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Influence of Bleaching and Aging Procedures on Color and Whiteness of Dental Composites

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Clinical Relevance

Color changes after bleaching resin-based composites were clinically acceptable, while aging caused clinically perceptible color changes.

SUMMARY

Bleaching can cause perceptible color changes on resin-based composite (RBC) restorations that may not be stable with aging. The objective of this study was to evaluate color stability and whiteness variations of RBCs after bleaching and aging procedures. Discs (10 mm in diameter and 1 mm thick) of shades A2 and A3 were fabricated from two RBCs (Filtek Z250 and Filtek Z350 XT) and divided into three subgroups (for each composite and shade) (n=5) as follows: control (no bleaching), at-home bleaching, and in-office bleaching. All specimens underwent an accelerated artificial aging up to 450 KJ/m^2 and 900 KJ/m^2 in an aging chamber (Suntest XXL+). A spectroradiometer (SpectraScan PR-670) was used to obtain CIE $L^*a^*b^*$ coordinates. CIEDE2000 color difference (ΔE_{00}) and whiteness index for dentistry (WI_D) were used to evaluate color stability. Color and whiteness differences data were analyzed considering the 50:50% visual color difference thresholds (perceptibility [PT] and acceptability [AT]) and 50:50% whiteness thresholds (whiteness perceptibility [WPT] and whiteness acceptability [WAT]). Analysis of variance and Tukey tests (α=0.05) were used to statistically analyze the data. After bleaching, all specimens showed ΔE_{00} and ΔWI_D values below their corresponding acceptability thresholds (AT and WAT, respectively). After aging, L^* and WI_D values decreased while b^* values increased ($p \leq 0.05$), resulting in ΔE_{00} and ΔWI_D values above AT and WAT, respectively. Color changes after bleaching RBCs were clinically acceptable, while aging provoked clinically perceptible color changes.

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INTRODUCTION

Tooth bleaching, which is a noninvasive procedure, is among the most popular treatments to improve tooth color and appearance.[1] Numerous products and methods for tooth bleaching have been described in the literature.[2,3] The original concept of at-home bleaching (HB) used 10% carbamide peroxide gel in a customized tray with supervision and guidance of a dental clinician.[1] Nowadays, there are many vital tooth bleaching procedures, including HB, in-office bleaching (OB) and over-the-counter bleaching systems.[2-4] Different bleaching agents, concentrations, times of application, product format, and application have been reported.[2]

Bleaching agents (carbamide peroxide and hydrogen peroxide) used in tooth bleaching are able to provide perceptible color changes. At the same time, these products may produce color and surface alterations of resin-based composite (RBC) restorations.[5] Such changes are influenced by the type and concentration of bleaching agents and bleaching time,[5-7] the type of the RBC (composition and percentage of organic and inorganic phases),[5,6] and various abrasive/erosive procedures related to diet and oral hygiene.[8]

CIELAB color space and its associated CIELAB (ΔE^*_{ab}) and CIEDE2000 (ΔE_{00}) total color difference formulas are extensively used for color research in dentistry. In this sense, whiteness variations are commonly evaluated by means of total color differences or differences among one of the three axes that describe the CIELAB color space (ΔL^*: differences in lightness; Δa^*: differences in red-green axis; and Δb^*: differences in yellow-blue axis).[9,10]

However, whiteness of a material is adequately portrayed with a whiteness index. Some whiteness indexes based on the CIE 1931 XYZ color notation system have been used in dental research: the CIE whiteness index (WIC),[11] the whiteness index (WI),[12] and the optimized whiteness index (WIO).[13] The most recent published whiteness index for dentistry (WI_D) is based on CIELAB space and correlates to perception of tooth whiteness.[14]

According to the latest guidance on color measurements published by the International Organization for Standardization,[15] color stability after aging and staining (or after bleaching procedures) should be assessed on the basis of 50:50% acceptability (AT: ΔE^*_{ab}=2.7 and ΔE_{00}=1.8) and 50:50% perceptibility (PT: ΔE^*_{ab}=1.2 and ΔE_{00}=0.8) thresholds.[16] In this sense, if the total color difference measured before and after aging or staining is at or below PT, it represents an excellent match; if the difference is between PT and AT, it represents an acceptable match; and if the difference is above AT, it represents an unacceptable match. In addition, WI_D variations (ΔWI_D) can be assessed through comparison with 50:50% acceptability and 50:50% perceptibility thresholds for whiteness (WPT=0.61; and WAT=2.9, respectively) obtained in a cohort study with laypersons.[17]

Therefore, the purpose of this study was to evaluate the color stability and whiteness of two RBCs subjected to dental bleaching procedures (at-home bleaching and in-office bleaching) and artificial accelerated aging (450 KJ/m^2 and 900 KJ/m^2), testing the hypothesis that both bleaching and aging procedures produce color changes and whiteness variations of RBCs greater than the 50:50% acceptability thresholds (AT and WAT).

METHODS AND MATERIALS

Specimen Preparation

A total of 180 disc-shaped specimens (10 mm in diameter and 1 mm thick) of shades A2 and A3 from two dental RBCs (Filtek Z250 [Z2] and Filtek Z350 XT [Z3]; Table 1) were fabricated using polytetrafluoroethylene molds. Thus, 45 specimens (n=5) were fabricated from each RBC-shade combination and divided into nine experimental treatments (Table 2).

RBCs were packed into the mold and pressed between two glass slides lined with polyester film (Mylar, DuPont, Wilmington, DE, USA). The specimens were light activated (40 seconds; 20 s/side) using a light curing unit (Radii; SDI, Bayswater, Victoria, Australia) at 1200 mW/cm^2. Specimens were kept in a dark environment at 37°C before testing. Combinations of experimental treatments, according to different bleaching and accelerated aging procedures, are described in Table 2.

Bleaching Procedures

Bleaching products used in the present study are described in Table 1. Two bleaching procedures (OB and HB) were performed according to manufacturer's instructions. As OB treatments usually need three applications of the product, the bleaching gel was applied on the specimens for 15 min/d for three consecutive days. HB treatments usually last for 3 weeks; therefore, the bleaching gel was applied on the specimens for 2 h/d for 21 consecutive days. After each application, bleaching products were washed out and specimens were stored in 37°C distilled water. All bleaching procedures were performed by

Table 1: *Description of the Materials used in this Study*

Material	Composition[a]	Manufacturer
Z2-Filtek Z250 (Z2.2- shade A2; and Z2.3- shade A3)	Micro-hybrid dental restorative resin composite; *Organic matrix:* Bis-GMA, UDMA, Bis-EMA, and TEGDMA; *Filler particles:* SiO_2-ZrO_2 particles (0.01-3.5 μm), (60% by vol.)	3M ESPE (St Paul, MN, USA)
Z3-Filtek Z350 XT (Z3.2- shade A2; and Z3.3- shade A3)	Nanocomposite; *Organic matrix:* Bis-GMA, UDMA, Bis-EMA, TEGDMA. and PEGDMA; *Filler particles:* Non-agglomerated/non-aggregated; nanosilica (5-20 nm) and zirconia (4-11 nm) fillers and aggregated SiO_2-ZrO_2 nanoclusters (0.6-10 μm), (63.3% by vol. and 78.5% by weight)	3M ESPE
Whiteness HP Blue 35%	In-office Bleaching product (35% hydrogen peroxide gel)	FGM Dental Products (Joinville, SC, Brazil)
White Class 6%	At-home Bleaching product (6% hydrogen peroxide gel)	FGM Dental Products

Abbreviations: Bis-GMA - bisphenol A-glycidyl methacrylate; UDMA - urethane dimethacrylate; Bis-EMA - bisphenol A diglycidyl methacrylate ethoxylated; TEGDMA - triethylene glycol dimethacrylate; PEGDMA - Poly(ethylene glycol) dimethacrylate
[a] *Data provided by manufacturers.*

one experienced dentist. Specimens not bleached serve as the control group.

Accelerated Aging Procedures

Specimens were subjected to artificial accelerated aging (Suntest XXL+, Ametek Atlas, Mount Prospect, IL, USA) according to International Organization for Standardization (ISO) 4892-2[18] and ISO 7491[19] standards. The artificial aging cycle consisted of 102 minutes of light exposure and 18 minutes of water spraying under artificial daylight (CIE D65 illuminant) at 38°C±3°C constant temperature and 50%±10% relative humidity, with a black panel temperature of 65°C and irradiance control in the 300 to 400 nm interval of 60 W/m^2.[20] The aging cycles were repeated in 150 KJ/m^2 increments until switch-off criteria of 450 KJ/m^2 (T1: estimating 1 year of aging) and 900 KJ/m^2 (T2: estimating 2 years of aging) total dosage levels were achieved.[21] For all OB and HB groups, accelerated aging was performed after bleaching procedures. Specimens that were not aged (T0) served as controls.

Color Measurements

A noncontact spectroradiometer ([SP], SpectraScan PR-670, Photo Research, Chatsworth, CA, USA) was used to obtain the spectral reflectance (380 to 780 nm; interval of 2 nm) from all RBC specimens. A white ceramic background (L^*=94.2, a^*=1.3, b^*=1.7) was used for color measurements, while a black ceramic background (L^*=3.1, a^*=0.7, b^*=2.4) was used for WI_D calculations. A coupling agent (refractive index n≈1.5) was used as contact media between specimen and background.[22-24]

As reported in previous studies,[25,26] since the SP field of measurement is 1°, the specimens were placed 35 cm away from SP, on a 45° tilted base and under constant illumination (CIE D65 standard illuminant). Illuminating/measuring configuration corresponds to CIE d/0°.[22,27,28] Three short-term measurements without replacement were performed for each specimen. The results for each specimen and background were averaged over the three measurements. CIELAB color coordinates for all specimens were calculated according to CIE D65 Standard Illuminant and CIE 2° Standard Colorimetric Observer.[29]

Color Differences

Computations for the CIEDE2000 color difference (ΔE_{00}) metric were done according to the following equation[29,30]:

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)\right]^{1/2} \quad (1)$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are the differences in each

Table 2: *Experimental Treatments Used in the Study*

Acronym	Description
CT0	Control group at baseline
CT1	Control group after chromatic aging (450 KJ/m^2)
CT2	Control group after chromatic aging (900 KJ/m^2)
OBT0	In-office bleaching at baseline
OBT1	In-office bleaching after chromatic aging (450 KJ/m^2)
OBT2	In-office bleaching after chromatic aging (900 KJ/m^2)
HBT0	At-home bleaching at baseline
HBT1	At-home bleaching after chromatic aging (450 KJ/m^2)
HBT2	At-home bleaching after chromatic aging (900 KJ/m^2)

Table 3: *Mean and Standard Deviation Values of CIELAB Color Coordinates and Whiteness Index (WI_D) Followed by the Statistical Groupings for Specimens of Filtek Z250 Shade A2 (Z2.2)* [a]

Groups	CIELAB Color Coordinates			WI_D
	L^*	a^*	b^*	
Z2.2-CT0	68.54 ± 0.59 aA	–1.10 ± 0.03 bB	9.97 ± 0.32 cB	26.62 ± 0.36 aA
Z2.2-CT1	66.02 ± 0.43 bA	–1.02 ± 0.14 bB	19.06 ± 0.73 bA	15.14 ± 1.12 bA
Z2.2-CT2	64.86 ± 0.30 cA	–0.33 ± 0.24 aA	22.12 ± 0.33 aB	9.58 ± 0.85 cA
Z2.2-OBT0	67.67 ± 0.29 aB	–0.73 ± 0.14 bA	11.02 ± 0.65 cA	24.15 ± 0.91 aB
Z2.2-OBT1	66.41 ± 0.33 bA	–0.83 ± 0.15 bA	20.43 ± 0.46 bA	13.38 ± 0.95 bA
Z2.2-OBT2	65.41 ± 0.82 cA	–0.31 ± 0.16 aA	23.06 ± 0.30 aA	8.78 ± 0.81 cA
Z2.2-HBT0	68.27 ± 0.28 aA	–0.62 ± 0.03 bA	11.23 ± 0.39 cA	23.99 ± 0.40 aB
Z2.2-HBT1	65.90 ± 1.12 bA	–0.97 ± 0.30 cA	19.97 ± 0.68 bA	13.97 ± 1.96 bA
Z2.2-HBT2	64.54 ± 0.39 cA	–0.26 ± 0.17 aA	22.99 ± 0.23 aA	8.30 ± 0.60 cA

Abbreviations: C, control; HB, at-home bleaching; OB, in-office bleaching; T0, no aging; T1, chromatic aging procedure (450 KJ/m^2) equivalent to 1 year; T2, chromatic aging procedure (900 KJ/m^2) equivalent to 2 years.
[a] *CIELAB color coordinates and WI_D values using a black background ($p \leq 0.05$; two-way analysis of variance). Different lowercase letters show statistical differences for mean values (color parameters) between different aging procedures (T0, T1, and T2) within the same bleaching procedure (C, OB, or HB) (column). Different capital letters show statistical differences for mean values (color parameters) between different bleaching procedures (C, OB, and HB) within the aging procedures (T0, T1, or T2) (column).*

parameter (lightness, chroma, and hue, respectively) for a pair of specimens using CIEDE2000. The weighting functions (S_L, S_C, and S_H) adjust the total color difference for variation in the location of the color difference pair in L^*, a^*, b^* coordinates. The parametric factors (K_L, K_C, and K_H) are correction terms for experimental conditions. Finally, a rotation function (R_T) accounts for the interaction between chroma and hue differences in the blue region.[29,30] To calculate the CIEDE2000 color difference formula, discontinuities due to mean hue computation and hue-difference computation were taken into account.[31]

Color differences were finally evaluated through comparisons with the 50:50% color difference thresholds (PT=0.81 ΔE_{00} units and AT=1.77 ΔE_{00} units) for tooth-colored restorative materials, established in a prospective multicenter research project.[16]

Whiteness Index for Dentistry

The Whiteness Index for Dentistry (WI_D) is a CIELAB-based index with a linear formulation. WI_D values were obtained according to the following equation:[14]

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

WI_D variations (ΔWI_D) can be assessed through comparison with recently published data on acceptability and perceptibility thresholds for whiteness obtained in a cohort study with laypersons.[17] The 50:50% perceptibility level was determined at 0.61 ΔWI units (WPT=0.61) while 50:50% acceptability level was determined at 2.90 ΔWI_D units (WAT=2.90).[17]

Statistical Analysis

The color parameters L^*, a^*, b^* and the WI_D values were statistically evaluated. Two-way analysis of variance (ANOVA) was used to evaluate significance for the factors: bleaching and accelerated aging. The Tukey post hoc test was used to identify differences between groups. A global significance level of 95% was used.

RESULTS

CIELAB color coordinates (L^*, a^* and b^*) and WI_D values for Z2.2, Z2.3, Z3.2, and Z3.3, before and after bleaching and with different accelerated aging procedures are shown in Tables 3 through 6. As the time of aging increased, the mean values of L* and WI_D decreased ($p \leq 0.05$) (Tables 3 through 6).

CIEDE2000 total color difference (ΔE_{00}) values between two different bleaching treatments on the same composite/shade group for each aging protocol are shown in Figure 1. Comparing different bleaching treatments at T0, T1, and T2, all values of color difference (ΔE_{00}) were below AT (acceptable match). Color differences below PT (excellent match) were shown by the following comparisons: Z2.2 (T2), Z2.3 (T0 and T2), Z3.2 (T0 and T2), and Z3.3 (T0 and T1) (Figure 1).

ΔE_{00} values between two different aging procedures on the same composite/shade group for each bleaching treatment are shown in Figure 2. Considering different aging procedures, the comparison

Table 4: *Mean and Standard Deviation Values of CIELAB Color Coordinates and Whiteness Index (WI_D) Followed by the Statistical Groupings for Specimens of Filtek Z250 Shade A3 (Z2.3)* [a]

Groups	CIELAB Color Coordinates			WI_D
	L^*	a^*	b^*	
Z2.3-CT0	66.38 ± 0.36 aA	–0.35 ± 0.04 cB	14.51 ± 0.22 cA	18.78 ± 0.39 aA
Z2.3-CT1	64.35 ± 0.79 bA	0.21 ± 0.26 bA	21.14 ± 2.81 bAB	9.13 ± 2.93 bA
Z2.3-CT2	62.40 ± 0.11 cC	0.43 ± 0.09 aA	23.74 ± 0.16 aA	4.78 ± 0.36 cB
Z2.3-OBT0	65.36 ± 0.19 aB	–0.23 ± 0.04 bA	14.27 ± 0.28 cA	18.23 ± 0.32 aA
Z2.3-OBT1	63.43 ± 0.25 bA	–0.52 ± 0.09 cB	21.50 ± 0.24 bA	9.96 ± 0.48 bA
Z2.3-OBT2	62.91 ± 0.33 cB	0.13 ± 0.11 aB	23.64 ± 0.31 aA	5.84 ± 0.52 cA
Z2.3-HBT0	65.45 ± 0.24 aB	–0.20 ± 0.05 bA	14.08 ± 0.15 cA	18.42 ± 0.34 aA
Z2.3-HBT1	64.34 ± 1.44 abA	–0.62 ± 0.26 cB	20.35 ± 0.89 bB	11.93 ± 2.05 bA
Z2.3-HBT2	63.39 ± 0.19 bA	0.14 ± 0.10 aB	23.66 ± 0.34 aA	6.04 ± 0.53 cA

Abbreviations: C, control; HB, at-home bleaching; OB, in-office bleaching; T0, no aging; T1, chromatic aging procedure (450 KJ/m^2) equivalent to 1 year; T2, chromatic aging procedure (900 KJ/m^2) equivalent to 2 years.

[a] *CIELAB color coordinates and WI_D values using a black background ($p \leq 0.05$; two-way analysis of variance). Different lowercase letters show statistical differences for mean values (color parameters) between different aging procedures (T0, T1, and T2) within the same bleaching procedure (C, OB, or HB) (column). Different capital letters show statistical differences for mean values (color parameters) between different bleaching procedures (C, OB, and HB) within the aging procedures (T0, T1, or T2) (column).*

between T1 and T2 showed CIEDE color differences below AT (acceptable match) for Z2.2, Z2.3, and Z3.3 within C and OB groups (Figure 2A,B) and for Z2.3 within HB group (Figure 2C). For all other groups, mean values of ΔE_{00} were above AT (unacceptable match) (Figure 2).

Figures 3 and 4 show mean and standard deviation values of WI_D after different bleaching treatments and accelerated aging procedures on Z2 and Z3, respectively. Comparing different aging procedures always showed significant differences ($p \leq 0.05$) (Tables 3 through 6). All values of ΔWI_D between bleaching treatments and control group for the same aging procedure were below WAT. Only some values of ΔWI_D were below WPT (Table 7).

DISCUSSION

The present study was designed to respond to relevant questions regarding color changes in RBC after bleaching and aging procedures. Although the CIELAB color difference metric is the most commonly used in dentistry, it has been demonstrated that the CIELAB color space assumes equal influence or weight for all color coordinates.[32] However, some studies[33,34] have suggested a discrepancy on sensitivity to the different color coordinates within the dental color space. In recent years, CIEDE2000[29]

Table 5: *Mean and Standard Deviation Values of CIELAB Color Coordinates and Whiteness Index (WI_D) Followed by the Statistical Groupings for Specimens of Filtek Z350 Shade A2 (Z3.2)* [a]

Groups	CIELAB Color Coordinates			WI_D
	L^*	a^*	b^*	
Z3.2-CT0	64.36 ± 0.68 aA	–1.31 ± 0.04 cC	7.67 ± 0.30 cA	27.49 ± 0.23 aA
Z3.2-CT1	63.13 ± 0.94 bA	–0.96 ± 0.50 bA	14.17 ± 3.92 bB	18.92 ± 3.62 bA
Z3.2-CT2	61.99 ± 0.51 cA	–0.67 ± 0.11 aA	20.57 ± 0.22 aB	10.60 ± 0.55 cA
Z3.2-OBT0	63.79 ± 0.43 aA	–1.15 ± 0.03 bB	7.74 ± 0.23 cA	26.77 ± 0.23 aB
Z3.2-OBT1	62.82 ± 0.61 bA	–1.33 ± 0.19 cB	16.85 ± 0.95 bA	16.65 ± 1.19 bB
Z3.2-OBT2	61.55 ± 0.34 cA	–0.79 ± 0.17 aA	20.60 ± 0.39 aB	10.63 ± 0.79 cA
Z3.2-HBT0	64.32 ± 0.18 aA	–1.07 ± 0.05 bA	7.13 ± 0.19 cB	27.51 ± 0.29 aA
Z3.2-HBT1	62.50 ± 0.21 bA	–1.49 ± 0.06 cC	16.63 ± 0.32 bA	17.11 ± 0.40 bB
Z3.2-HBT2	61.97 ± 0.34 cA	–0.53 ± 0.34 aA	21.28 ± 0.44 aA	9.48 ± 1.23 cA

Abbreviations: C, control; HB, at-home bleaching; OB, in-office bleaching; T0, no aging; T1, chromatic aging procedure (450 KJ/m^2) equivalent to 1 year; T2, chromatic aging procedure (900 KJ/m^2) equivalent to 2 years.

[a] *CIELAB color coordinates and WI_D values using a black background ($p \leq 0.05$; two-way analysis of variance). Different lowercase letters show statistical differences for mean values (color parameters) between different aging procedures (T0, T1, and T2) within the same bleaching procedure (C, OB, or HB) (column). Different capital letters show statistical differences for mean values (color parameters) between different bleaching procedures (C, OB, and HB) within the aging procedures (T0, T1, or T2) (column).*

Table 6: *Mean and Standard Deviation Values of CIELAB Color Coordinates and Whiteness Index (WI_D) Followed by the Statistical Groupings for Specimens of Filtek Z350 Shade A3 (Z3.3)* [a]

Groups	CIELAB Color Coordinates			WI_D
	L^*	a^*	b^*	
Z3.3-CT0	63.32 ± 0.44 aA	–1.07 ± 0.07 cB	10.61 ± 0.39 cA	23.16 ± 0.59 aA
Z3.3-CT1	62.05 ± 0.39 bA	–0.69 ± 0.07 bA	18.82 ± 0.35 bAB	12.61 ± 0.61 bA
Z3.3-CT2	61.43 ± 0.69 cAB	–0.47 ± 0.10 aB	21.20 ± 0.38 aB	9.16 ± 0.56 cA
Z3.3-OBT0	62.65 ± 0.23 aB	–0.92 ± 0.11 cA	10.50 ± 0.42 cA	22.60 ± 0.61 aA
Z3.3-OBT1	61.76 ± 0.52 bA	–0.87 ± 0.13 bA	19.45 ± 0.34 bA	12.19 ± 0.82 bA
Z3.3-OBT2	61.13 ± 0.48 cB	–0.41 ± 0.09 aB	21.65 ± 0.27 aB	8.38 ± 0.70 cA
Z3.3-HBT0	63.62 ± 0.49 aA	–0.77 ± 0.05 cA	10.62 ± 0.24 cA	22.63 ± 0.37 aA
Z3.3-HBT1	61.74 ± 0.31 cA	–0.81 ± 0.11 bA	19.13 ± 0.28 bB	12.40 ± 0.54 bA
Z3.3-HBT2	62.41 ± 0.54 bA	–0.17 ± 0.07 aA	22.70 ± 0.21 aA	7.32 ± 0.29 cB

Abbreviations: C, control; HB, at-home bleaching; OB, in-office bleaching; T0, no aging; T1, chromatic aging procedure (450 KJ/m²) equivalent to 1 year; T2, chromatic aging procedure (900 KJ/m²) equivalent to 2 years.
[a] *CIELAB color coordinates and WI_D values using a black background ($p \leq 0.05$; two-way analysis of variance). Different lowercase letters show statistical differences for mean values (color parameters) between different aging procedures (T0, T1, and T2) within the same bleaching procedure (C, OB, or HB) (column). Different capital letters show statistical differences for mean values (color parameters) between different bleaching procedures (C, OB, and HB) within the aging procedures (T0, T1, or T2) (column).*

color difference was increasingly implemented in color research. Studies suggested that ΔE_{00} shows a better correlation with visual perception than ΔE^*_{ab},[25,32,35,36] which is the reason for using the CIEDE2000 color difference metric in the present study. Nevertheless, there is only one study on color changes after dental bleaching using this metric.[8]

The use of total color differences, ΔE^*_{ab} [6,7,37-39] and ΔE_{00},[8] is very popular for evaluating color changes after dental bleaching. Yet, understanding and considering color differences within the visual perceptibility and acceptability thresholds is very relevant in clinical dentistry. Thus, studies on dental color should qualify their statistical analysis of the data associating them to PT and AT values. The most popular value for acceptable color difference used to be 3.3 ΔE^*_{ab} units.[6,7,37-39] Recently, an ISO standard[15] defined PT and AT values for tooth colored restorative materials. Such values were established in a prospective multicenter study[16] that used CIELAB (ΔE^*_{ab}) and CIEDE2000 (ΔE_{00}) total color difference metrics. The present study used PT and AT values reported in that work.[16]

Although it is common to use color difference formulas to evaluate color changes after bleaching procedures, a sole evaluation of color differences does not offer enough information on how color coordinates change. Thus, it is not adequate to compare whiteness values using only color difference metrics (ΔE^*_{ab} or ΔE_{00}). Although previous studies used other indexes for evaluating whiteness,[13,26,40,41] the present study used a recently published whiteness index (WI_D), which is based on CIELAB color space and was specifically designed for dentistry and dental applications.[14] WI_D was compared with other

Table 7: *Mean and Standard Deviation Values of Differences in Whiteness Index (ΔWI_D) for Specimens of Filtek Z250 (Z2.2 = Shade A2 and Z2.3 = Shade A3) and Filtek Z350 (Z3.2 = Shade A2 and Z3.3 = Shade A3) Between each Bleaching Procedure (OB or HB) and Control Group for the Same Aging Procedure (T0, T1, and T2)* [a]

Groups	ΔWI_D			
	Z2.2	Z2.3	Z3.2	Z3.3
OBT0-CT0	–2.47 ± 0.82	–0.55 ± 0.57[a]	–0.73 ± 0.44	–0.56 ± 0.69[a]
OBT1-CT1	–1.76 ± 0.63	0.83 ± 0.26	–2.26 ± 0.69	–0.42 ± 0.25[a]
OBT2-CT2	–0.80 ± 0.91	1.06 ± 0.72	0.02 ± 0.37[a]	–0.78 ± 0.64
HBT0-CT0	–2.63 ± 0.53	–0.36 ± 0.45[a]	0.02 ± 0.13[a]	–0.53 ± 0.61[a]
HBT1-CT1	–1.17 ± 0.48	2.80 ± 0.48	–1.81 ± 0.57	–0.21 ± 0.10[a]
HBT2-CT2	–1.28 ± 0.80	1.25 ± 0.52	–1.13 ± 0.46	–1.84 ± 0.41

Abbreviations: C, control; HB, at-home bleaching; OB, in-office bleaching; T0, no aging; T1, chromatic aging procedure (450 KJ/m²) equivalent to 1 year; T2, chromatic aging procedure (900 KJ/m²) equivalent to 2 years.
[a] *Mean values below 50:50% perceptibility whiteness thresholds for laypersons (ΔWI_D=0.61).[17] Negative values indicate that bleaching procedure groups (OB or HB) showed lower values of WI_D compared with control group (C).*

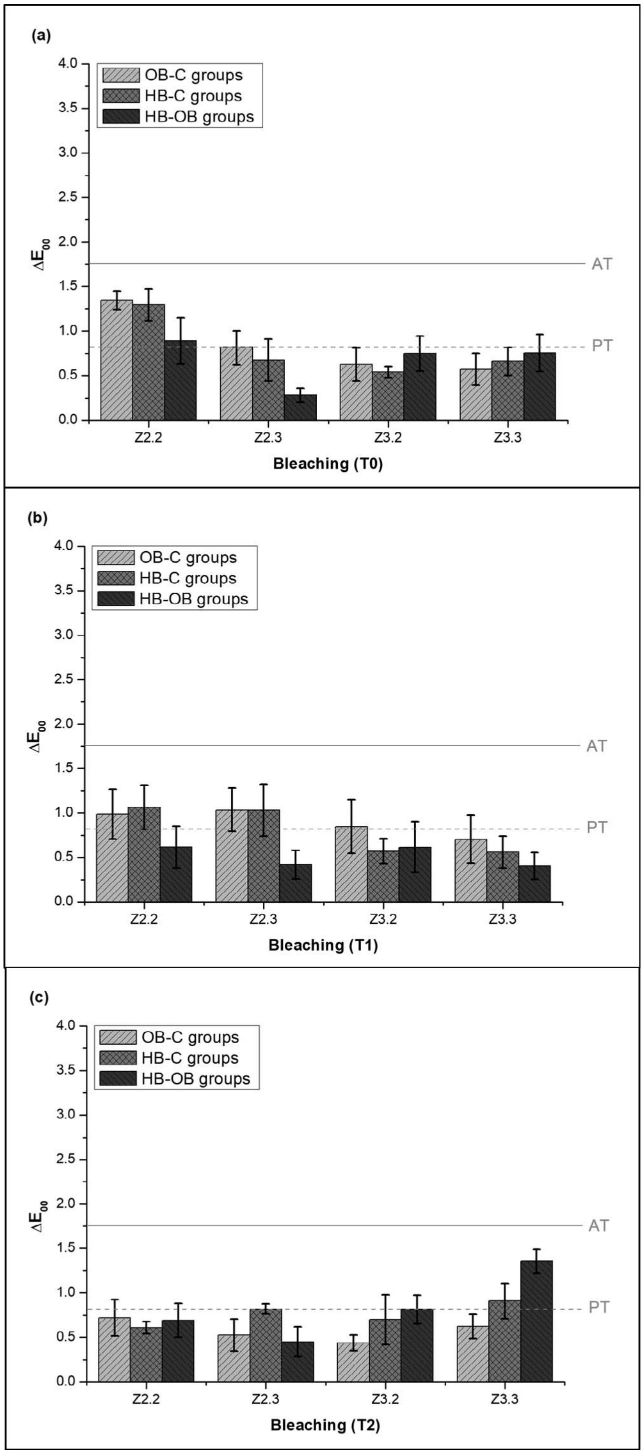


Figure 1. *Mean and standard deviation values of ΔE_{00} between two different bleaching treatments, in-office bleaching (OB) or at-home bleaching (HB) and control (C; no bleaching) on the same composite/ shade group at (A): baseline (T0); (B): 450 KJ/m^2 estimating 1 year (T1); and (C): 900 KJ/m^2 estimating 2 years (T2). The horizontal lines at 1.77 and 0.81 (ΔE_{00} units) represent the 50:50% acceptability (AT) and the 50:50% perceptibility (PT) thresholds, respectively.*[16]

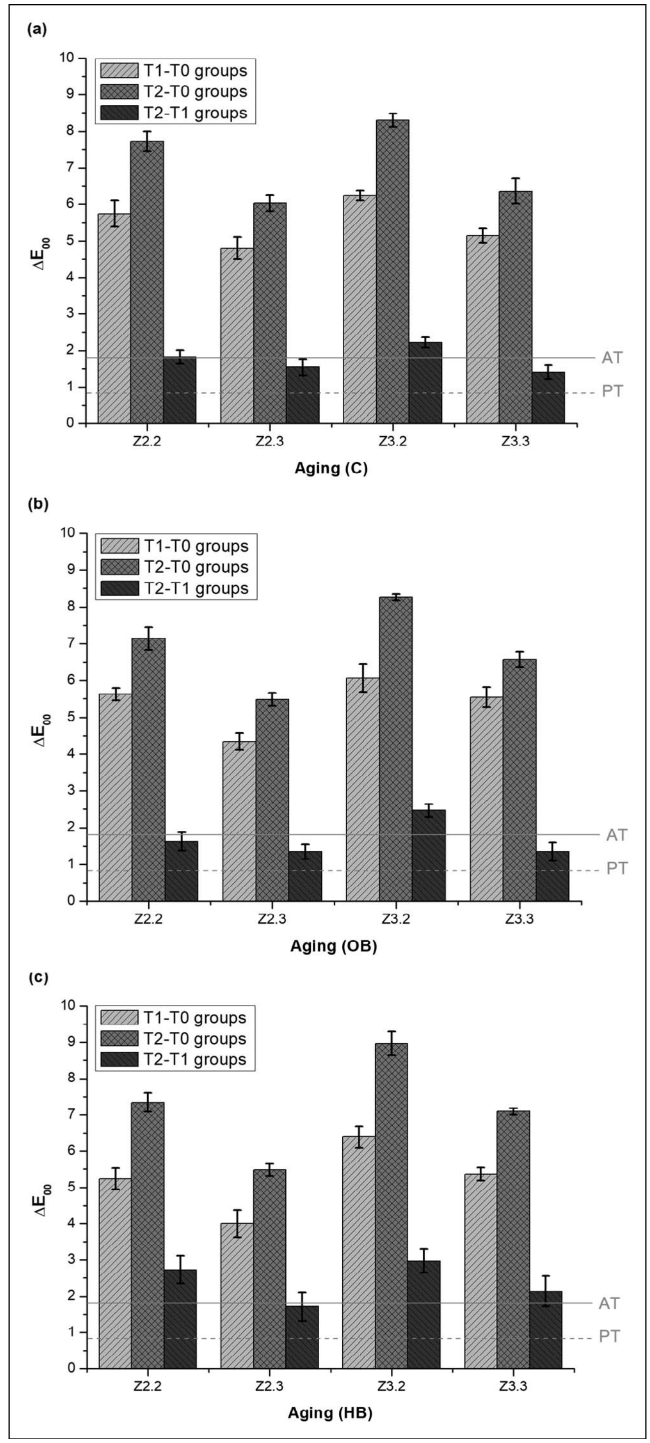
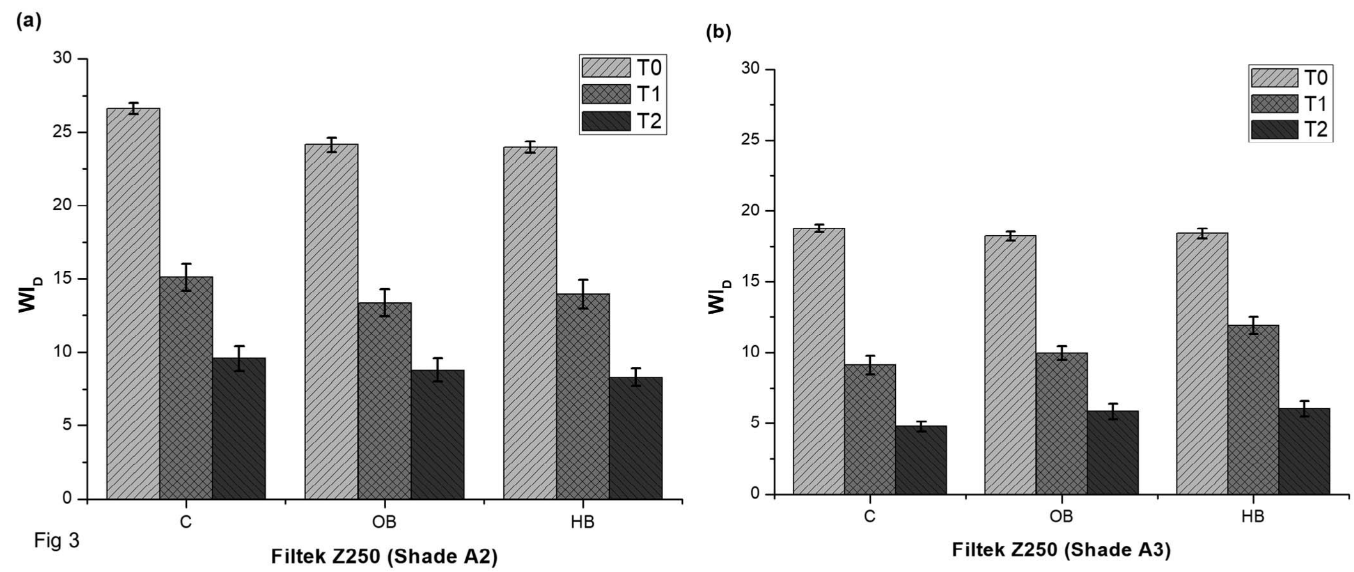


Figure 2. *Mean and standard deviation values of ΔE_{00} between two different chromatic aging procedures, 450 KJ/m^2 estimating 1 year (T1) or 900 KJ/m^2 estimating 2 years (T2) and the control (T0; no aging) on the same composite/shade for (A): control (C) groups; (B): in-office bleaching (OB) groups; and (**C**) at-home bleaching (HB) groups. The horizontal lines at 1.77 and 0.81 (ΔE_{00} units) represent 50:50% acceptability (AT) and 50:50% perceptibility (PT) thresholds, respectively.*[16]



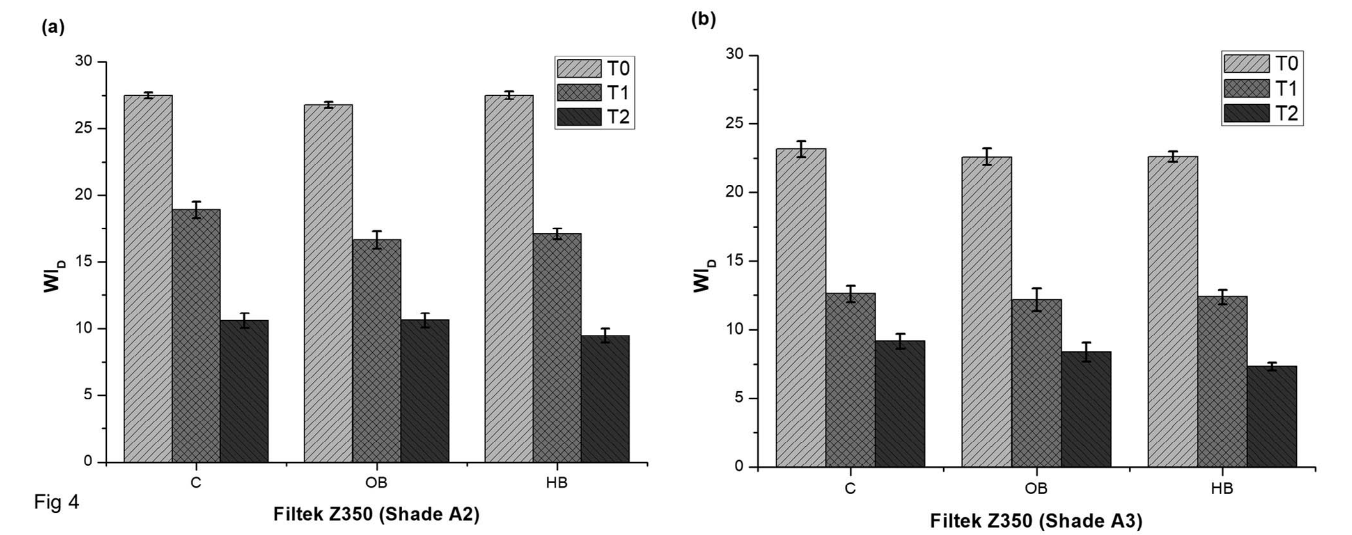


Figure 3. *Mean and standard deviation values of* WI_D *for Filtek Z250 shades (A): A2 and (B): A3 after different bleaching treatment (C, control; OB, in-office bleaching; and HB, at-home bleaching) and different chromatic aging procedures (T0, control; T1, after 450 KJ/m*^{2} *estimating 1 year; and T2, after 900 KJ/m*^{2} *estimating 2 years).*

Figure 4. *Mean and standard deviation values of* WI_D *for composite Filtek Z350 shades (A): A2 and (B): A3 after different bleaching treatment (C, control; OB, in-office bleaching]; and HB, at-home bleaching) and different chromatic aging procedures (T0, control; T1, after 450 KJ/m*^{2} *estimating 1 year; and T2, after 900 KJ/m*^{2} *estimating 2 years).*

whiteness indexes and showed a strong correlation to visual perception of tooth whiteness.[14]

The ΔWI_D values between different bleaching treatments (OB, HB, and control) for the same aging procedure (Table 7) were analyzed using values of whiteness thresholds (WPT and WAT) from a previous study[17] that found different WPT and WAT values for different observer groups (WPT = 0.61 and WAT = 2.90 for laypersons and WPT = 0.44 and WAT = 2.15 for dentists). Since patients are the evaluators (observers) of dental bleaching treatments, and the influence of observer population on color difference thresholds (PT and AT) has been previously reported,[16] the present study used WPT = 0.61 and WAT = 2.90.

Considering color differences and whiteness variations after bleaching of all experimental groups, the mean values of ΔE_{00} and ΔWI_D were below their corresponding acceptability value (AT=1.77 and WAT=2.90, respectively). Therefore, despite the variations, the color changes and whiteness variations should be acceptable to observers (patients). Thus, the first part of the study hypothesis was not confirmed because bleaching procedures did not produce color changes and whiteness variations of RBCs greater than the 50:50% acceptability thresholds (AT and WAT).

The term "color stability" has been widely used in dental color research. A physical magnitude is stable when its variation along a process (in this case, bleaching or aging) is lower than the instrumental error. However, color is a psychophysical property; therefore, observer's interpretations (evaluations) should be considered. In this sense, color variations below the perceptibility threshold will not be detectable by a standard observer. Thus, color stability of a dental material, from an observer point of view, can be defined as a color variation (described by a color difference) lower than the PT. In most cases, the bleached nanocomposite showed color differences below PT values (Z3.3 after T0 and T1 and Z3.2 at time of aging) (Figure 1), suggesting this material presents appropriate color stability for the aging protocols evaluated in the present study.

Previous studies showed that bleaching treatments may affect the elution of monomers and other substances from RBCs.[42-44] The three-dimensional polymer network of RBCs, which consists of carbon-carbon (C-C)-single or (C-C)-double bonds, may react with oxidants like hydroxide peroxide, increasing unpolymerized monomers, additives and unspecific oxidative products release.[43,44] Complete polymerization of RBCs is still a challenge to overcome. Thus, the lower the conversion rate of an RBC, the more residual monomers can be eluted.[45] Both RBCs used in the present study were light activated under the same conditions (eg, activation time, light energy and distance), therefore they should not be considered as study variables. Yet, though the manufacturer did not provide the exact percentage of monomers, the three-dimensional polymer network is very similar for both RBCs. The main difference between the two RBCs is the amount of inorganic phase, which can influence the degree of conversion of an RBC. As is known, as the filler loading increases, the degree of conversion increases and the water sorption decreases. Thus, the greater color stability of the nanocomposite may be associated to its higher filler content (Table 1).

Previous studies showed that total bleaching time is more important than the concentration of the bleaching agent.[2,8] Although it was not an objective of the present study, the results did not show a significant difference between the effect of the different bleaching treatments on color of RBCs (Figure 1A).

Color stability of RBCs has been evaluated using an artificial aging chamber, exposing the specimens to ultraviolet light and elevated temperatures[20,21,46] or by immersing the RBC in various staining beverages.[47,48] The present study used an artificial aging procedure to simulate clinical service because restorations are exposed to different variables, such as temperature changes and constant humidity. This procedure reproduces, in a short period of time, the effects of long-term exposure of RBCs in an oral environment. However, as with most *in vitro* experiments, there are limitations to the accelerated aging process that do not consider clinical variables, such as the influence of the saliva components, pH levels, and brushing. Further, and as mentioned previously, bleaching treatments may affect the elution of monomers and other substances from RBCs, which may also affect the surface roughness of these materials and, as a consequence, changing color perception. A previous study showed changes in the value of L^* coordinate with different surface roughness values.[49]

After the accelerated aging process, L^* and WI_D values decreased (specimens became darker), while b^* values increased (specimens became more chromatic) for both composites (Table 3 through 6). In addition, a^* values generally increased. In all cases color changes and whiteness variations after aging procedures, which estimated 1 year and 2 years of clinical service,[21] were above acceptability thresholds: AT = 1.77 (Figure 2) and WAT = 2.90 (Figures 3 and 4). Therefore, the second part of the study hypothesis was accepted, meaning aging procedures produced color changes and whiteness variations of RBCs greater than the 50:50% acceptability thresholds (AT and WAT).

Previous studies also showed a decrease of L^* values and an increase of b^* values after artificial aging procedures of RBCs.[20,21,46-48] However, the assessment of color and/or whiteness variations in these studies was based solely on a quantitative evaluation without taking into account the limits of visual perception and, therefore, its clinical impact.

CONCLUSIONS

Within the limitations of this study, aging produced unacceptable color matches of RBCs while bleaching treatments produced, in most cases, imperceptible color changes of nanocomposites.

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Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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