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# Effects of Different Color Measurement Methods on the Translucency and Whiteness of Resin Composites

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This study evaluated the reliability of relative translucency parameter ($RTP_{00}$) and whiteness index ($WI_D$) measurements of single-shade and multi-shade resin composites (RCs) with different thicknesses using a spectrophotometer and a mobile colorimeter application. A total of 192 specimens were prepared from six RCs, including three single-shade and three multi-shade materials, with 1 mm and 2 mm thicknesses. Color measurements were performed at baseline and after 7 days using a spectrophotometer and a mobile colorimeter application. $RTP_{00}$ values were calculated using the CIEDE2000 formula, and $WI_D$ values were calculated using the CIELAB-based formula. Reliability was assessed using intraclass correlation coefficients, and data were analyzed with robust ANOVA. Single-shade RCs showed higher $RTP_{00}$ and $WI_D$ values than multi-shade RCs. ColorMeter values were higher than spectrophotometer values. Material and method effects were significant for $\Delta RTP_{00}$ and $\Delta WI_D$, with interactions. Reliability analysis showed higher consistency for the spectrophotometer. Mobile colorimeters provide practical and cost-effective measurements, while spectrophotometers remain a more reliable option for precise color assessment. Material type, thickness, and measurement method should be considered when evaluating optical properties for clinical use.

*Keywords:* color, dental materials, resin composite, spectrophotometry, translucency, whiteness index.

## 1. INTRODUCTION

Resin composites (RCs) are widely used in anterior and posterior tooth restorations due to minimal tooth preparation, low cost, and esthetic advantages. However, successful esthetic results depend on the correct color selection [1]. For this purpose, clinicians utilize RCs of different colors and layering techniques [2]. Although color selection can be performed by applying light-cured composite samples to the tooth surface [3, 4], this method is time-consuming. Recently, optically enhanced universal single-shade RCs have been developed to achieve color harmony with surrounding tooth structures. These materials simplify shade selection in direct restorations while shortening the restorative procedure time and provide natural color adjustment, known as the blending effect, by exhibiting chromatic harmony with surrounding tooth structures after placement [5]. Color matching between dental tissues and restorative materials, color stability, and color interaction with various layers and adjacent tooth structures are important optical properties of restorative esthetic materials from a therapeutic perspective [6].

Translucency, one of the key optical characteristics, is essential for the ability of RCs to replicate the color and appearance of enamel tissue [7]. The translucency parameter (TP) of a material can be used to describe its translucency [4]. The color difference of a material that is optically uniform throughout its thickness on ideal black and white backgrounds is known as TP. Accordingly, a material with a TP value of 0 is defined as completely opaque, while a TP value of 100 is defined as complete transparency [8]. Nevertheless, if the background conditions deviate from the ideal, the application of the relative translucency parameter (RTP) is required to assess translucency differences accurately [9]. The use of the CIEDE2000 ($\Delta E_{00}$) color difference metric which more accurately reflects human color perception, is recommended for TP calculations [10, 11]. It has been reported that the use of RTP based on the actual color values of the backgrounds is more appropriate, particularly when evaluating materials that are not completely homogeneous throughout their thickness [12]. Translucency plays a critical role in achieving esthetic success; optimal translucency compatibility enhances shade matching and frequently contributes to highly satisfactory restorative outcomes [13].

The whiteness index ($WI_D$), which shows the degree of whiteness, is another optical characteristic of RCs [14]. The proposed whiteness index ($WI_D$) is a simple linear formula based on CIELAB color coordinates. It can be easily applied in electronic color measurement devices; high positive $WI_D$ values indicate higher whiteness, while low or negative values indicate lower whiteness [15]. In dentistry, this term has been introduced as a tool for assessing the degree of whiteness under both laboratory and clinical conditions [16]. Based on CIELAB, the most recent $WI_D$ for dentistry is available [15].

Although spectrophotometers provide high accuracy and reliability in color measurement processes, their routine use by clinicians is limited due to their limited cost-effectiveness. On the other hand, smartphones have become increasingly prevalent in modern society and are also starting to be used in dentistry [17]. Smartphones facilitate the acquisition and analysis of visual data thanks to their advanced camera hardware and portability [18]. Mobile

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colorimeter applications integrated into these devices offer a low-cost and accessible alternative for color measurement; they can convert image-derived data into the CIE L*a*b* color system [18].

Although the translucency parameter and whiteness index of RCs have been investigated, previous studies have been based on spectrophotometric measurements conducted under laboratory conditions. Furthermore, while existing studies generally focus on a single optical parameter or specific composites, limited attention has been paid to the combined effect of composite type, material thickness, and color measurement method. Moreover, the reliability of smartphone-based colorimeter applications for evaluating parameters related to translucency and whiteness has not yet been comprehensively assessed.

Therefore, this study provides a novel contribution by simultaneously investigating the effects of composite type (single-shade and multi-shade), specimen thickness, and measurement method on translucency and whiteness outcomes. In addition, it is among the first studies to evaluate the reliability of a smartphone-based colorimeter application for assessing these optical properties and to compare its performance with that of a spectrophotometer. The findings may contribute to the development and validation of accessible digital color assessment tools for both research and clinical dentistry.

The null hypotheses of this study were as follows:

1. There is no statistically significant difference between the translucency and whiteness index values of single-shade and multi-shade RCs with different thicknesses.
2. There is no statistically significant difference between translucency and whiteness index values obtained using different color measurement methods (spectrophotometer and mobile colorimeter application).

## 2. MATERIALS AND METHODS

### 2.1. Sample size selection

The sample size calculation was conducted using G*Power software (version 3.1.9.4; Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany) [19]. For this study, the variables included material thickness, color measurement method, and material type. Based on previous studies [14, 17], the minimal sample size for the study was determined to be $n = 6$ for each subgroup, using a 95 % confidence interval, 90% test power, and a large effect size parameter ($f = 0.4$). A sample size of $n = 8$ RC specimens per subgroup was used to minimize potential experimental losses.

### 2.2. Preparation of resin composite specimens

In this study, multi-shade and single-shade RCs were used. Multi-shade RCs were selected from A1-A2-A3 shades. Details of the RCs are given in Table 1. The RCs were placed in polytetrafluoroethylene molds (8 mm diameter × 1 mm thickness and 8 mm in diameter × 2 mm thickness). The Mylar strip was placed over the RC, and a 5 kg load was used for three minutes to obtain a uniform thickness [20]. Slight pressure was applied to remove excess material and achieve a smooth surface. Each RC specimen was polymerized using a curing device (Elipar DeepCure-S, 3M ESPE, St. Paul, MN, USA) at 1,200 mW/cm² for 20 seconds. During light polymerization, the tip of the light-curing unit was positioned in direct contact with the Mylar strip covering the resin composite specimen to ensure a standardized curing distance. The upper and lower surfaces of the resin composite discs were photopolymerized according to the manufacturer's recommended curing time to ensure complete polymerization. For each RC, two thicknesses (1 mm and 2 mm) were prepared, and multi-shade RCs were prepared to contain three color shades each (A1, A2, and A3). Each subgroup consisted of 8 specimens, and 192 specimens were prepared. The flowchart of the study is presented in Fig. 1.

All RC specimens were manually ground for 3 minutes using 600-, 800-, 1000- and 1200-grit silicon carbide papers to ensure surface smoothness [21]. Specimen preparation and surface treatments were performed by the same person to minimize surface variability. Surface polishing of all samples was performed with the same polishing system (Zenit Flex Pop On; President Dental GmbH, Munich, Germany) by a single operator using linear movements with a 10,000 rpm micromotor at slight pressure. Surface polishing was performed under dry conditions for 15 seconds. RC specimens were thoroughly rinsed for 10 seconds between each application step and air-dried for 5 seconds [21]. The final thickness of the discs was measured with a digital caliper (Insize, Insize Co, China) (for thickness 1 mm; $1.0 \pm 0.05$ and for thickness 2 mm; $2.0 \pm 0.05$) [22]. The RC discs were stored in dark bottles without light until color measurements were performed. The prepared RC specimens were kept in an incubator at 37 °C in distilled water for 24 hours [23] and then dried with blotting paper and slight air pressure. The specimens were kept under the same conditions (distilled water at 37 °C in a temperature-controlled incubator and protected from light) until the measurements were performed. For all RC types, it was ensured that RC specimens were from the same production lot.

### 2.3. Experimental design and measurement procedure for color values

A mobile colorimeter application (MCA) [ColorMeter RGB Colorimeter (ColorMeter), iOS version 2.2.0, <5 USD, White Marten GmbH (Baden-Württemberg, Germany)] was used. Each specimen was measured with a spectrophotometer (Vita Easyshade V; Vita Zahnfabrik, Bad Sackingen, Germany). Color measurements using the ColorMeter application were performed with an iPhone 15 Pro (6.1-inch display, 2556 × 1179 resolution, triple-camera system: 48 MP/12 MP/12 MP; Apple, Cupertino, CA, USA) running the iOS operating system. The telephoto lens of the smartphone camera was selected for all ColorMeter measurements. The color values of the RCs were obtained. Three consecutive measurements were taken for each sample, and separate average L*, a*, and b* values were calculated from these three readings.

The Vita Easyshade V was selected as the reference instrument because of its established accuracy and widespread use in dental color research.

**Table 1.** List of materials used in present study

| Resin Composites | Type | Manufacturer | Composition |
|---|---|---|---|
| **Charisma Smart (CS)**<br>Lot No:A1:N010534<br>Lot No:A2:N010553<br>Lot No:A3:N010551 | Multi-shade | Kulzer, Hanau, Germany | Bis-GMA, barium-aluminum-fluoride glass, silicon dioxide, 0.005 – 10 µm |
| **Opallis (OP)**<br>Lot No:EA1:040923<br>Lot No:EA2:220623<br>Lot No:EA3:200923 | Multi-shade | FGM, Joinville, SC, Brazil | Bis-GMA, Bis-EMA, TEGDMA, urethane dimethacrylate and barium aluminum silicate, silicon oxide nanoparticles, camphorquinone, accelerators, stabilizers, and pigments. |
| **Estelite Σ Quick (ES)**<br>Lot No:A1:211E23<br>Lot No:A2:284EY3<br>Lot No:A3:292E03 | Multi-shade | Tokuyama, Tokyo, Japan | Spherical submicron filler (0.1 – 0.3 µm) Bis-GMA, TEGDMA, silica-zirconia |
| **Vittra APS Unique (V)**<br>Lot No:040723 | Single-shade | FGM, Joinville, SC, Brazil | UDMA, TEGDMA, photo initiator composition (APS), co-initiators, silane, boron-aluminum-silicate glass |
| **Omnichroma (O)**<br>Lot No:156E84 | Single-shade | Tokuyama, Tokyo, Japan | UDMA, TEGDMA, uniform sized supra-nano spherical filler (260 nm spherical $SiO_2$-$ZrO_2$) and filler |
| **Charisma Diamond One (C)**<br>Lot No:N010209 | Single-shade | Kulzer, Hanau, Germany | $B_2O_3$-F-$Al_2O_3$-$SiO_2$, silica, $TiO_2$, fluorescent pigments, metallic oxide pigments, organic pigments, 5 nm – 20 µm |

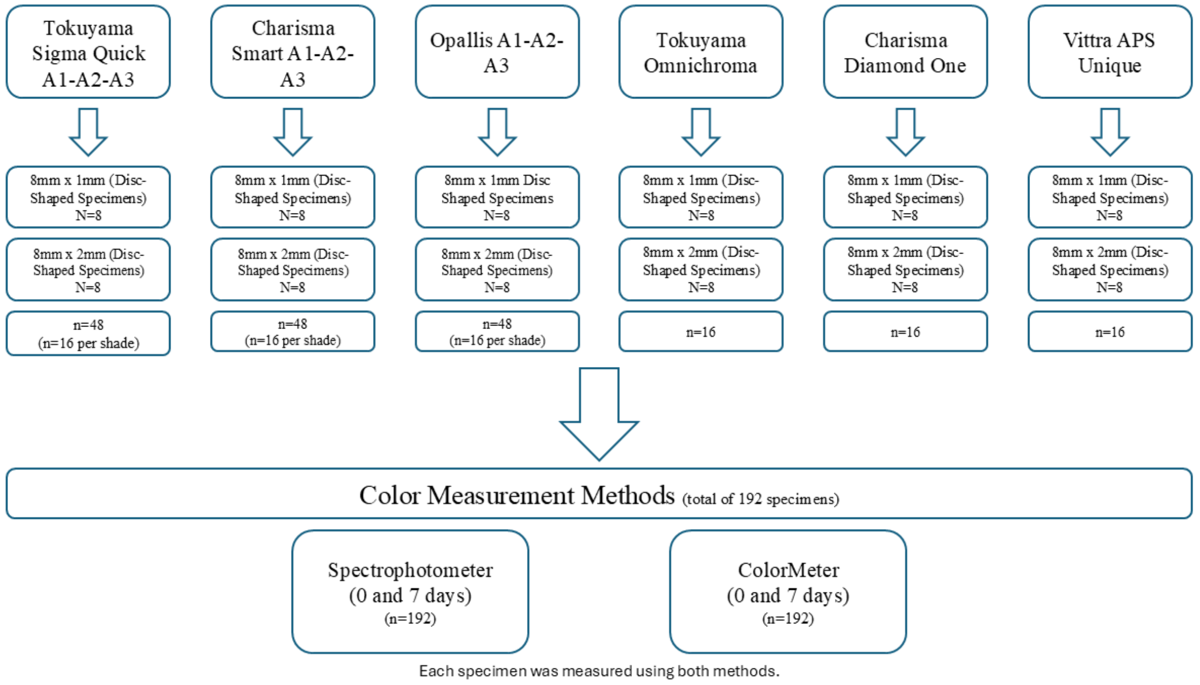


**Fig. 1.** Flowchart of the study design

The ColorMeter application was included because smartphone-based color assessment systems have recently gained increasing attention as practical, low-cost, and easily accessible alternatives for digital color evaluation in clinical dentistry.

An apparatus was established to measure the color values of the RCs. A schematic illustration of the experimental apparatus is shown in Fig. 2. The experimental setup was established in a darkened room using a neutral gray viewing stand, a light source, and a mobile phone holder. The light source was a CIE Standard Illuminant D65, with a CRI of at least 90 at an illumination level of 1,000 lx [17]. The holder was produced with specimens positioned at a 45° angle from the floor and had a matte black finish.

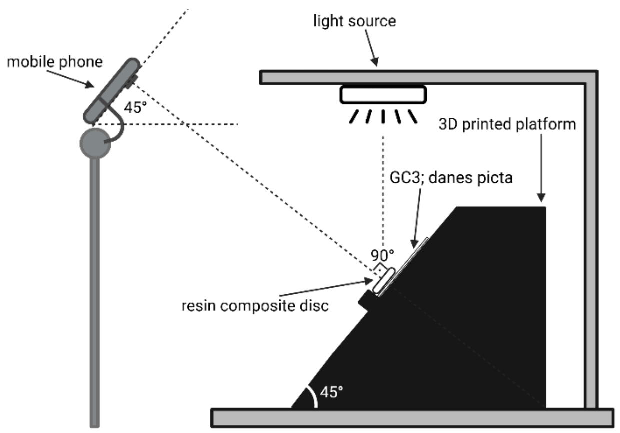


**Fig. 2.** Schematic illustration of the experimental apparatus

The cell phone holder was calibrated to position the phone camera at a 0° angle relative to the RC specimen. The light was positioned at a 45° angle relative to the specimen, thereby establishing a 45°/0° optical geometry. The mobile phone holder was situated 30 cm from the RC specimen [18, 24]. The required angles were verified using a digital inclinometer. All measurements were conducted by a single investigator to ensure uniformity and minimize inconsistencies in the measuring technique. The color values were measured on both black (L = 8, a = 1, b = −1) and white (L = 96, a = 0, b = 1) (GC3; Danes Picta) [25] backgrounds. Each RC specimen was measured with the spectrophotometer and the ColorMeter. Measurements were performed on the same samples under standardized conditions to ensure consistency and comparability between devices. For the ColorMeter, the target points on the display were directed toward the center of the specimens. Color data was obtained by targeting the specified location and activating the record button on the specialized screen inside the ColorMeter interface. The data was captured soon afterward, and the L*a*b* values were documented and assessed appropriately. The flash was disabled during the color assessment. For the spectrophotometer, the color values were measured using a spectrophotometer (VITA Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany).

The RC specimens were measured at two time periods, Day 0 (t0) and Day 7 (t1) (1 week after Day 0), and three measurements were made on each day, to mimic long-term reliability [17].

## 2.4. Determination of relative translucency parameter values

The color measurements were conducted under typical D65 circumstances on both black (L = 8, a = 1, b = −1) and white (L = 96, a = 0, b = 1) backgrounds using a spectrophotometer (Vita Easyshade V; Vita Zahnfabrik, Bad Sackingen, Germany) and the mobile colorimeter application (ColorMeter). The CIEDE2000 (1:1:1) formula was used to compute the $RTP_{00}$ values [10, 26]:

$$\mathrm{RTP}_{00} = [(\frac{L'_\mathrm{B}-L'_\mathrm{W}}{K_\mathrm{L}S_\mathrm{L}})^2 + (\frac{C'_\mathrm{B}-C'_\mathrm{W}}{K_\mathrm{C}S_\mathrm{C}})^2 + (\frac{H'_\mathrm{B}-H'_\mathrm{W}}{K_\mathrm{H}S_\mathrm{H}})^2 + R_\mathrm{T}(\frac{C'_\mathrm{B}-C'_\mathrm{W}}{K_\mathrm{C}S_\mathrm{C}})(\frac{H'_\mathrm{B}-H'_\mathrm{W}}{K_\mathrm{H}S_\mathrm{H}})]^{\frac{1}{2}}, \quad (1)$$

where *B* and *W* describe brightness ($L'$), chroma ($C'$), and hue ($H'$) of the specimens against the black and white backgrounds, respectively. The rotation function $R_T$ considers the interaction between hue and chroma variations in the blue spectrum. $S_L$, $S_C$, and $S_H$ are the weighting factors used to modify the overall color difference in accordance with perceived variances, dependent on positional differences in color coordinates between the two color assessments. The parametric factors ($K_L$, $K_C$, and $K_H$) were determined at 1 [$RTP_{00}$ (1:1:1)] [8, 27].

ΔRTP values obtained between t0 and t1 for each device were used to assess reliability. The calculation for the relative translucency parameter difference (ΔRTP) was carried out as follows [10]: $\Delta RTP_{00}=RTP1_{00}-RTP0_{00}$. Finally, published data on 50% translucency perceptibility ($TPT_{00}$ = 0.62) and acceptance ($TAT_{00}$ = 2.62) thresholds were used [27].

## 2.5. Determination of whiteness index values

Color values of RC specimens were measured using a Vita Easyshade V (Vita Zahnfabrik, Bad Sackingen, Germany) and the mobile colorimeter application (ColorMeter) on a black background (L = 8, a = 1, b = −1). The $WI_D$ is a linear formulation based on the CIELAB, which can be calculated using the following equation [15]:

$$WI_D = 0.511L^* - 2.324a^* - 1.100b^*. \quad (2)$$

The $\Delta WI_D$ from each device at time points t0−t1 was used for the evaluation of reliability. The computation of whiteness index difference ($\Delta WI_D$) was executed as follows: $\Delta WI_D = \Delta WI1_D - \Delta WI0_D$. The differences in the $WI_D$ ($\Delta WI_D$) were assessed using the whiteness 50 %:50 % perceptibility (WPT) and 50 %:50 % acceptability (WAT) thresholds, which were accepted in previous research and correspond to 0.72 $\Delta WI_D$ units and 2.60 $\Delta WI_D$ units, respectively [16].

## 2.6. Statistical analysis

Data were analyzed using Jamovi v2.3.28 (The Jamovi Project, Sydney, Australia). The Shapiro-Wilk test was used to assess compliance with normal distribution. Robust ANOVA was used to examine data that deviated from normal distribution based on material, thickness, and methods. In the tables, the values reported as total have been calculated to provide a general summary of the effects of material type, thickness, and measurement method within the robust ANOVA. These values have been included to facilitate the interpretation of overall effect models and possible interactions. Multiple comparisons were evaluated using the Bonferroni Test. Analyses were conducted using the Walrus module in Jamovi (version 2.3.28). The 5 % trimming level was selected considering the subgroup sample size, as higher trimming proportions would substantially reduce the effective sample size and statistical power. The reliability of $RTP_{00}$ and $WI_D$ measurements was evaluated using the intraclass correlation coefficient (ICC). ICC analyses were performed in Jamovi statistical software (version v2.3.28, The Jamovi Project, Sydney, Australia). A two-way mixed-effects model for absolute agreement was applied. The 95 % confidence intervals (CI) were calculated, and statistical significance was set at $P < 0.05$. ICC values were interpreted as follows: < 0.50 poor, 0.50 – 0.75 moderate, 0.75 – 0.90 good, and >0.90 excellent reliability [28].

# 3. RESULTS

Table 2 presents the Robust ANOVA results for $\Delta RTP_{00}$. Table 3 presents the descriptive data for $\Delta RTP_{00}$. The main effect of material for $\Delta RTP_{00}$ was statistically significant ($P < 0.001$). The main effect of thickness on $\Delta RTP_{00}$ was not statistically significant ($P = 0.970$). In addition, no significant interactions including thickness were found ($P > 0.05$). Regardless of thickness and method, the highest $\Delta RTP_{00}$ value was observed in material C. However, no significant differences were found between materials V, CS-A3, OP-A1, OP-A2, and OP-A3 (Table 3). The main effect of the method was also statistically significant ($P = 0.012$), with higher $\Delta RTP_{00}$ values observed for the ColorMeter than for the spectrophotometer, independent of material and thickness.

**Table 2.** Robust ANOVA results for $\Delta RTP_{00}$ and $\Delta WI_D$ main effects and interactions (material, thickness, and method)

| $\Delta RTP_{00}$ | Test statistic | $p^x$ |
|---|---|---|
| Material | 66.914 | <0.001 |
| Thickness | 0.002 | 0.970 |
| Method | 6.668 | 0.012 |
| Material × thickness | 11.388 | 0.490 |
| Material × method | 61.623 | 0.001 |
| Thickness × method | 0.001 | 0.971 |
| Material × thickness × method | 20.495 | 0.081 |
| $\Delta WI_D$ | Test statistic | $p^x$ |
| Material | 267.410 | <0.001 |
| Thickness | 1.040 | 0.320 |
| Method | 41.730 | 0.001 |
| Material × thickness | 75.830 | 0.001 |
| Material × method | 299.510 | 0.001 |
| Thickness × method | 5.660 | 0.019 |
| Material × thickness × method | 79.780 | 0.001 |

The interaction between material and method was statistically significant (P = 0.001). The highest interaction value was found in the C × ColorMeter group. However, no significant differences were detected among the V, CS-A1, CS-A2, CS-A3, OP-A2, OP-A3 × ColorMeter combinations and the ES-A3, OP-A1, OP-A3 × spectrophotometer combinations. When $\Delta RTP_{00}$ values were evaluated according to the perceptibility ($TPT_{00} = 0.62$) and acceptability (TAT00 = 2.62) thresholds, no material × thickness × method combination exceeded the acceptability threshold. Most $\Delta RTP_{00}$ values remained below the perceptibility threshold.

Table 2 presents the main effects and interactions from the Robust ANOVA analysis for $\Delta WI_D$, with descriptive data shown in Table 4. The material's main effect on $\Delta WI_D$ was statistically significant (P < 0.001), with the highest value observed for OP-A3, regardless of thickness and method. The main effect of the method was also significant (P = 0.001); the highest $\Delta WI_D$ value was recorded for the ColorMeter and the lowest for the spectrophotometer.

**Table 3.** Descriptive statistics for the comparison of $\Delta RTP_{00}$ values according to variables (material, thickness, and method)

| Method | Material | Thickness | | Total |
|---|---|---|---|---|
| | | 1 mm | 2 mm | |
| Spectrophotometer | CS-A1 | 0.07 ± 0.28 | 0.25 ± 0.37 | 0.16 ± 0.22$^{AB}$ |
| | CS-A2 | 0.13 ± 0.23 | 0.2 ± 0.09 | 0.16 ± 0.12$^{AB}$ |
| | CS-A3 | -0.09 ± 0.46 | 0.16 ± 0.06 | 0.03 ± 0.22$^{AB}$ |
| | ES-A1 | -0.22 ± 0.17 | -0.01 ± 0.07 | -0.11 ± 0.09$^{AB}$ |
| | ES-A2 | 0.07 ± 0.1 | 0.06 ± 0.06 | 0.06 ± 0.05$^{AB}$ |
| | ES-A3 | -0.2 ± 0.89 | 0.12 ± 0.32 | -0.04 ± 0.46$^{ABC}$ |
| | OP-A1 | 0.04 ± 0.44 | -0.37 ± 0.24 | -0.17 ± 0.25$^{ABC}$ |
| | OP-A2 | 0.07 ± 0.17 | 0.11 ± 0.03 | 0.09 ± 0.08$^{AB}$ |
| | OP-A3 | 0.1 ± 0.87 | 0.4 ± 0.35 | 0.25 ± 0.45$^{ABC}$ |
| | C | -0.05 ± 0.23 | -0.22 ± 0.14 | -0.13 ± 0.13$^{AB}$ |
| | O | 0.44 ± 0.33 | 0.03 ± 0.12 | 0.23 ± 0.18$^{AB}$ |
| | V | 0.22 ± 0.05 | -0.09 ± 0.1 | 0.06 ± 0.07$^{AB}$ |
| | Total | 0.09 ± 0.1 | 0.02 ± 0.04 | 0.06 ± 0.04$^{X}$ |
| ColorMeter | CS-A1 | 0.17 ± 0.19 | -0.23 ± 0.52 | -0.03 ± 0.27$^{ABC}$ |
| | CS-A2 | 0.17 ± 0.21 | -0.24 ± 0.47 | -0.03 ± 0.26$^{ABC}$ |
| | CS-A3 | -0.04 ± 0.37 | -0.35 ± 0.38 | -0.19 ± 0.26$^{ABC}$ |
| | ES-A1 | 0.17 ± 0.17 | 0.85 ± 0.27 | 0.51 ± 0.18$^{A}$ |
| | ES-A2 | -0.01 ± 0.23 | -0.26 ± 0.24 | -0.13 ± 0.16$^{AB}$ |
| | ES-A3 | 0.51 ± 0.64 | 0.73 ± 0.27 | 0.62 ± 0.34$^{AB}$ |
| | OP-A1 | -0.25 ± 0.25 | -0.01 ± 0.28 | -0.13 ± 0.18$^{AB}$ |
| | OP-A2 | -0.57 ± 0.25 | -0.7 ± 0.25 | -0.64 ± 0.17$^{BC}$ |
| | OP-A3 | -0.38 ± 0.29 | -0.71 ± 0.29 | -0.54 ± 0.2$^{BC}$ |
| | C | -1.09 ± 0.2 | -1.21 ± 0.23 | -1.15 ± 0.15$^{C}$ |
| | O | 0.07 ± 0.25 | 0.22 ± 0.15 | 0.14 ± 0.14$^{AB}$ |
| | V | -0.75 ± 0.2 | -0.09 ± 0.15 | -0.42 ± 0.15$^{BC}$ |
| | Total | -0.21 ± 0.08 | -0.15 ± 0.1 | -0.18 ± 0.06$^{Y}$ |
| Total | CS-A1 | 0.12 ± 0.16 | 0.01 ± 0.31 | 0.08 ± 0.13$^{a}$ |
| | CS-A2 | 0.15 ± 0.15 | -0.02 ± 0.24 | 0.09 ± 0.11$^{a}$ |
| | CS-A3 | -0.07 ± 0.28 | -0.1 ± 0.2 | -0.06 ± 0.16$^{ab}$ |
| | ES-A1 | -0.02 ± 0.13 | 0.42 ± 0.18 | 0.19 ± 0.11$^{a}$ |
| | ES-A2 | 0.03 ± 0.12 | -0.1 ± 0.13 | -0.03 ± 0.09$^{a}$ |
| | ES-A3 | 0.16 ± 0.54 | 0.42 ± 0.22 | 0.34 ± 0.21$^{a}$ |
| | OP-A1 | -0.11 ± 0.25 | -0.19 ± 0.18 | -0.18 ± 0.13$^{ab}$ |
| | OP-A2 | -0.25 ± 0.17 | -0.3 ± 0.17 | -0.25 ± 0.12$^{ab}$ |
| | OP-A3 | -0.14 ± 0.45 | -0.15 ± 0.27 | -0.11 ± 0.22$^{ab}$ |
| | C | -0.57 ± 0.21 | -0.71 ± 0.19 | -0.66 ± 0.13$^{b}$ |
| | O | 0.25 ± 0.21 | 0.12 ± 0.1 | 0.16 ± 0.09$^{a}$ |
| | V | -0.27 ± 0.17 | -0.09 ± 0.09 | -0.16 ± 0.09$^{ab}$ |
| | Total | -0.06 ± 0.06 | -0.05 ± 0.05 | |

The total values represent the means obtained from robust ANOVA analyses and are provided to show the data for the main effects and interaction values. Trimmed mean±standard error (trimmed value = 0.05); a-b There is no difference between composite, with the same letter. X-Y There is no difference between methods with the same letter in the column. A-C There is no difference between interaction (material × method) with the same letter.

**Table 4**. Descriptive statistics for the comparison of $\Delta WI_D$ values according to variables (material, thickness, and method)

| Method | Material | Thickness: 1 mm | Thickness: 2 mm | Total |
|---|---|---|---|---|
| Spectrophotometer | CS-A1 | $-0.35 \pm 0.25^{\text{ABCDEFGHİJKL}}$ | $-0.28 \pm 0.34^{\text{ABCDEHİJKL}}$ | $-0.32 \pm 0.2^{\text{ABC}}$ |
| | CS-A2 | $-0.1 \pm 0.17^{\text{ABCDEFGHİJKL}}$ | $-0.06 \pm 0.17^{\text{ABCDEHİJKL}}$ | $-0.08 \pm 0.12^{\text{A}}$ |
| | CS-A3 | $0.27 \pm 0.41^{\text{ABCDEKL}}$ | $-0.18 \pm 0.13^{\text{ABDEFHJK}}$ | $0.05 \pm 0.22^{\text{AF}}$ |
| | ES-A1 | $-0.82 \pm 0.11^{\text{ACDFGHİLMNO}}$ | $-1.13 \pm 0.08^{\text{CGİLMNO}}$ | $-0.97 \pm 0.08^{\text{BC}}$ |
| | ES-A2 | $-0.07 \pm 0.16^{\text{ABDEFHJK}}$ | $-0.07 \pm 0.16^{\text{ABCDEFGHİJKL}}$ | $-0.07 \pm 0.11^{\text{A}}$ |
| | ES-A3 | $0.63 \pm 0.65^{\text{ABCDEKLN}}$ | $-0.05 \pm 0.3^{\text{ABCDEHİJKL}}$ | $0.29 \pm 0.36^{\text{ACF}}$ |
| | OP-A1 | $0.34 \pm 0.41^{\text{ABCDEKL}}$ | $-0.04 \pm 0.28^{\text{ABCDEHİJKL}}$ | $0.15 \pm 0.24^{\text{AF}}$ |
| | OP-A2 | $0.04 \pm 0.21^{\text{ABCDEHİJKL}}$ | $-0.17 \pm 0.23^{\text{ABCDEHİJKL}}$ | $-0.07 \pm 0.15^{\text{A}}$ |
| | OP-A3 | $0.49 \pm 0.78^{\text{ABCDEHİJKLNOQ}}$ | $0.57 \pm 0.35^{\text{ABCDEKL}}$ | $0.53 \pm 0.41^{\text{ACF}}$ |
| | C | $0.27 \pm 0.07^{\text{BEJK}}$ | $-0.01 \pm 0.14^{\text{ABDEFHJK}}$ | $0.13 \pm 0.08^{\text{A}}$ |
| | O | $0.99 \pm 0.24^{\text{BE}}$ | $0.59 \pm 0.1^{\text{BEJK}}$ | $0.79 \pm 0.14^{\text{F}}$ |
| | V | $0.32 \pm 0.1^{\text{BEJK}}$ | $0.28 \pm 0.07^{\text{BEJK}}$ | $0.3 \pm 0.06^{\text{AF}}$ |
| | Total | $0.11 \pm 0.08^{\text{A}}$ | $-0.03 \pm 0.07^{\text{A}}$ | $0.03 \pm 0.05^{\text{X}}$ |
| ColorMeter | CS-A1 | $-1.66 \pm 0.71^{\text{ABCFGHİJKMNOPQ}}$ | $-2.47 \pm 0.96^{\text{ABCFGHİJKMNOPQ}}$ | $-2.07 \pm 0.59^{\text{ABCDE}}$ |
| | CS-A2 | $-0.67 \pm 0.34^{\text{ABCDEFGHİJKLMNO}}$ | $-3.33 \pm 1.16^{\text{ABCFGHİJKMNOPQ}}$ | $-2 \pm 0.7^{\text{ABCDEF}}$ |
| | CS-A3 | $-0.28 \pm 1.22^{\text{ABCDEFGHİJKLMNOPQ}}$ | $-1.43 \pm 0.86^{\text{ABCFGHİJKMNOPQ}}$ | $-0.85 \pm 0.74^{\text{ABCDEF}}$ |
| | ES-A1 | $-1.61 \pm 0.62^{\text{ABCFGHİJKMNOPQ}}$ | $0.07 \pm 0.82^{\text{ABCDEFGHİJKLMNOPQ}}$ | $-0.77 \pm 0.55^{\text{ABCF}}$ |
| | ES-A2 | $-2.26 \pm 0.95^{\text{ABCFGHİJKMNOPQ}}$ | $-3.2 \pm 0.71^{\text{ABCFGHİJKMNOPQ}}$ | $-2.73 \pm 0.59^{\text{BDE}}$ |
| | ES-A3 | $-0.08 \pm 1.12^{\text{ABCDEFGHİJKLMNOPQ}}$ | $1.67 \pm 0.85^{\text{ABCDEKLN}}$ | $0.8 \pm 0.73^{\text{ACF}}$ |
| | OP-A1 | $-0.76 \pm 0.72^{\text{ABCFGHİJKMNOPQ}}$ | $-1.48 \pm 0.78^{\text{ABCFGHİJKMNOPQ}}$ | $-1.12 \pm 0.52^{\text{ABCDF}}$ |
| | OP-A2 | $-2.58 \pm 0.62^{\text{ABCFGHİJKMNOPQ}}$ | $-5.31 \pm 0.71^{\text{FGMP}}$ | $-3.95 \pm 0.6^{\text{DE}}$ |
| | OP-A3 | $6.77 \pm 1.14^{\text{DEL}}$ | $10.54 \pm 1.01^{\text{R}}$ | $8.66 \pm 0.91^{\text{G}}$ |
| | C | $-4 \pm 0.62^{\text{FGHİJMOPQ}}$ | $0 \pm 0^{\text{ABDEFHJK}}$ | $-2 \pm 0.65^{\text{ABCDE}}$ |
| | O | $-4.67 \pm 0.28^{\text{PQ}}$ | $-2.98 \pm 0.56^{\text{ACFGHİJKMNOPQ}}$ | $-3.83 \pm 0.39^{\text{E}}$ |
| | V | $-2.69 \pm 0.3^{\text{MNOPQ}}$ | $-0.26 \pm 0.51^{\text{ABCDEHİJKLNO}}$ | $-1.48 \pm 0.45^{\text{ABCD}}$ |
| | Total | $-1.45 \pm 0.36^{\text{B}}$ | $-0.97 \pm 0.43^{\text{AB}}$ | $-1.25 \pm 0.27^{\text{Y}}$ |
| Total<br>The total values represent the means obtained from robust ANOVA analyses and are provided to show the data for the main effects and interaction values. Trimmed mean±standard error (trimmed value = 0.05); $^{a-c}$ There is no difference between composites with the same letter. $^{X-Y}$ There is no difference between methods, with the same letter in the column. $^{x}$ There is no difference between thicknesses with the same letter in the row. $^{A-R}$ There is no difference between interactions with the same letter | CS-A1 | $-1.01 \pm 0.41^{\text{ABC}}$ | $-1.38 \pm 0.58^{\text{AB}}$ | $-1.09 \pm 0.31^{\text{ab}}$ |
| | CS-A2 | $-0.39 \pm 0.2^{\text{ABC}}$ | $-1.69 \pm 0.74^{\text{A}}$ | $-0.84 \pm 0.32^{\text{ab}}$ |
| | CS-A3 | $-0.01 \pm 0.63^{\text{ABC}}$ | $-0.8 \pm 0.46^{\text{ABC}}$ | $-0.48 \pm 0.34^{\text{ab}}$ |
| | ES-A1 | $-1.21 \pm 0.33^{\text{AB}}$ | $-0.53 \pm 0.44^{\text{ABC}}$ | $-0.89 \pm 0.25^{\text{ab}}$ |
| | ES-A2 | $-1.16 \pm 0.56^{\text{ABC}}$ | $-1.63 \pm 0.57^{\text{A}}$ | $-1.41 \pm 0.37^{\text{ab}}$ |
| | ES-A3 | $0.28 \pm 0.63^{\text{ABC}}$ | $0.81 \pm 0.5^{\text{ABC}}$ | $0.47 \pm 0.38^{\text{b}}$ |
| | OP-A1 | $-0.21 \pm 0.43^{\text{ABC}}$ | $-0.76 \pm 0.45^{\text{ABC}}$ | $-0.45 \pm 0.31^{\text{ab}}$ |
| | OP-A2 | $-1.27 \pm 0.49^{\text{AB}}$ | $-2.74 \pm 0.82^{\text{A}}$ | $-1.92 \pm 0.48^{\text{ab}}$ |
| | OP-A3 | $3.63 \pm 1.12^{\text{BC}}$ | $5.56 \pm 1.52^{\text{C}}$ | $4.48 \pm 0.93^{\text{c}}$ |
| | C | $-1.87 \pm 0.68^{\text{A}}$ | $0 \pm 0.07^{\text{ABC}}$ | $-0.84 \pm 0.38^{\text{ab}}$ |
| | O | $-1.84 \pm 0.83^{\text{A}}$ | $-1.2 \pm 0.58^{\text{AB}}$ | $-1.49 \pm 0.49^{\text{ab}}$ |
| | V | $-1.19 \pm 0.46^{\text{AB}}$ | $0.01 \pm 0.26^{\text{ABC}}$ | $-0.55 \pm 0.28^{\text{ab}}$ |
| | Total | $-0.68 \pm 0.17^{\text{x}}$ | $-0.58 \pm 0.17^{\text{x}}$ | |

Although the main effect of thickness on $\Delta WI_D$ was not statistically significant ($P = 0.320$), thickness was involved in significant two-way and three-way interactions. $\Delta WI_D$ values varied between 1 mm and 2 mm depending on material type and measurement method. A significant three-way interaction (material × thickness × method) was found for $\Delta WI_D$ with the highest interaction value observed in the OP-A3 × 2 mm × ColorMeter combination. The evaluation of $\Delta WI_D$ values based on the detectability (WPT = 0.72) and acceptability (WAT = 2.60) thresholds showed that they exceeded the detectability threshold in some combinations. The OP-A3 × ColorMeter group exceeded the acceptability threshold, indicating a clinically noticeable and potentially unacceptable level of whiteness change. Most other material and method combinations remained below the acceptability threshold.

The reliability of translucency measurements obtained with the spectrophotometer was assessed using a two-way mixed-effects model for absolute agreement. The intraclass correlation coefficient (ICC) indicated excellent reliability (ICC = 0.988; 95 % CI: 0.984 – 0.991; $P < 0.001$), demonstrating very high agreement between t0 and t1 measurements.

The reliability of whiteness measurements obtained with the spectrophotometer was assessed using a two-way mixed-effects model for absolute agreement. The intraclass correlation coefficient indicated excellent reliability (ICC = 0.999; 95% CI: 0.999–0.999; $P < 0.001$), demonstrating very high agreement between t0 and t1 measurements.

The reliability of translucency parameter (TP) measurements obtained with the colorimeter was assessed using a two-way mixed-effects model for absolute agreement. The intraclass correlation coefficient indicated good reliability (ICC = 0.754; 95 % CI: 0.671 – 0.816; $P < 0.001$), demonstrating moderate agreement between t0 and t1 measurements. The reliability of whiteness measurements obtained with the colorimeter was assessed using a two-way mixed-effects model for absolute agreement. The intraclass correlation coefficient indicated excellent reliability (ICC = 0.964; 95 % CI: 0.950 – 0.973; $P < 0.001$), demonstrating very high agreement between t0 and t1 measurements. This suggests that the spectrophotometer and colorimeter are not interchangeable for $\Delta$TP assessment.

The agreement between the spectrophotometer and the colorimeter for $\Delta$TP values was assessed using a two-way mixed-effects model for absolute agreement. The intraclass correlation coefficient indicated poor reliability (ICC = 0.316; 95 % CI: 0.096 – 0.483; $P = 0.004$), demonstrating low agreement between the two devices for $\Delta$TP measurements. The agreement between the spectrophotometer and the colorimeter for $\Delta WI_D$ values was assessed using a two-way mixed-effects model for absolute agreement. The intraclass correlation coefficient indicated poor reliability (ICC = −0.021; 95 % CI: −0.333–0.221; $P = 0.560$), and demonstrated no significant agreement between the two devices for $\Delta WI_D$.

## 4. DISCUSSION

In this study, the $RTP_{00}$ and $WI_D$ values of single-shade and multi-shade RCs of different thicknesses were evaluated using a spectrophotometer and a mobile phone color measurement application. The hypotheses tested in this study were rejected. The spectrophotometer demonstrated better performance than the ColorMeter in terms of both $RTP_{00}$ and $WI_D$. The optical properties of the devices used may have different sensitivity levels, and differences may also affect clinical evaluations. When examining the structural properties of RC materials, it has been observed that single-shade RCs generally exhibit higher transparency and whiteness index values compared to multi-shade alternatives. This result indicates that single-shade options may provide certain clinical benefits, particularly in achieving better optical adaptation and more esthetic results.

Translucency describes a material’s ability to allow light to pass through it partially. This property can vary depending on several factors, such as the thickness of the material, how the resin matrix scatters and absorbs light, the type of filler particle used, and the inclusion of colorants or opacifying agents [3]. The relative translucency parameter offers a numerical way to evaluate how translucent a material is by comparing its color appearance over black and white backgrounds at a specific thickness [4]. RTP is often used when evaluating translucency, since it depends on color difference calculations and helps provide a more objective framework for interpreting clinical findings. This study's RTP values were evaluated for clinical significance using the 50:50 perceptibility and acceptability threshold values that have been previously proposed in the literature [27]. In the literature, the CIEDE2000 color difference formula is preferred because it provides results that are more consistent with human visual perception than the CIELAB system. This can be attributed to the CIEDE2000 formula, which incorporates corrections for the perceptual non-uniformities present in the CIELAB color space [24, 29]. Since this method was considered to better reflect clinical conditions, the CIEDE2000 formula was applied for $RTP_{00}$ measurement in our study [30].

The results of this study indicate that as the thickness of RC materials increases, there is a tendency for $RTP_{00}$ values to decrease. This decrease is not statistically significant in terms of thickness and interactions. However, this observed variable is consistent with the well-known inverse relationship between material thickness and light transmittance. Previous studies have reported that increasing composite thickness leads to a decrease in light transmittance due to increased light scattering and absorption within the material matrix [31, 32]. When examining the $RTP_{00}$ values of different RCs, it was observed that the type of material had a significant effect on this optical parameter. When evaluated using both color measurement methods (spectrophotometer and ColorMeter), single-shade RCs were found to have generally higher $RTP_{00}$ values than multi-shade RCs. This finding can be explained by the simplified pigment structure and optimized filler-matrix interaction of single-shade materials designed to increase light diffusion and mixing capacity. Clinically, higher $RTP_{00}$ values may contribute to better color integration with the surrounding tooth structure, particularly in minimally invasive restorations.

Omnichroma with a thickness of 1 mm demonstrated the highest $RTP_{00}$ values compared to other materials. This finding suggests that the high translucency of Omnichroma may be attributed to a specific combination of the type and weight fraction of its inorganic phase [33]. The compatibility between the refractive index of the resin matrix and that of the filler particles promotes a more uniform light scattering, thereby contributing to the material’s high translucency. However, variations in the type and amount of filler may influence the optimized translucency level in monochromatic composites and alter the mechanism of structural color formation. Therefore, not only the filler size but also the type of resin monomer used and the specific combination of resin and filler components play a critical role in determining translucency [7]. In addition, it has been reported that other components such as manufacturer-derived pigments and additives may also have significant effects on the optical properties [34].

Omnichroma's high translucency value may increase the possibility of underlying colors being reflected, particularly in esthetic restorations in the anterior regions, so the use of this material alone may be limited. To address this issue, the manufacturer recommends the use of a “blocker” material [34]. The literature emphasizes that single-shade RC, owing to their high translucency, exhibit enhanced adaptation to surrounding tooth structures and improved esthetic integration [17]. Nevertheless, several studies indicate that the optical characteristics of RCs may fluctuate depending on the manufacturing method employed [34, 35]. The results indicate that single-shade RCs may offer esthetic advantages in clinical settings, and that the technique employed for color assessment might markedly affect the translucency values recorded.

Based on the findings related to the $WI_D$, some shades of multi-shade composites indicated higher values of whiteness. It was also observed that changes in the thickness of the material had a notable influence on this optical characteristic [14]. The observation of higher $WI_D$ values, particularly in samples with a thickness of 1 mm, suggests that this thickness may have a greater potential to reflect light, which in turn could positively influence the esthetic appearance [36]. The $WI_D$ formula used in this study was calculated based on the CIELAB color coordinate values [37]. Changes in $WI_D$ values were evaluated with reference to the perceptibility and acceptability thresholds previously suggested in the literature [16]. Significant differences were observed between different thickness levels; it was determined that the $WI_D$ values of composite materials with a thickness of 1 mm were generally higher than those with a thickness of 2 mm. However, it was observed that $WI_D$ values decreased as thickness increased and that $WI_D$ differences remained below the acceptability threshold (WAT) in all materials except the OP-A3 group. It is considered that structural factors such as the type of filler particles, mismatches in refractive indices, and the presence of additives may influence $WI_D$ values. Optical values related to higher translucency and whiteness are not inherently superior and should be interpreted in a clinical context. Increased transparency and whiteness may enhance optical harmony in certain esthetic situations, but their masking ability may be disadvantageous when required; therefore, their clinical significance depends on the restoration situation.

Variations in color measurement results among devices may depend on the light sources used, the sensitivity of the optical sensor, and the image processing algorithms. Therefore, conducting comparative measurements using reference devices is essential for assessing the clinical relevance of the obtained color data [18]. Findings from this study suggest that the translucency and whiteness index values measured using the ColorMeter application were higher than those obtained with the spectrophotometer. One possible explanation for these differences is the way mobile device cameras respond to surrounding light, combined with inconsistencies in hardware across different models and the absence of clear standards in how images are processed. Based on the current findings, improving the reliability of mobile color measurement tools like ColorMeter will likely depend on better calibration systems, technical upgrades, and consistent measurement standards.

The inter-method agreement between the spectrophotometer and mobile phone colorimeter was evaluated using ICC for $\Delta$RTP and $\Delta WI_D$ values. Since both devices measure the same optical parameters, a two-way mixed-effects model for absolute agreement was used to assess their interchangeability. ICC analysis showed low agreement for $\Delta$RTP and no significant agreement for $\Delta WI_D$, indicating that the two devices cannot be considered interchangeable for these parameters. In addition, mean differences between the methods were compared with established detectability thresholds to determine their potential clinical significance. The inconsistencies exceeded the detectability threshold for $\Delta$RTP, suggesting clinically discernible variation between devices, whereas the inconsistency and wide confidence intervals for $\Delta WI_D$ indicated only minimal comparability between the two measurement systems.

One of the strongest aspects of this study is that it combines the evaluation of critical esthetic optical parameters such as translucency and whiteness index. Moreover, presenting data on time-dependent stability across different material thicknesses may provide valuable support for clinical decision-making in restorative dentistry. However, given the study was performed under in vitro circumstances, it fails to comprehensively represent the many attributes of the oral environment, including factors such as light reflection, moisture, the impact of adjacent tissues, and variations in illumination. In this context, future research is recommended to be conducted under clinical conditions for example, using extracted teeth mounted on typodonts or through direct applications on volunteer participants. Such studies could contribute to the development of calibration protocols, lighting standardization, and correction algorithms for mobile colorimeter applications.

This study has some limitations. First, only a spectrophotometer and a single smartphone-based colorimeter application were evaluated. The inclusion of other contemporary dental color-matching devices, such as OptiShade, could provide additional information regarding the clinical performance and comparability of mobile color assessment systems. Second, all smartphone-based measurements were performed using a single mobile device model (iPhone 15 Pro). Because camera sensors, image-processing algorithms, and hardware specifications vary among smartphones, the findings may not be directly applicable to other devices. Future studies should evaluate different smartphone models and dedicated dental color-matching systems to improve the generalizability of the results.

## 5. CONCLUSIONS

Within the limitations of this study, single-shade RCs generally showed higher translucency and whiteness index values than multi-shade RCs. The spectrophotometer provided more consistent and reliable measurements than the mobile colorimeter application. Although mobile-based colorimetric tools may be useful because of their practicality, accessibility, and low cost, their accuracy appears limited for precise color assessment. Therefore, both the restorative material and the measurement device should be considered when interpreting color-related parameters, and mobile colorimeter applications should be used with caution until further validation is available.

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