*Original Article*

# Effect of aging and mechanical brushing on color stability and translucency of three-dimensionally printed and thermoformed aligners of different thicknesses

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## ABSTRACT

**Objectives:** The aim of this study was to evaluate the effect of aging and mechanical brushing on the color stability and translucency of three-dimensionally (3D) printed and thermoformed transparent aligners (clear aligners [CAs]) of different thicknesses.

**Materials and Methods:** Three types of CAs (Dentsply Sirona Essix [Group 1], Scheu-Dental Thermoforming Foils [Group 2], and 3D-printed Nexdent [Group 3]) in two thicknesses (0.75 mm and 1.0 mm) were used. Each group was divided into cleaned and noncleaned subgroups (n = 10). Samples were aged in artificial saliva and subjected to mechanical brushing. Color differences ($\Delta E_{00}$) and relative translucency parameter values ($RTP_{00}$) were recorded at 1-week intervals over 4 weeks. Statistical analyses included generalized linear models and repeated measures analyses of variance (ANOVAs) for normally distributed parameters, and robust ANOVAs and Friedman tests for nonnormally distributed parameters ($P < .05$).

**Results:** Group 1 had the highest mean $RTP_{00}$ values, while Group 3 had the lowest mean $RTP_{00}$ values. Noncleaned CAs exhibited higher $RTP_{00}$ values than cleaned CAs ($P < .05$). $RTP_{00}$ values decreased significantly over time, with Group 3 showing notable differences between cleaned and noncleaned subgroups. Thinner materials (0.75 mm) displayed greater color changes than thicker ones (1 mm).

**Conclusions:** 3D-printed CAs demonstrated more significant color variation and less translucency in comparison to thermoformed CAs. Regular cleaning helps maintain translucency and color stability, but the choice of aligner material is crucial. (*Angle Orthod*. 2025;00:000–000.)


**KEY WORDS:** 3D Printing; Aligner; Color stability; Translucency parameter



## INTRODUCTION

Increasing demand for clear aligners (CAs) in recent years has necessitated the development of more esthetic and durable orthodontic materials. CAs can be fabricated using either ready-made thermoforming techniques or directly through three-dimensional (3D) printing.[1] In orthodontics, 3D printers have become crucial for producing CAs that meet the high esthetic and comfort demands of patients.[2] Thermoplastic CAs can be 3D-printed accurately from a digital image of the teeth, eliminating the need for physical models, reducing costs, and enhancing treatment performance and patient comfort.[3,4] Thermoforming is the process of heating a polymer sheet until it becomes flexible and then molding it over a tooth to make an aligner.[5] In comparison, 3D printing, or additive manufacturing, builds the aligner layer by layer directly from a digital model, with the mechanical and physical properties of the print material being affected by the thickness of each printed layer.[6] The latest breakthrough in CA therapy is centered on the direct printing of aligners.[7]

CAs are used not only for short periods during orthodontic tooth movements but also for long-term retention after orthodontic treatment.[8] Due to esthetic and comfort concerns, adults prefer that transparency

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and light permeability are not compromised during the use of CAs. Color stability is crucial for CAs, as any color change can significantly reduce their esthetics. Discoloration indicates aging or material damage caused by stain accumulation, dissolution of material components, and fluid absorption.[9] Authors of previous studies have focused on the mechanical properties and biomechanics of individual tooth movements in CA treatment.[10] However, research on the optical and esthetic stability of CAs is limited. Ideally, the color stability of each aligner should be maintained for the duration of aligner wear.

3D-printing offers numerous advantages, including the capability to fabricate CAs with intricate geometries and customized fittings. However, comparison of the optical properties of the material, including different thicknesses and mechanical cleaning factors, with thermoformed materials has not been adequately investigated. The aim of this study was to evaluate and compare the color stability and translucency of three types of orthodontic CA materials with two different thicknesses before and after exposure to artificial saliva solutions and according to cleaning procedures at different times. The research hypothesis was that the main effects or interactions of thickness, orthodontic material type, and cleaning method would not affect the color stability and translucency parameters at different aging times.

## MATERIALS AND METHODS

### Manufacturing of the Aligners

Previous studies were reviewed within the parameters examined in this study.[1,11] Sample size calculation was performed using the G*Power 3.1.9.4 program, based on parameters examined in previous studies. The statistical significance level was set at $\alpha = 0.05$. In the analysis including three main groups, two thickness groups, and two cleaning groups (for a total of 12 groups) and measurement intervals with an effect size of 0.25 (medium effect size, Cohen's f), 5% margin of error ($\alpha$ err prob = 0.05), and 95% power (1-$\beta$ err prob = 0.95), the correlation between measurements was 0.5, and the sphericity correction coefficient ($\varepsilon$) was 1.0. As a result of the calculations, it was determined that a total of at least 84 samples should be reached, assuming equally seven samples for each group. In this study, it was decided to include 10 samples in each subgroup.

The acrylic upper teeth and base of a maxillary phantom jaw model were scanned with a 3D scanner (Trios 3, 3Shape, Copenhagen, Denmark), and a STL file of upper teeth was obtained. The STL file was then converted into a series of standard printed resin upper jaw models. The materials used in the study were chosen in two thicknesses due to the use of 125 $\times$ 0.75 mm in orthodontic tooth movement with CAs and 125 $\times$ 1 mm being the preferred size for retainer plates after orthodontic treatment. Different thicknesses of the thermoformed plates were chosen: Dentsply Sirona Essix (Group 1), Scheu-Dental Thermoforming Foils (Group 2), and 3D-printed Nexdent (Group 3). Detailed descriptions of the main groups are (subgroups are described in more detail in Figure 1):

- Dentsply Sirona Essix ACE Plastic Clear ø 125 $\times$ 0.75 mm (PETG, Dentsply Sirona Orthodontics Inc., Fla).
- Dentsply Sirona Essix ACE Plastic Clear ø 125 $\times$ 1 mm. (PETG).
- Scheu-Dental CA Pro Thermoforming Foils, ø 125 $\times$ 0.75 mm (Scheu-Dental GmbH, Iserlohn, Germany, Product 22027).
- Scheu-Dental Duran + Thermoforming Foils, ø 125 $\times$ 1 mm (Scheu-Dental GmbH, Product 21371).

### Sample Preparation

Transparent thermoplastic sheets were transformed into transparent dental CAs of 0.75 mm and 1 mm thickness under the vacuum thermoforming process with 4 bar pressure at 700°C as per the manufacturer's instructions (Biostar, Scheu-Dental GmbH). A total of 80 CAs were thermoformed.

On the previous standard maxillary STL model file, the STL folders for 125 $\times$ 0.75 mm and 125 $\times$ 1 mm 3D CAs were designed using Clear Aligner Studio software (3Shape) and printed using 3D Sprint Software V2.13 (Vertex-Dental BV, Soesterberg, Netherlands). NextDent Ortho Flex (transparent 3D print material for splints and retainers, Vertex-Dental BV) and NextDent 5100 3D Printer and LC-3D Print Box UV Post Curing Unit (Vertex-Dental VB) were used to produce different-sized 3D CAs according to the guidelines provided by the manufacturer. A total of 40 CAs were printed for these two dimensions (Group 3).

Finally, the three main groups were divided into two as 0.75 mm and 1 mm, and each subgroup was divided into two subgroups as daily cleaned and non-cleaned. A total of 120 samples were prepared for this study: 12 groups (n = 10 each; Figure 1).

### Aging Procedure

All specimens were kept in artificial saliva in a Nuve Incubator (Ankara, Turkey) at 37°C for 4 weeks. CAs were immersed in 50 mL of artificial saliva in a glass beaker, as reported in a previous study.[12] The components of artificial saliva were as described in a previous study,[13] and the solution was renewed daily. For

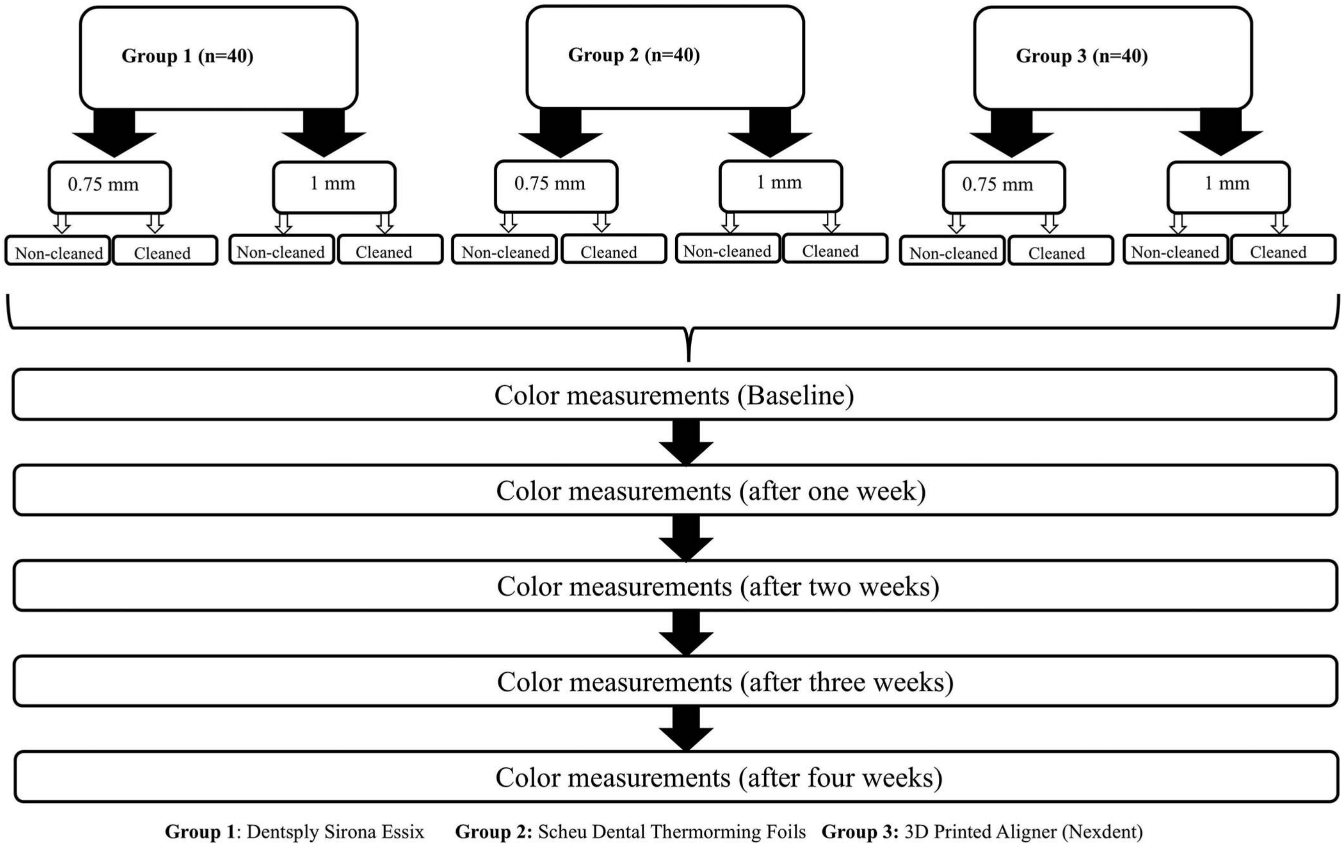


**Figure 1.** Flowchart of the study.

mechanical cleaning of the samples in the daily cleaning group, cleaning was accomplished for 30 seconds using a Colgate 360° whole-mouth clean medium toothbrush, and Colgate cavity protection fluoride toothpaste was applied.[14] The color measurement was conducted on the buccal midregion of tooth number 11 on each aligner.

## Determination of Color Change ($\Delta E_{00}$) Values

The color values of the CAs were measured on a white background (L = 96, a = 0, b = 1; GC3; Danes Picta) with a spectrophotometer (VITA Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany; probe area: 5 mm). A silicon matrix was prepared with a silicon impression to standardize the measurements. A perforation area (buccal midregion of tooth on each aligner) was created in the silicon matrix by removing the measurement area suitable for the size of the spectrophotometer tip with a 6-mm diameter circular cutting tool. Each sample was subjected to three measurements, and the mean value was calculated. The $\Delta E_{00}$ value according to time intervals was calculated using the CIEDE 2000 formula system:[15]

$$\Delta(1:1:1) = \left[\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)\right]^{1/2}.$$

The formula descriptions were presented in previous studies.[16,17] Here, $\Delta E_{00}$ values were calculated according to time intervals as $\Delta E1_{00}$ (baseline − after 1 week aging), $\Delta E2_{00}$ (baseline − after 2 weeks aging), $\Delta E3_{00}$ (baseline − after 3 weeks aging), and $\Delta E4_{00}$ (baseline − after 4 weeks aging). The $\Delta E_{00}$ threshold was set at 0.8 for perceptibility and 1.8 for acceptability.[18]

## Determination of Relative Translucency Parameter ($RTP_{00}$) Values

The same spectrophotometer was used for translucency evaluation. Color values of the samples were placed on white (L = 96, a = 0, b = 1) and black (L = 8, a = 1, b = −1) backgrounds. The $RTP_{00}$ values of the same specimen were measured at baseline ($RTP0_{00}$), after 1 week ($RTP1_{00}$), after 2 weeks ($RTP2_{00}$), after 3 weeks ($RTP3_{00}$), and after 4 weeks

($RTP4_{00}$) aging. The values were calculated using the CIEDE2000 (1:1:1) color formula:[17,19]

$$RTP_{00} = \left[\left(\frac{L' - L'_W}{K_L S_L}\right)^2 + \left(\frac{C'_B - C'_W}{K_C S_C}\right)^2 + \left(\frac{H'_B - H'_W}{K_H S_H}\right)^2 + \left(\frac{C'_B - C'_W}{K_C S_C}\right)\left(\frac{H'_B - H'_W}{K_H S_H}\right)\right]^{1/2}.$$

The terms within the formula have been previously stated in detail (subscript B: black background; subscript W: white background).[19,20] The relative translucency parameter differences ($\Delta RTP_{00}$) were calculated $\Delta RTP_{00} = RTP_{00final} - RTP_{00baseline}$. The time intervals of $\Delta RTP_{00}$ values were determined as $\Delta RTP1_{00}$, $\Delta RTP2_{00}$, $\Delta RTP3_{00}$, and $\Delta RTP4_{00}$. Translucency differences were evaluated using the translucency perceptibility ($TPT_{00} = 0.62$) and acceptability ($TAT_{00} = 2.62$) thresholds.[19]

### Statistical Analyses

The obtained data were analyzed with SPSS version 23 (IBM, Armonk, NY) and Jamovi (Jamovi Project, version 2.3.28, https://www.jamovi.org). Data distribution was analyzed according to Kolmogorov-Smirnov test and Skewness-Kurtosis values. Generalized linear models were used to compare the relative translucency parameter ($RTP_{00}$) that fit the normal distribution according to thickness type, cleaning method, time, and material type. Multiple comparisons were performed using the Bonferroni test. Generalized linear models were used to compare the parameters $\Delta E1_{00}$ (baseline − after 1 week aging) and $\Delta E3_{00}$ (baseline − after 3 weeks aging), which fit the normal distribution according to the thickness type, cleaning method, and plaque type. Robust analyses of variance (ANOVAs) were used to compare $\Delta E2_{00}$ (baseline − after 2 weeks aging) and $\Delta E4_{00}$ (baseline − after 4 weeks aging), which did not conform to a normal distribution according to thickness type, cleaning method, and plaque type. Repeated measures ANOVAs were used to compare values measured three or more times that conformed to a normal distribution. The Friedman test was used to compare values measured three or more times that did not conform to a normal distribution. Multiple comparisons were made with the Dunn test. Results are presented as means ± standard deviations, trimmed means ± standard errors, and medians (minima–maxima) for data. The significance level was $P < .05$.

## RESULTS

Regarding translucency, $RTP_{00}$ values decreased over time for all groups, with 3D-printed aligners demonstrating a more rapid decline than thermoformed CAs. This collective trend suggested that both the production method and cleaning protocols critically influenced the optical properties of CAs, with 3D-printed materials being particularly vulnerable to adverse changes. When the factors affecting the $RTP_{00}$ parameter were examined (Table 1), the main effect of plaque types was found to be statistically significant on the $RTP_{00}$ parameter ($P < .001$). In Table 2, the mean $RTP_{00}$ value in Group 1 was 29.75, the mean $RTP_{00}$ value in Group 2 was 28.37, and the mean $RTP_{00}$ value in Group 3 was 15.54. In Table 1, the main effect of the cleaning method on $RTP_{00}$ was found to be statistically significant ($P < .001$). In Table 2, the mean $RTP_{00}$ value in the noncleaned group was 24.96, while the mean $RTP_{00}$ value in the cleaned group was 24.15. In Table 1, the main effect of time was found to be statistically significant on the $RTP_{00}$ parameter ($P < .001$). In Table 2, the $RTP4_{00}$ value was significantly higher than the $RTP0_{00}$ value ($P < .001$). However, the values for other times were similar. Plaque type × cleaning method interaction was found to be statistically significant on $RTP_{00}$ ($P = .006$). The combinations of Group 1 with the noncleaned subgroup and Group 1 with the cleaned subgroup showed higher mean $RTP_{00}$ values (29.89 and 29.61, respectively) than other combinations. The mean variations in $\Delta RTP_{00}$ for all groups in relation to threshold values are shown in Figure 2.

The analysis revealed that 3D-printed aligners exhibited significantly higher $\Delta E_{00}$ values than thermoformed aligners across all time intervals ($P < .05$), indicating a greater degree of color change over time. An increase in the color difference value indicates an increase in the coloration of a material. Additionally, thinner aligners (0.75 mm) showed more pronounced discoloration than thicker aligners (1 mm), suggesting that reduced material thickness may increase susceptibility to staining. Additionally, the data indicated that noncleaned aligners had significantly higher $\Delta E_{00}$ values than their cleaned counterparts, underscoring the beneficial effect of regular cleaning on maintaining color stability. Comparative color change values of all groups at all times are shown in Table 3. In Table 3, for the Group 1/0.75 mm/noncleaned subgroup, $\Delta E1_{00}$ and $\Delta E4_{00}$ values were different from each other; these were like the other groups. For the Group 1/1 mm/cleaned subgroup, $\Delta E1_{00}$ and $\Delta E4_{00}$ values were different from each other; these are like the others. For the Group 3/0.75 mm/noncleaned subgroup, $\Delta E1_{00}$, $\Delta E2_{00}$, and $\Delta E3_{00}$ values were like each other but significantly lower than $\Delta E4_{00}$. For the Group 3/0.75 mm/cleaned subgroup, the $\Delta E4_{00}$ value was found to be significantly higher than the other times. The values for $\Delta E2_{00}$ and $\Delta E3_{00}$ were different from each other. For the Group 3/1 mm/noncleaned

**Table 1.** Generalized Linear Model Results for Relative Translucency Parameter

| | Wald $\chi^2$ | df | *P* |
|---|---|---|---|
| Plaque type | 6669.351 | 2 | $<.001$* |
| Thickness | 2.453 | 1 | .117 |
| Cleaning method | 26.232 | 1 | $<.001$* |
| Time | 40.017 | 4 | $<.001$* |
| Plaque × thickness | 1.286 | 2 | .526 |
| Plaque type × cleaning method | 10.306 | 2 | .006* |
| Plaque type × time | 10.72 | 8 | .218 |
| Thickness × cleaning method | 0.457 | 1 | .499 |
| Thickness × time | 0.183 | 4 | .996 |
| Cleaning method × time | 1.76 | 4 | .780 |
| Plaque type × thickness × cleaning method | 1.941 | 2 | .379 |
| Plaque type × thickness × time | 0.252 | 8 | 1.000 |
| Plaque type × cleaning method × time | 3.228 | 8 | .919 |
| Thickness × cleaning method × time | 0.243 | 4 | .993 |
| Plaque type × thickness × cleaning method × time | 0.108 | 8 | 1.000 |

* Statistical significance at $P < .05$.

subgroup, the $\Delta E4_{00}$ value was significantly higher than $\Delta E1_{00}$ but like the $\Delta E2_{00}$ and $\Delta E3_{00}$ values. For the Group 3/1 mm/cleaned subgroup, the $\Delta E4_{00}$ value was significantly higher than $\Delta E1_{00}$ but like the $\Delta E2_{00}$ and $\Delta E3_{00}$ values. The color differences of all groups at different times are shown in Figure 3.

In addition, the main factors and interactions for color stability for all times were added in Supplemental Tables 1 through 8.

## DISCUSSION

The hypothesis under investigation was partially accepted in this study. One option for orthodontic treatment is thermoplastic orthodontic CAs, which offer a popular alternative to traditional fixed appliances such as braces.[21] Significant differences were observed between the three groups in terms of thickness, except for $\Delta E2_{00}$. At all time intervals evaluated compared with the baseline, 0.75-mm-thick materials showed higher color change than 1-mm-thick materials (Supplemental Tables 2, 5, and 8).

In this study, the $\Delta E_{00}$ value was used to quantify the degree of color change over the time interval. An increase in $\Delta E_{00}$ indicated greater color deviation, reflecting a deterioration in color stability. Conversely, a decrease in $\Delta E_{00}$ indicated an improvement in color stability.[18] The parameter $RTP_{00}$ was used for translucency. A decrease in $RTP_{00}$ values over time indicated a loss of translucency that could compromise the esthetic quality of the aligners.[17]

Thinner CAs may be more prone to staining than thicker CAs. This is attributed to the reduced material thickness, making them more susceptible to external influences.[1] The results of this research were like those in previous research, indicating that both material type and cleaning methods can influence the color stability and translucency of CAs.[6,22,23] Šimunović et al.[6] also found that 3D-printed aligners exhibited higher color stability than thermoformed aligners, particularly when exposed to staining agents. Similarly, Lombardo et al.[22] reported that different types of CAs showed varying degrees of color change after aging, with some materials exhibiting more noticeable discoloration than others. The process used to make CAs has a substantial impact on their color stability, and thermoformed aligners are less sensitive to color fluctuations than those made via 3D printing. A plastic sheet is heated to a flexible forming temperature, shaped in a mold, and then cut to produce a usable product. This technique, known as thermoforming, tends to better retain the original color integrity of the material.[24,25] A greater degree of discoloration over time may result from micropores or other modifications made to the material by 3D printing, which adds material layer by layer to form the finished product. These changes might enhance the propensity of the material to absorb colors from outside sources. It was considered that the surface morphology may affect the color stability of the 3D-printed groups produced in this study. The results of this investigation demonstrated that the color stability of thermoforming and 3D-printed aligner materials changes over time, with noticeable discoloration occurring after 7 days. Confirming this, authors have emphasized that optical, chemical, and morphological changes occur when CAs are worn in the mouth for the same period.[22,26] Color changes were more pronounced in the noncleaned groups, further emphasizing the importance of regular cleaning in maintaining the esthetic appearance of CAs. However, it is important to note that the color changes observed in this study were generally within the range of clinically acceptable thresholds.

Meme et al.[27] included 12 Invisalign CAs in their study. At the end of the study, a colorimetry analysis was performed to assess changes in color and transparency. The samples in the coloring agents showed significant color changes between the groups tested. In this study, we built on prior research into the color stability and translucency of orthodontic CAs, offering both confirmation and new insights. For instance, findings agreed with those of studies such as Liu et al.,[1] who reported the significance of material type and cleaning protocols on aligner esthetics. However, in this study, we extended on their scope by introducing a comparative analysis of both 3D-printed and thermoformed CAs, which was not thoroughly explored in previous literature. The observed discoloration thresholds in this study generally conformed to those reported by Bernard et al.,[23] yet the current findings highlight notable differences in discoloration patterns between cleaned and noncleaned groups,

**Table 2.** Descriptive Statistics and Differences for Relative Translucency Parameter[a]

| Thickness | Cleaning Method | Time | Plaque Type | | | Total |
|---|---|---|---|---|---|---|
| | | | Group 1 | Group 2 | Group 3 | |
| 0.75 mm | Noncleaned | T0 | 30.88 ± 1.09 | 29.60 ± 1.59 | 16.92 ± 2.57 | 25.80 ± 6.66 |
| | | T1 | 30.15 ± 0.98 | 29.12 ± 1.36 | 16.50 ± 3.05 | 25.26 ± 6.60 |
| | | T2 | 30.18 ± 1.74 | 28.37 ± 1.28 | 16.54 ± 2.80 | 25.03 ± 6.46 |
| | | T3 | 30.10 ± 1.71 | 28.19 ± 3.49 | 16.25 ± 2.35 | 24.85 ± 6.73 |
| | | T4 | 29.27 ± 1.19 | 28.05 ± 1.65 | 15.29 ± 2.06 | 24.20 ± 6.63 |
| | | Total | 30.11 ± 1.42 | 28.67 ± 2.05 | 16.30 ± 2.54 | 25.03 ± 6.55 |
| | Cleaned | T0 | 30.22 ± 1.36 | 29.53 ± 1.85 | 15.67 ± 3.18 | 25.14 ± 7.16 |
| | | T1 | 30.04 ± 1.20 | 29.09 ± 1.26 | 15.15 ± 2.68 | 24.76 ± 7.15 |
| | | T2 | 29.74 ± 1.18 | 27.37 ± 1.32 | 15.19 ± 3.80 | 24.10 ± 6.89 |
| | | T3 | 29.41 ± 2.23 | 27.28 ± 1.00 | 15.06 ± 3.15 | 23.92 ± 6.81 |
| | | T4 | 29.05 ± 1.84 | 27.16 ± 2.56 | 14.98 ± 1.96 | 23.73 ± 6.67 |
| | | Total | 29.69 ± 1.61 | 28.09 ± 1.92 | 15.21 ± 2.90 | 24.33 ± 6.86 |
| | Total | T0 | 30.55 ± 1.25 | 29.57 ± 1.68 | 16.29 ± 2.88 | 25.47 ± 6.86 |
| | | T1 | 30.10 ± 1.07 | 29.11 ± 1.28 | 15.83 ± 2.88 | 25.01 ± 6.83 |
| | | T2 | 29.96 ± 1.47 | 27.87 ± 1.37 | 15.87 ± 3.32 | 24.56 ± 6.64 |
| | | T3 | 29.76 ± 1.97 | 27.73 ± 2.54 | 15.65 ± 2.77 | 24.38 ± 6.73 |
| | | T4 | 29.16 ± 1.51 | 27.60 ± 2.15 | 15.14 ± 1.96 | 23.97 ± 6.60 |
| | | Total | 29.90 ± 1.52 | 28.38 ± 2.00 | 15.76 ± 2.77 | 24.68 ± 6.71 |
| 1 mm | Noncleaned | T0 | 30.00 ± 0.74 | 29.48 ± 1.77 | 16.75 ± 2.07 | 25.41 ± 6.43 |
| | | T1 | 29.74 ± 0.66 | 29.46 ± 1.39 | 16.59 ± 1.51 | 25.26 ± 6.36 |
| | | T2 | 29.82 ± 1.77 | 28.34 ± 1.20 | 16.44 ± 1.81 | 24.87 ± 6.29 |
| | | T3 | 29.68 ± 1.38 | 28.27 ± 2.90 | 16.35 ± 3.90 | 24.77 ± 6.70 |
| | | T4 | 29.14 ± 1.77 | 28.02 ± 1.39 | 15.22 ± 1.97 | 24.13 ± 6.64 |
| | | Total | 29.68 ± 1.33 | 28.72 ± 1.87 | 16.27 ± 2.37 | 24.89 ± 6.41 |
| | Cleaned | T0 | 30.05 ± 1.23 | 29.43 ± 1.49 | 14.99 ± 2.30 | 24.82 ± 7.27 |
| | | T1 | 29.73 ± 1.14 | 29.04 ± 1.68 | 14.30 ± 1.93 | 24.36 ± 7.41 |
| | | T2 | 29.47 ± 2.10 | 27.33 ± 1.69 | 14.20 ± 2.43 | 23.67 ± 7.16 |
| | | T3 | 29.35 ± 1.34 | 27.22 ± 1.13 | 14.28 ± 2.33 | 23.62 ± 6.96 |
| | | T4 | 29.00 ± 2.27 | 27.12 ± 2.50 | 14.18 ± 1.96 | 23.43 ± 7.05 |
| | | Total | 29.52 ± 1.65 | 28.03 ± 1.96 | 14.39 ± 2.13 | 23.98 ± 7.09 |
| | Total | T0 | 30.03 ± 0.99 | 29.46 ± 1.59 | 15.87 ± 2.31 | 25.12 ± 6.81 |
| | | T1 | 29.73 ± 0.91 | 29.25 ± 1.52 | 15.44 ± 2.05 | 24.81 ± 6.86 |
| | | T2 | 29.65 ± 1.90 | 27.84 ± 1.52 | 15.32 ± 2.38 | 24.27 ± 6.71 |
| | | T3 | 29.52 ± 1.33 | 27.74 ± 2.21 | 15.32 ± 3.31 | 24.19 ± 6.80 |
| | | T4 | 29.07 ± 1.98 | 27.57 ± 2.02 | 14.70 ± 1.99 | 23.78 ± 6.79 |
| | | Total | 29.60 ± 1.49 | 28.37 ± 1.94 | 15.33 ± 2.43 | 24.43 ± 6.77 |
| Total | Noncleaned | T0 | 30.44 ± 1.01 | 29.54 ± 1.64 | 16.83 ± 2.27 | 25.61 ± 6.49 |
| | | T1 | 29.94 ± 0.84 | 29.29 ± 1.35 | 16.54 ± 2.34 | 25.26 ± 6.43 |
| | | T2 | 30.00 ± 1.72 | 28.35 ± 1.21 | 16.49 ± 2.30 | 24.95 ± 6.32 |
| | | T3 | 29.89 ± 1.53 | 28.23 ± 3.12 | 16.30 ± 3.13 | 24.81 ± 6.66 |
| | | T4 | 29.20 ± 1.47 | 28.04 ± 1.48 | 15.25 ± 1.97 | 24.16 ± 6.58 |
| | | Total | 29.89 ± 1.39[a] | 28.69 ± 1.95[b] | 16.28 ± 2.45[c] | 24.96 ± 6.47[x] |
| | Cleaned | T0 | 30.14 ± 1.27 | 29.48 ± 1.63 | 15.33 ± 2.72 | 24.98 ± 7.16 |
| | | T1 | 29.89 ± 1.15 | 29.07 ± 1.45 | 14.72 ± 2.32 | 24.56 ± 7.22 |
| | | T2 | 29.61 ± 1.66 | 27.35 ± 1.48 | 14.70 ± 3.15 | 23.88 ± 6.97 |
| | | T3 | 29.38 ± 1.79 | 27.25 ± 1.04 | 14.67 ± 2.73 | 23.77 ± 6.83 |
| | | T4 | 29.03 ± 2.01 | 27.14 ± 2.46 | 14.58 ± 1.95 | 23.58 ± 6.80 |
| | | Total | 29.61 ± 1.62[a] | 28.06 ± 1.93[b] | 14.80 ± 2.57[d] | 24.15 ± 6.97[y] |
| | Total | T0 | 30.29 ± 1.14 | 29.51 ± 1.61 | 16.08 ± 2.59 | 25.29 ± 6.81[a] |
| | | T1 | 29.91 ± 1.00 | 29.18 ± 1.39 | 15.63 ± 2.48 | 24.91 ± 6.81[ac] |
| | | T2 | 29.80 ± 1.68 | 27.85 ± 1.42 | 15.59 ± 2.87 | 24.42 ± 6.64[bc] |
| | | T3 | 29.64 ± 1.66 | 27.74 ± 2.35 | 15.48 ± 3.02 | 24.29 ± 6.74[bc] |
| | | T4 | 29.11 ± 1.74 | 27.59 ± 2.06 | 14.92 ± 1.96 | 23.87 ± 6.67[b] |
| | | Total | 29.75 ± 1.51[a] | 28.37 ± 1.96[b] | 15.54 ± 2.61[c] | 24.56 ± 6.73 |

[a] Mean ± SD; no difference between main effects or interactions with the same letter. Statistical significance at $P < .05$.

particularly for 3D-printed CAs. This adds a novel dimension to existing knowledge, emphasizing the importance of material surface morphology and production methods in influencing optical properties.

Thermoformed CAs are typically marketed as transparent thermoplastic sheets. The 3D-printed CAs are built layer by layer using liquid resins.[28] These inherent differences in material composition and production

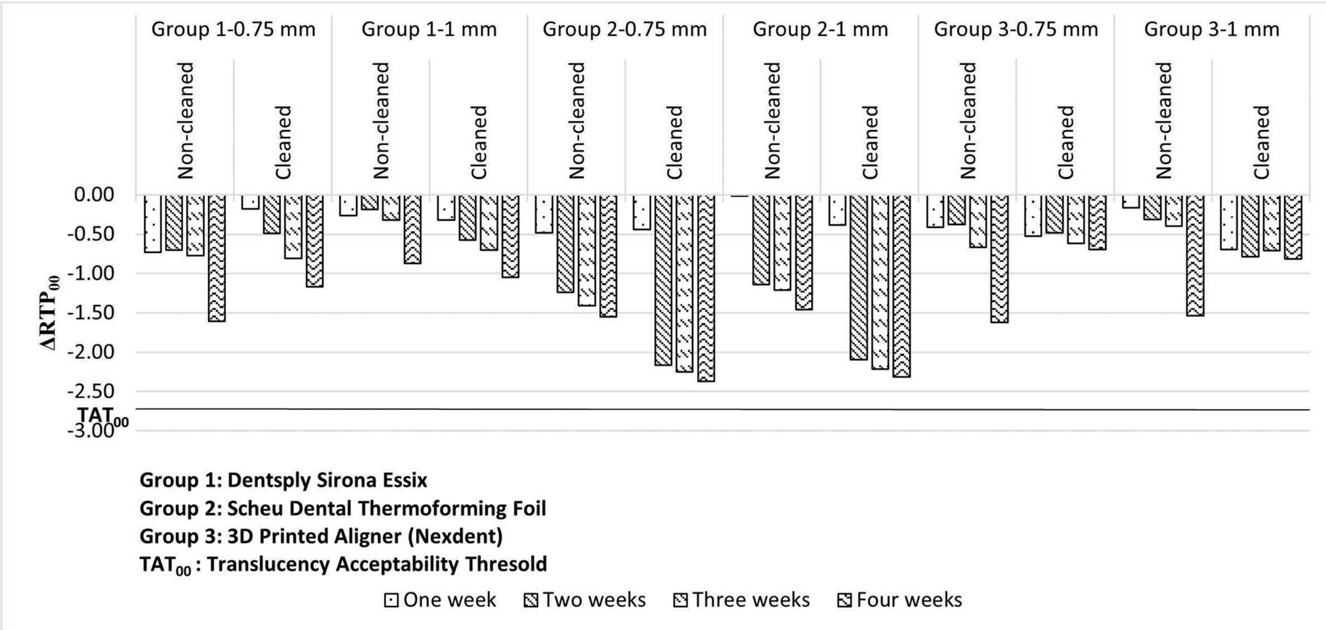


**Figure 2.** Mean changes for all $\Delta RTP_{00}$ value groups.

technique may contribute to the observed variations in translucency. Compared with conventional braces, CAs are more esthetically pleasing since they are almost undetectable. However, improper cleaning might reduce their efficacy and esthetic appeal.[29] Maintaining the smooth surface of the CAs with a soft-bristled toothbrush and nonabrasive cleaning methods helps avoid scratches that might contain germs and further

**Table 3.** Comparison of Different Times and Differences for Color Change Values [Mean ± Standard Deviation; Median (Minimum–Maximum)]

| | $\Delta E1_{00}$ (T0-T1) | $\Delta E2_{00}$ (T0-T2) | $\Delta E3_{00}$ (T0-T3) | $\Delta E4_{00}$ (T0-T4) | Test statistic | *P* |
|---|---|---|---|---|---|---|
| **Group 1 / 0.75 mm / Non-cleaned** | 1.32 ± 0.69$^{b}$<br>1.3 (0.41–2.61) | 1.88 ± 1.2$^{ab}$<br>1.62 (0.32–3.99) | 2.19 ± 1.17$^{ab}$<br>1.86 (0.4–4.04) | 3.09 ± 1.5$^{a}$<br>3.37 (0.42–4.81) | 3.243 | .037$^{*x}$ |
| **Group 1 / 0.75 mm / Cleaned** | 1.18 ± 0.64<br>1.12 (0.33–2.14) | 1.78 ± 1.13<br>1.53 (0.42–4.27) | 2.08 ± 1.27<br>1.8 (0.47–3.99) | 2.09 ± 1.56<br>1.71 (0.47–4.63) | 1.532 | .229$^{x}$ |
| **Group 1 / 1 mm / Non-cleaned** | 1.76 ± 0.46<br>1.62 (1.21–2.48) | 2.47 ± 1.37<br>1.97 (0.9–4.62) | 2.68 ± 1.11<br>2.4 (1.31–4.21) | 3.18 ± 1.19<br>3.2 (1.53–5.45) | 2.858 | .056$^{x}$ |
| **Group 1 / 1 mm / Cleaned** | 1.23 ± 0.59$^{b}$<br>1.19 (0.57–2.43) | 1.86 ± 1.07$^{ab}$<br>1.56 (0.26–3.75) | 2.12 ± 0.63$^{ab}$<br>2.1 (1.1–2.95) | 2.26 ± 0.58$^{a}$<br>2.25 (1.42–3.23) | 4.069 | .017$^{*x}$ |
| **Group 2 / 0.75 mm / Non-cleaned** | 2.05 ± 1.7<br>1.42 (0.17–4.84) | 2.12 ± 1.51<br>2.4 (0.13–4.04) | 2.82 ± 1.31<br>2.45 (1.37–5.12) | 2.84 ± 1.42<br>2.77 (0.9–5.79) | 1.006 | .405$^{x}$ |
| **Group 2 / 0.75 mm / Cleaned** | 1.84 ± 1.82<br>0.95 (0.21–5.8) | 2.53 ± 1.71<br>2.19 (0.3–5.83) | 2.56 ± 1.33<br>2.43 (0.79–4.98) | 2.69 ± 1.41<br>3.04 (0.71–5.33) | 0.976 | .419$^{x}$ |
| **Group 2 / 1 mm / Non-cleaned** | 1.93 ± 1.05<br>2.21 (0.59–3.09) | 2.1 ± 1.47<br>1.69 (0.31–4.32) | 2.65 ± 1.78<br>2.45 (0.53–5.86) | 2.82 ± 1.38<br>2.51 (1.07–5.63) | 0.886 | .461$^{x}$ |
| **Group 2 / 1 mm / Cleaned** | 1.9 ± 0.54<br>1.77 (1.07–2.89) | 2.02 ± 0.73<br>2.14 (1.01–3.06) | 2.42 ± 0.63<br>2.39 (1.57–3.81) | 2.81 ± 1.44<br>2.71 (0.27–4.93) | 2.007 | .178$^{x}$ |
| **Group 3 / 0.75 mm / Non-cleaned** | 5.19 ± 2.49<br>3.95 (2.9–10.58)$^{b}$ | 5.17 ± 1.35<br>4.85 (4.06–8.73)$^{b}$ | 5.93 ± 0.58<br>5.86 (5.11–6.84)$^{ab}$ | 7.6 ± 0.81<br>7.36 (6.87–9.54)$^{a}$ | 16.920 | .001$^{*y}$ |
| **Group 3 / 0.75 mm / Cleaned** | 4.74 ± 1.58$^{cd}$<br>4.42 (2.57–7.88) | 4.77 ± 0.87$^{c}$<br>4.76 (3.77–6.54) | 5.78 ± 1.03$^{bd}$<br>5.57 (4.94–8.21) | 7 ± 1.18$^{a}$<br>7.33 (4.96–8.58) | 13.893 | < .001$^{*x}$ |
| **Group 3 / 1 mm / Non-cleaned** | 3.34 ± 0.93$^{bc}$<br>3.51 (2.01–4.85) | 4.13 ± 0.93$^{ac}$<br>4.22 (2.71–5.45) | 4.18 ± 0.85$^{ac}$<br>4.2 (3.11–5.34) | 4.71 ± 0.81$^{a}$<br>4.81 (3.51–5.89) | 4.021 | .017$^{*x}$ |
| **Group 3 / 1 mm / Cleaned** | 3.31 ± 0.23<br>3.26 (2.94–3.72)$^{bc}$ | 4.1 ± 1.29<br>3.91 (2.62–5.86)$^{ac}$ | 4.16 ± 0.8<br>4.23 (3.11–5.7)$^{ac}$ | 4.67 ± 1.22<br>4.46 (3.54–7.86)$^{a}$ | 9.000 | .029$^{*y}$ |

* Statistical significance at $P < .05$.
x Friedman Test
y Repeated Measures Analysis of Variance
a-c There is no difference between values with the same letter.

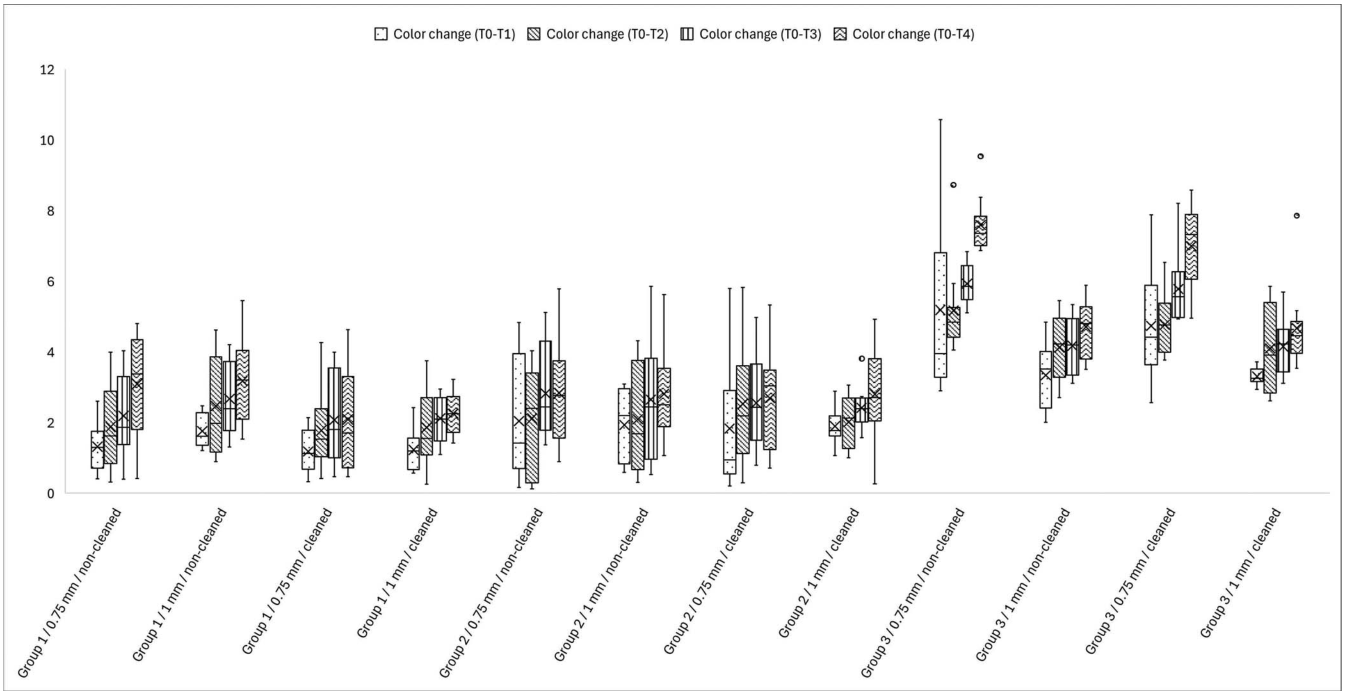


**Figure 3.** Color differences of all groups at different times.

decrease translucency.[30] The findings revealed that the type of aligner material significantly influenced the translucency,[31] with 3D-printed CAs exhibiting lower $RTP_{00}$ values than thermoformed CAs. This observation suggests that 3D-printed CAs may appear less clear than their thermoformed counterparts, potentially impacting the desired invisible appearance sought by patients undergoing CA treatment. Variations between the two types of production methods used for CAs and material qualities may be the cause of the variance in their $RTP_{00}$ values.

In this study, we also identified a significant effect of time on translucency, with a general trend of decreasing $RTP_{00}$ values over the 4 weeks. This decrease suggests that the CAs became less translucent over time, likely due to the cumulative effects of exposure to artificial saliva and potential surface changes.[11] However, the magnitude of these changes was generally small and may not be clinically perceptible to the human eye. Although the translucency values of the materials were different in all of them, the translucency change values were observed to be below the clinical acceptability values according to the time changes of all groups (Figure 2).

Effective cleaning is important to prevent bacterial accumulation on the surface during long-term aligner wear.[32] The impact of cleaning procedures in this study was in agreement with previous findings that highlighted the importance of proper cleaning in preserving the esthetics of CAs.[14,33] Chang et al.[14] reported that both mechanical and chemical cleaning methods were effective in reducing staining and maintaining the translucency of Essix retainers. Wible et al.[33] further showed that long-term cleaning habits significantly influenced the color and surface properties of copolyester retainers. Although the cleaning method used in this study was found to reduce coloration compared with the noncleaning groups, no difference was found between the two groups. The aligners were kept under artificial saliva exposure for 4 weeks, simulating intraoral conditions.[34] CAs are used not only for short periods during orthodontic tooth movement but also for extended periods as a retainer after treatment. In orthodontic tooth movements, CAs are changed once a week or every 15 days. The data obtained in this study represented both the short-term CA replacement period and the long-term retention timespan.[33,35]

The choice of aligner material and the implementation of effective cleaning protocols can significantly impact long-term esthetics and patient satisfaction with CA treatment. Clinicians should consider these factors when selecting aligner materials and provide patients with clear instructions on proper cleaning techniques to ensure optimal outcomes.

One of the limitations of this study was that it was conducted using an in vitro model, which might not accurately represent the intricate oral environment. To confirm these results, more investigation, including clinical trials, is required.

## CONCLUSIONS

- Translucency and color stability may be preserved with routine cleaning; however, color stability is greatly influenced by aligner material selection.
- 3D-printed aligners exhibited significantly greater discoloration and reduced translucency compared with thermoformed aligners.
- Thinner aligners (0.75 mm) were more susceptible to color changes than thicker aligners (1 mm).
- Regular cleaning played a critical role in preserving both color stability and translucency, though its effectiveness varied among the different materials.
- Clinicians can use these insights to provide patients with informed recommendations regarding aligner selection and care.

## SUPPLEMENTAL DATA

Supplemental Tables 1 through 8 are available online.

## DISCLOSURE

None of the authors has a competing interest.

## DATA AVAILABILITY STATEMENT

Data will be made available on reasonable request.

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