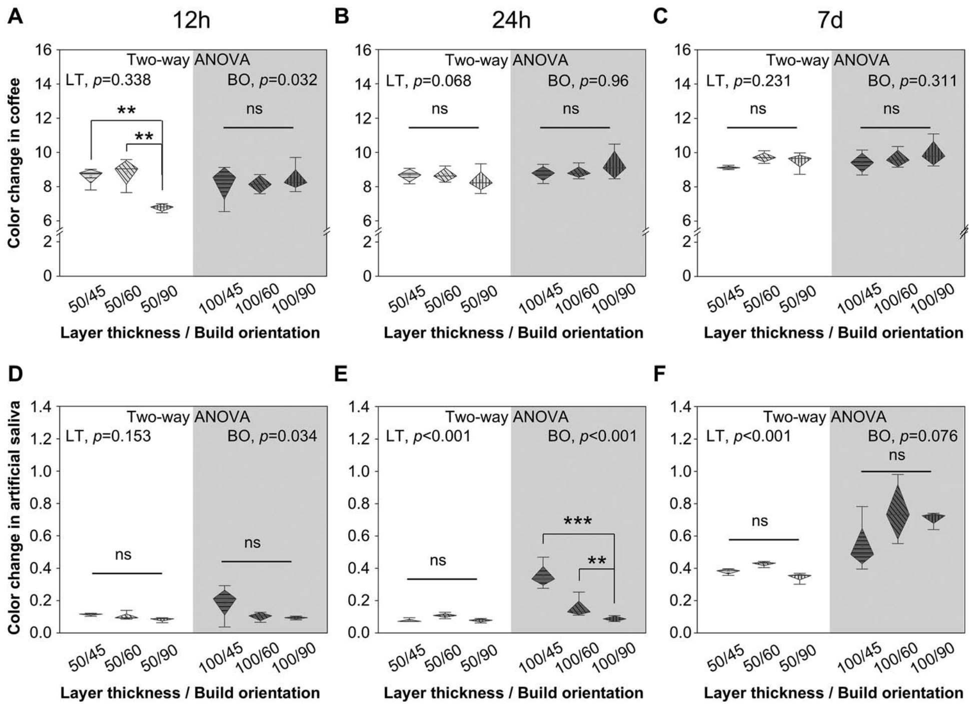

Figure 2. Color change of each group in coffee and artificial saliva at various time intervals. The first line displays the coffee-stained sample, while the second line exhibits the sample stained with artificial saliva. (A, D) Stained for 12 hours; (B, E) 24 hours; (C, F) 7 days. LT indicates layer thickness; BO, build orientation. A post-hoc Tukey's honestly significant difference (HSD) test was performed for multiple comparisons. (n = 4; ** $P < .01$; *** $P < .001$; ns indicates not significant).

less color change than the other groups (Figure 2A). As staining time increased, ΔE* continued to rise, but no significant differences were observed among the groups at 24 hours or 7 days (Figure 2B,C).

A significant interaction between layer thickness and build orientation was observed after 24 hours of artificial saliva staining ($P < .05$, two-way ANOVA), but not after 12 hours or 7 days. Build orientation significantly influenced color change in artificial saliva before the 24-hour staining ($P < .05$, Figure 2D,E). In the 100 μm layer thickness group, smaller build orientations resulted in higher ΔE* values. Layer thickness also significantly affected color change after 24 hours ($P < .05$, Figure 2E,F). As exposure time in artificial saliva increased, the ΔE* value rose markedly, especially in the 100 μm group.

NBS Rating

After 12 hours of coffee staining, all specimen groups displayed significant color changes (Figure 3A), with coloration gradually intensifying over time. In contrast, the experimental group with a 50 μm layer thickness showed only minimal color change after 7 days in artificial saliva, regardless of build orientation (Figure 3A). After 7 days, only the 100 μm thickness group exhibited slight color changes in artificial saliva, whereas the other groups maintained excellent color stability with negligible changes. After 7 days of staining, the coffee-stained samples developed a noticeable brown hue, whereas the artificial saliva samples remained largely transparent (Figure 3B). No significant color differences were observed within each respective staining group.

Surface Roughness

A significant interaction between layer thickness and build orientation was observed in the two-way ANOVA ($P < .05$), showing that both factors influenced surface roughness (Figure 4). The smoothest surfaces were achieved with a 90° build orientation, regardless of layer thickness. Reducing the build orientation significantly increased surface roughness, and thicker printed layers under the same orientation also resulted in rougher surfaces.

DISCUSSION

The present study aimed to investigate the impact of different printing layer thicknesses and build orientations on 3D printing clear aligner resin. Experimental results demonstrated that the mechanical properties and color stability of clear aligner resin were affected by layer thickness and build orientation, thereby causing rejection of the null hypotheses.

The evaluated mechanical properties of 3D-printed clear aligner resin were affected by both layer thickness

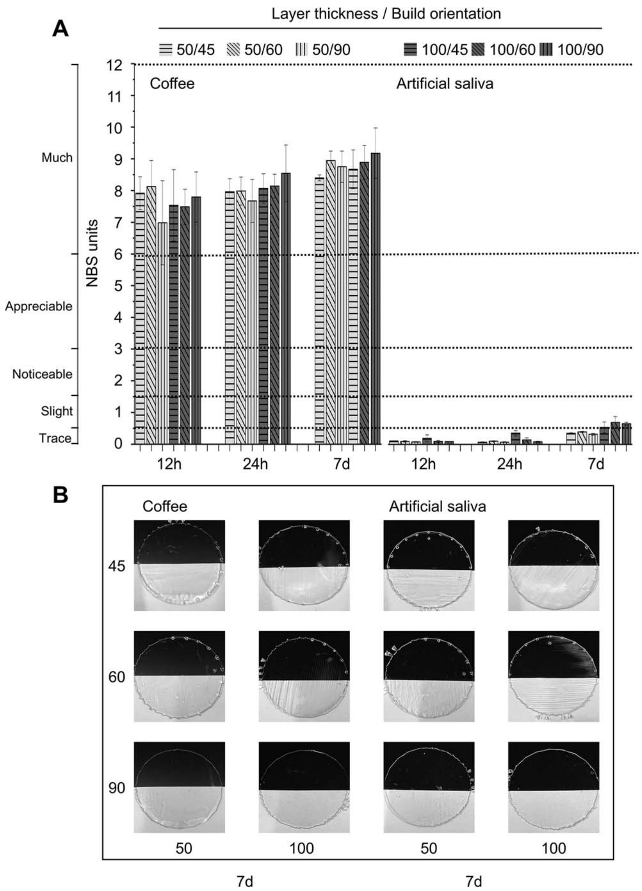

Figure 3. Color change ratings and sample images. (A) NBS units and color change ratings of each group in coffee and artificial saliva at various time intervals, (B) real sample images of color changes after 7 days. NBS indicates National Bureau of Standards.

and build orientation. Samples printed at 45° and 60° had significantly higher tensile properties than those printed at 90°. These results were in agreement with previous studies using 3D printing resins.[13] Additionally, previous findings suggested that specimens oriented vertically to the load direction exhibited inferior mechanical properties due to weaker interlayer adhesion compared to intralayer strength.[14] However, a recent study showed no marked effect in break strength of the same resin, which was similar at horizontal and vertical orientation.[15] Considering comparable results to vertical samples in this study, intermediate layer orientation may have a higher effect on tensile features. However, no significant differences in fracture strain were observed across different build orientations, suggesting that build orientation has a minimal impact on surface brittleness, reducing the risk of failure during laboratory finishing.

The increasing popularity of clear aligners is largely driven by their superior esthetics, making color stability crucial.[16] In this study, coffee staining caused

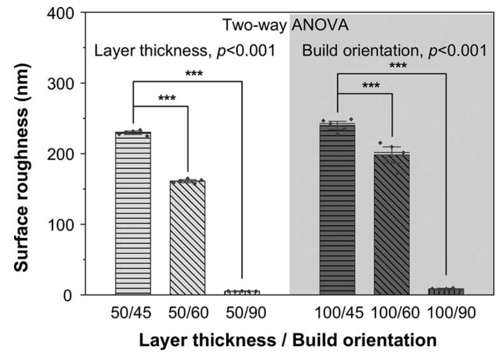

Figure 4. Results of surface roughness. A post-hoc Tukey's honestly significant difference (HSD) test was performed for multiple comparisons. (n = 5; *** $P < .001$).

significant color changes within just 12 hours. This may have been due to the polyurethane base of the TC 85 resin, known for its susceptibility to staining agents.[17] Notably, the sample with a 50 µm layer thickness and a 90° build orientation showed significantly less color change in the first 12 hours, suggesting enhanced resistance to coffee staining over a short period compared to the other groups.

The influence of build orientation on color change in artificial saliva was more pronounced than layer thickness within the initial 24-hour period. Early color changes in clear aligner resin were primarily driven by surface roughness, as research shows that textured surfaces tend to interact more with dyes, accelerating pigment accumulation.[18] By the seventh day, layer thickness became a key factor in color alteration, with thinner layers (50 µm) showing better color stability over extended staining periods. This may have been because thicker layers could produce less uniform interlayer adhesion, resulting in microgaps and increased porosity,[19] which traps staining agents more easily than smoother, thinner layers.

The NBS system effectively correlated color variations in dye samples with clinical standards, highlighting the impact of these changes. All experimental groups showed significant color changes after 12 hours of immersion in coffee. To maintain color stability, patients should be advised to minimize direct contact between 3D-printed clear aligners and coffee or similar beverages, including any residual coffee on teeth. The aligners should remain unaffected by saliva, as they are continuously exposed to it during use. A smaller build orientation (45°) exhibited pronounced color changes during the initial stages of artificial saliva staining, with samples printed at a 100 µm layer thickness showing even greater instability. Given the more complex composition of natural saliva compared to artificial saliva, it is likely to exert a stronger influence on color stability.[20] Conversely, samples oriented at 90° displayed improved color stability, particularly with the thinner printing layer thickness of 50 μm being more optimal.

The experimental group 100 μm/45° exhibited the highest level of surface roughness. It was found that reducing build orientation and increasing layer thickness led to higher surface roughness of the samples. The build orientation of 45° was linked stepwise, and the step edges between layers induced higher surface roughness.[14] The layer thickness of 50 μm could mitigate the staircase effect and improve surface smoothness.[19]

This study provides valuable insights into the impact of printing layer thickness and build orientation on mechanical properties and color stability of 3D-printed clear aligner resin. Results suggest that opting for a thinner printing layer thickness of 50 μm and a build orientation of 90° yields the minimum surface roughness and enhances color stability. However, limitations exist due to the differences between experimental specimens and the actual morphology of clear aligners. Further investigation is needed to establish clinical relevance by examining clear aligners with varying printing layer thicknesses and build orientations. Additionally, previous research showed that printing orientation influences the accuracy of orthodontic appliances.[21] Future research should explore how different printing directions (labial, posterior, and buccal) affect the accuracy of 3D-printed clear aligners in treating crowded malocclusion cases.

CONCLUSIONS

- Mechanical properties and color stability of 3D-printed clear aligner resins are influenced by printing layer thickness and build orientation.
- This study provides a theoretical basis for selecting printing parameters for 3D-printed clear aligners.
- Opting for a thinner printing layer thickness of 50 μm and a build orientation of 90° results in reduced surface roughness and improved color stability.

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REFERENCES

1. De Couto Nascimento V, De Castro Ferreira Conti AC, De Almeida Cardoso M, Valarelli DP, De Almeida-Pedrin RR. Impact of orthodontic treatment on self-esteem and quality of life of adult patients requiring oral rehabilitation. *Angle Orthod.* 2016;86(5):839–845.
2. Tartaglia GM, Mapelli A, Maspero C, et al. Direct 3D printing of clear orthodontic aligners: current state and future possibilities. *Materials (Basel).* 2021;14(7):1799.
3. Wu C, Mangal U, Seo JY, et al. Enhancing biofilm resistance and preserving optical translucency of 3D printed clear aligners through carboxybetaine-copolymer surface treatment. *Dent Mater.* 2024;40(10):1575–1583.
4. Pratto I, Busato MCA, Bittencourt PRS. Thermal and mechanical characterization of thermoplastic orthodontic aligners discs after molding process. *J Mech Behav Biomed Mater.* 2022;126:104991.
5. Bichu YM, Alwafi A, Liu X, et al. Advances in orthodontic clear aligner materials. *Bioact Mater.* 2023;22:384–403.
6. Grymak A, Waddell JN, Aarts JM, Ma S, Choi JJE. Evaluation of wear behaviour of various occlusal splint materials and manufacturing processes. *J Mech Behav Biomed Mater.* 2022;126:105053.
7. Dias Resende CC, Quirino Barbosa TA, Moura GF, et al. Cost and effectiveness of 3-dimensionally printed model using three different printing layer parameters and two resins. *J Prosthet Dent.* 2023;129(2):350–353.
8. Unkovskiy A, Bui PH, Schille C, Geis-Gerstorfer J, Huettig F, Spintzyk S. Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin. *Dent Mater.* 2018;34 (12):e324–e333.
9. Lee EH, Ahn JS, Lim YJ, Kwon HB, Kim MJ. Effect of layer thickness and printing orientation on the color stability and stainability of a 3D-printed resin material. *J Prosthet Dent.* 2022;127(5):784.e1–784.e7.
10. Johnston WM. Color measurement in dentistry. *J Dent.* 2009;37 Suppl 1:e2–6.
11. Liu CL, Sun WT, Liao W, et al. Colour stabilities of three types of orthodontic clear aligners exposed to staining agents. *Int J Oral Sci.* 2016;8(4):246–253.
12. Da Silva DL, Mattos CT, De Araújo MVA, De Oliveira Ruellas AC. Color stability and fluorescence of different orthodontic esthetic archwires. *Angle Orthod.* 2013;83(1): 127–132.
13. Schittecatte L, Geertsen V, Bonamy D, Nguyen T, Guenoun P. From resin formulation and process parameters to the final mechanical properties of 3D printed acrylate materials. *MRS Commun.* 2023;13(3):357–377.
14. Shim JS, Kim JE, Jeong SH, Choi YJ, Ryu JJ. Printing accuracy, mechanical properties, surface characteristics, and microbial adhesion of 3D-printed resins with various printing orientations. *J Prosthet Dent.* 2020;124(4):468–475.
15. Camenisch L, Polychronis G, Panayi N, et al. Effect of printing orientation on mechanical properties of 3D-printed orthodontic aligners. *J Orofac Orthop.* 2024. Online ahead of print.
16. Macrì M, Murmura G, Varvara G, Traini T, Festa F. Clinical performances and biological features of clear aligners materials in orthodontics. *Front Mater.* 2022;9.

17. Šimunović L, Čekalović Agović S, Marić AJ, et al. Color and chemical stability of 3D-printed and thermoformed polyurethane-based aligners. *Polymers (Basel).* 2024;16(8):1067.
18. Lee YK, Lu H, Oguri M, Powers JM. Changes in color and staining of dental composite resins after wear simulation. *J Biomed Mater Res B Appl Biomater.* 2007;82(2):313–319.
19. Borella PS, Alvares LAS, Ribeiro MTH, et al. Physical and mechanical properties of four 3D-printed resins at two different thick layers: an in vitro comparative study. *Dent Mater.* 2023;39(8):686.
20. Gal J-Y, Fovet Y, Adib-Yadzi M. About a synthetic saliva for in vitro studies. *Talanta.* 2001;53(6):1103–1115.
21. Elshebiny T, Menezes LMD, Matthaios S, Tsolakis IA, Palomo JM. Effect of printing technology and orientation on the accuracy of three-dimensional printed retainers. *Angle Orthod.* 2024;94(6):657–663.