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Study of the Variation between CIELAB ΔE* and CIEDE2000 Color-differences of Resin Composites

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This study sought to assess the significance of the corrections introduced in the new CIEDE2000 color difference formula with respect to ΔE^*_{ab}. The purpose of which was to provide sounder knowledge, and hence more informed decision-making, about applying this new formula to dental resin composites. With two different hybrid composites, color differences were calculated between unpolymerized and polymerized resin composites, between polymerized resin composites of different thicknesses (1 and 2 mm), and between polymerized resin composites cured with halogen and LED light curing units (LCUs). The two formulas differed significantly, with V_{AB}(E) (equal size) values higher than the inter-observer variability (V_{AB}(E)=11%) and V_{AB}(O) (original size) values greater than 25% for each of the data sets analyzed. Results obtained in this study agreed with and thus supported the recent recommendation of the Commission Internationale de l'Éclairage (CIE), whereby the new CIEDE2000 formula should be used to evaluate color differences of resin composites.

Keywords: CIEDE2000, CIELAB ΔE*, Resin composites

INTRODUCTION

A color difference formula is designed to give a quantitative representation (ΔE) of the perceived color difference (ΔV) between a pair of colored samples under a given set of experimental conditions. Typical applications of color difference formulas include color tolerance control, color reproduction, and color stability—all of which are highly important in the field of aesthetic dentistry[1-3].

Color stability is an important parameter for modern resin composites. Several factors influence the color stability of current photocuring materials, such as the photoinitiator system, resin matrix, light curing unit (LCU) used for polymerization, and irradiation time[4-9]. Color changes of resin composites have been reported[10-12], as well as the magnitude of color changes, whereby the results obtained depended on the experimental conditions used during color measurement: geometry, illumination, and aperture size of measuring instrument[13,14].

Presently, in dental color study, colors and color differences are quantified respectively using the CIELAB space and the associated ΔE^*_{ab}[15], as shown below:

$$\Delta E^*_{ab} = \left[(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2\right]^{1/2} \quad (1)$$

With the aim of improving the correction between computed and perceived color differences in industrial applications, two CIELAB color difference formulas were recently proposed by the CIE: CIE94[16] and CIEDE2000[15,17] color difference formulas. Both incorporate specific corrections for non-uniformity of the CIELAB space (the so-called weighting functions S_L, S_C, and S_H) and parameters accounting for the influence of illuminating and viewing conditions in color difference evaluation (the so-called parametric factors K_L, K_C, and K_H). Therefore, the parametric factors are correction terms for variations of experimental conditions. The CIE[15] indicated that under reference experimental conditions[15,16] representative of industrial practice, the value of each parametric factor is equal to 1.0. In particular, the CIEDE2000 color difference formula[15,17,18] is given as follows:

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

where ΔL′, ΔC′, and ΔH′ are the differences in lightness, chroma, and hue for a pair of samples in CIEDE2000, and R_T is a function (the so-called rotation term) that accounts for the interaction between chroma and hue differences in the blue region.

Then, in addition to the aforementioned specific weighting functions, parametric factors, and a rotation term, R_T, a modification of the a* axis of CIELAB—which affects mainly colors with low chroma (neutral colors)—is also included. In summary, five corrections on CIELAB have been introduced in CIEDE2000: lightness (S_L), chroma (S_C), and hue (S_H) weighting functions; the rotation term, which is the last term in Eqn (2); and the correction for neutral colors, which leads to the primed values in the lightness, chroma, and hue differences of Eqn (2).

Recent reports[19-21] showed significant correlations between ΔE^*_{ab} and ΔE_{00} values after polymerization

Table 1 Resin composites used.

Material	Shade	Batch N®	Manufacturer
Artemis	Super Clear Effect	F34461	Ivoclar Vivadent AG, FL-9494, USA
	Amber Effect	F29913	
	Clear Effect	F34462	
	Blue Effect	F29478	
	White Effect	F26569	
	EA1	F45383	
	EA2	F42804	
	EA3	G16805	
	EB2	F15278	
	ED2	F14794	
	EC2	F33695	
	DA2	F39767	
	DA3	G16503	
	DD2	F14783	
	DB3	F27974	
	DC4	F24479	
	DA4	F25457	
Esthet-X	A-E	0-410207	DENTSPLY Caulk Milford, De 19963-0359, USA
	Y-E	0-31204	
	A2	0-601071	
	A2-0	0-501125	
	A3	0-40928	
	A3,5	0-501052	
	C2	0-408241	
	B2	0-404283	
	B2-0	0-411171	
	A1	0-40925	
	C3	0-410087	
	C4-0	0-311251	
	D2	0-40813	
	D3-0	0-307251	
	GE	0-307216	
	CE	0-406172	

or thermocycling. In these reports[19-21], the authors could not find any significant involvement of the weighting functions for the lightness, chroma, and hue components. Instead, the reported correlations showed only that the values obtained from these formulas were proportional, but not that the two color differences formulas could be used interchangeably to evaluate the color differences of resin composites—but which was otherwise advocated by Lee[19]. Furthermore, any possible color variations between the two formulas were not statistically evaluated in these reports[19-21].

The goal of the current study, therefore, was to assess the possible significance of the corrections introduced in the CIEDE2000 color difference formula, so as to provide further knowledge of this formula for application to aesthetic dental materials. The working hypothesis of this study was that there were statistically significant differences between ΔE^*_{ab} and ΔE_{00} values after polymerization and when certain variables were changed, namely the light curing unit used and thickness of the resin composite.

MATERIALS AND METHODS

Resin composite samples

Table 1 lists the two light-cured resin composites used in this study and their accompanying shades: Artemis (Ivoclar Vivadent, Schaan, Liechtenstein) with 17 shades and Esthet-X (Dentsply, Konstanz, Germany) with 16 shades.

Special molds were made for sample preparation: 6 ± 1 mm in diameter, 1.00 ± 0.05 mm or 2.00 ± 0.05 mm in thickness. Six specimens were made for each shade. The materials were handled according to the manufacturers' instructions and packed into the molds. Precured resin composites were prepared on a glass plate with a clear plastic sheet on the top and bottom surfaces of the mold. The molds were slightly overfilled with the resin composite, and then another glass plate placed on top of the sample to extrude excess material between the glass plates. After removing the sample between the glass plates, color of the pre-polymerized samples was measured with the plastic sheets in place, as the effect of the plastic sheets on color measurement was negligible[22].

To standardize the distance between the light source and the sample, the top glass plate (1 mm thick) was placed over the sample before polymerizing. Each sample was then light-cured by placing the tip of the lamp over the glass. After polymerization, the samples were measured again.

Light curing units (LCUs)

Three samples were cured with a quartz tungsten halogen (QTH) LCU (Bluelight, Mectron, Carasco, Italy) and the other three samples with a LED LCU (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein), whereby irradiances were respectively 1400 and 1100 mW/cm^2. Exposure times of 13 and 17 seconds were employed to achieve total radiant exposure of close to 18 J/cm^2 in both cases, a value necessary for adequate polymerization of hybrid composites of 2-mm thickness[23-25]. Total irradiance of the LCUs was determined in our previous work in a laboratory[26] using a spectroradiometer (PR-650, Photo Research Inc., Chatsworth, USA). Its spectral range was 380-780 nm at a broadband resolution of 8 nm and exactitude of 4 nm (with a 2% measurement error). Irradiance was measured with a CR-600 cosine receptor.

Color measurement

Color measurements were made by a spectroradiometer (SpectraScan PR-704, Photo Research Inc., Chatsworth, USA) with a 4% measurement accuracy. With this instrument, repeatability percentage of the measurements was much lower (standard deviation of repeat measurements over a 15-minute period was less than 0.1%)[27]. Samples were situated in a color assessment cabinet (CAC portable, Verivide Limited, Leicester LE3 5AG, England), and a source simulating the relative spectral irradiance of CIE standard illuminant D65 was used. Illuminating and viewing configurations were CIE 45°/0° geometry[15] and the CIE 1964 10° supplementary standard colorimetric observer.

The L*, a*, b* values of the three polymerized samples with each LCU were averaged to establish a single set of values for each shade. For each shade, the resulting standard deviations were lower than the instrumental accuracy (4%). Therefore, we use the terms L^*_{QTH}, a^*_{QTH}, and b^*_{QTH} to represent the mean values of the chromatic coordinates of CIELAB (L*, a*, b*) color space for samples polymerized with QTH LCU. Similarly, L^*_{LED}, a^*_{LED}, and b^*_{LED} represented the chromatic coordinates measured from samples polymerized with the LED LCU.

Color difference calculation

Color difference was calculated with two different formulas. Color difference by ΔE^*_{ab} was calculated according to Eqn (1), and ΔE_{00} by Eqn (2). In the present study, the parametric factors K_L, K_C, and K_H of CIEDE2000 color difference formula were set to 1. To calculate using the CIEDE2000 color difference formula, discontinuities due to mean hue computation and hue-difference computation were taken into account, whereby both were pointed out and characterized by Sharma *et al.*[28] in a recent report.

Color difference was calculated for the following comparisons: (a) between polymerized and unpolymerized samples (with two different LCUs and 2-mm-thick samples); (b) between polymerized resin composites of 1-mm and 2-mm thicknesses; and (c) between polymerized resin composites cured with QTH and LED LCUs (2-mm thickness in both cases).

Statistical analysis

To analyze the statistical significance of the corrections introduced in the CIEDE2000 color difference formula, a parameter V_{AB} was used. This parameter allowed us to quantify the variation between two calculated color difference values obtained with two color difference formulas. This parameter, as proposed by Schultze[29], is usually given as a percentage. As for parameter F, it provided an overall scale correction between ΔE_A and ΔE_B. Specifically, V_{AB} and F were calculated using the following expressions:

$$V_{AB} = \left[\frac{1}{n} \sum_{i=1}^{n} \frac{\Delta E_A - F\Delta E_B}{\Delta E_A F \Delta E_B} \right]^{1/2} \quad (3)$$

$$F = \left(\sum_{i=1}^{n} \frac{\Delta E_A}{\Delta E_B} \Big/ \sum_{i=1}^{n} \frac{\Delta E_B}{\Delta E_A} \right)^{1/2} \quad (4)$$

where n indicates a given number of color differences, and ΔE_A and ΔE_B are color differences to be compared. As mentioned, F is an overall scale factor between the calculated values from both formulas. If F were fixed to be equal to 1, the scale factor would not be applied and the data sets of compared values from both color difference formulas would maintain their original sizes—in which case the V_{AB} parameter would be designated as $V_{AB}(O)$ (original size). If $F \neq 1$, this overall scale factor would be applied, normalizing both data sets to an equal size and the V_{AB} parameter designated as $V_{AB}(E)$ (equal size). In the latter case, Eqn (3) would be used with the F value given by Eqn (4).

As mentioned above, the parameter V_{AB} is usually given as a percentage. If there were perfect agreement between the two color difference formulas, its value should be zero. A higher V_{AB} value would therefore indicate worse disagreement. For example, a V_{AB} value of 0.30 indicates a typical disagreement of 30% between two data sets.

With a statistical program SSPS 13.0, regression analysis was used to determine the correlation between the color difference values of ΔE^*_{ab} and

Table 2 Ranges of color differences with ΔE_{ab} and ΔE_{00}.

After Polymerization (2mm in thickness)			Thickness (1mm-2mm)			LCUs (2mm in thickness)		
Material/LCU	ΔE^*_{ab}	ΔE_{00}	Material/LCU	ΔE^*_{ab}	ΔE_{00}	Material	ΔE^*_{ab}	ΔE_{00}
Artemis/Bluelight	2.6-7.3	1.8-4.8	Artemis/Bluelight	1.3-7.8	1.2-5.2	Artemis	0.7-3.3	0.5-2.6
Artemis/Bluephase	2.8-7.9	2.1-5.4	Artemis/Bluephase	3.3-9.6	2.2-6.8			
Esthet-X/Bluelight	1.8-5.6	0.9-4.1	Esthet-X/Bluelight	1.0-7.2	0.9-3.8	Esthet-X	0.8-4.6	0.7-3.4
Esthet-X/Bluephase	2.6-7.0	1.1-5.1	Esthet-X/Bluephase	4.3-8.8	3.6-6.6			
Both Materials and both LCUs	1.1-7.9	0.9-5.3	Both Materials and both LCUs	1.0-9.6	0.9-6.6	Both Materials	0.7-4.6	0.5-3.4

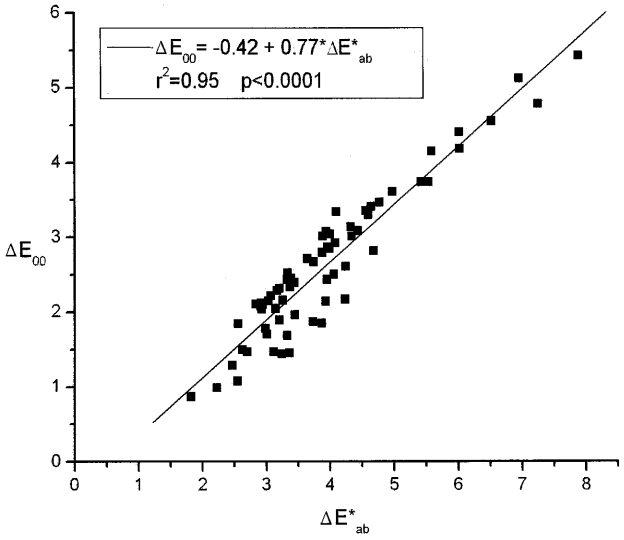

Fig. 1 Correlation between ΔE^*_{ab} and ΔE_{00} after polymerization.

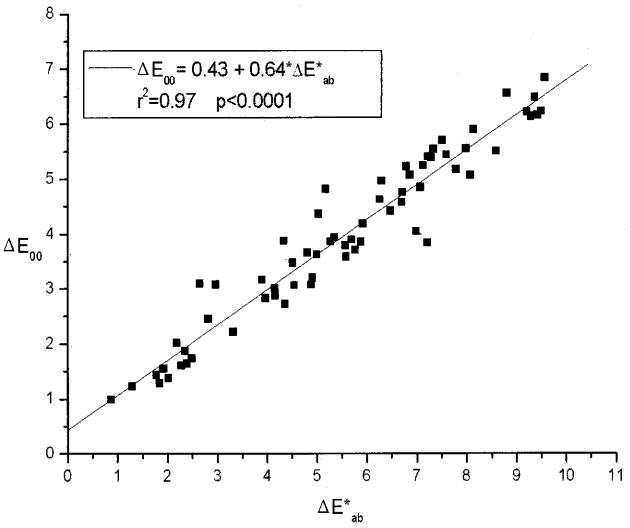

Fig. 2 Correlation between ΔE^*_{ab} and ΔE_{00} for polymerized composites of 1-mm and 2-mm thicknesses.

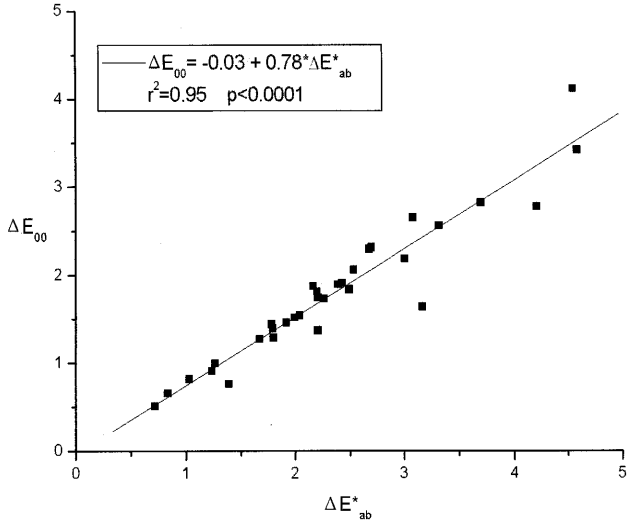

Fig. 3 Correlation between ΔE^*_{ab} and ΔE_{00} for composites cured with halogen and LED LCUs.

ΔE_{00}, where the value of statistical significance was set at $p<0.05$.

RESULTS

Table 2 shows the ranges of CIELAB and CIEDE2000 color differences found for each comparison. The first column shows the ranges of color differences between polymerized and unpolymerized samples; the second column shows the color difference ranges between polymerized composites of 1-mm and 2-mm thicknesses; and the last column, between polymerized resin composites cured with a halogen LCU and a LED LCU. The last row lists these results for the materials and LCUs jointly.

Figures 1 to 3 present the correlations corresponding to the data sets in Table 2. After polymerization, there was a significant correlation between ΔE^*_{ab} and ΔE_{00} ($r^2=0.95$ and $p<0.0001$). Similar results were found for the correlations in the case of

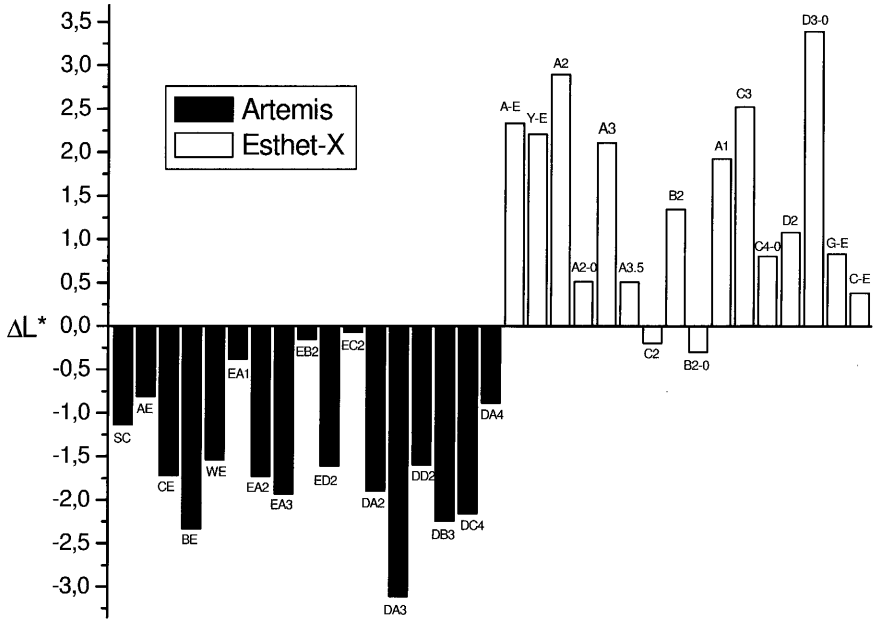

Fig. 4 ΔL* for both materials.

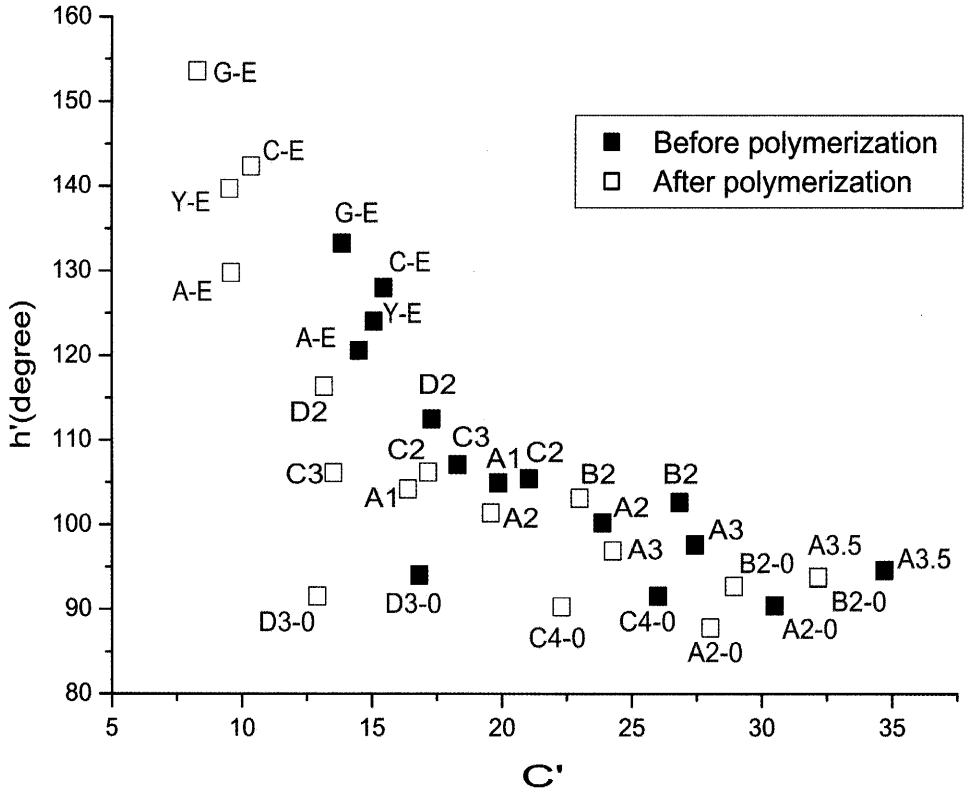

Fig. 5 Variations of C´ and h´ values after polymerization (Esthet-X and BluePhase)

color differences between polymerized samples of 1- and 2-mm thicknesses and between polymerized samples cured with QTH and LED LCUs. As shown in Table 2, polymerized resin composites of different thicknesses registered the largest color differences, whereas samples cured with different LCUs presented the smallest color differences.

Figure 4 shows the variations in L* (ΔL*) among the samples polymerized with the LED LCU and those polymerized with QTH LCU, *i.e.*, $\Delta L^*=L^*_{LED}-L^*_{QTH}$, for the two materials considered in our study.

By way of example, Fig. 5 presents the chroma and hue angle coordinates according to CIEDE2000 (C´and h´) for the shades of Esthet-X when polymerized with Bluephase.

Table 3 shows the values of the parameters $V_{AB}(E)$ and $V_{AB}(O)$ for each of the cases studied.

Table 3 Values of the parameter $V_{AB}(E)$ and $V_{AB}(O)$.

After Polymerization (2mm in thickness)			Thickness (1mm-2mm)			LCUs (2mm in thickness)		
Material/LCU	$V_{AB}(E)$	$V_{AB}(O)$	Material/LCU	$V_{AB}(E)$	$V_{AB}(O)$	Material	$V_{AB}(E)$	$V_{AB}(O)$
Artemis/Bluelight	0.032	0.316	Artemis/Bluelight	0.049	0.355	Artemis	0.127	0.274
Artemis/Bluephase	0.046	0.312	Artemis/Bluephase	0.104	0.296			
Esthet-X/Bluelight	0.174	0.560	Esthet-X/Bluelight	0.111	0.300	Esthet-X	0.166	0.254
Esthet-X/Bluephase	0.161	0.585	Esthet-X/Bluephase	0.205	0.251			

DISCUSSION

A ΔE^*_{ab} value higher than 3.3 is regarded as clinically perceptible[30]. The range of ΔE^*_{ab} values in the present study fell into both non-perceptible and visually perceptible ranges by a human observer. However, a closer study of Table 2 and Figs. 1 to 3 revealed that these color difference ranges depended on the variables considered, with higher values appearing between the polymerized resin composites of different thicknesses (Column 2 of Table 2).

As observed in Fig. 3 and Table 2 (last column), the range of ΔE^*_{ab} between polymerized samples cured with QTH and LED LCUs varied from 0.7 to 4.6 for both materials. However, this color difference range varied slightly between the two materials studied, where the difference was slightly higher for Esthet-X (0.8-4.6 as opposed to 0.7-3.3 for Astralis). Therefore, the results obtained were in collaboration with other studies[8,31], which showed that composite materials underwent measurable changes upon exposure to irradiation by LCUs. However, while a previous study[31] reported on ΔE^*_{ab} consistently below 2.5, results in the last column of Table 2 were found to exceed 2.5 — especially with the Esthet-X samples. Thus, the results of the present study clearly showed that the LCU used had an a gresater influence on the final color of resin composites.

While it was noted that the magnitude of color change depended on the material, the trend in color change was similar for both materials. Δa^* (a^*_{LED}-a^*_{QTH}) was positive, and Δb^* (b^*_{LED}-b^*_{QTH}) was generally positive too. These results indicated that samples cured with LED LCU presented generally higher chroma (C^*_{ab}) and hue angle (h_{ab}) — that is, shifted to the yellow region of the color space — than did samples cured with QTH LCU. However, similar conclusions could not be drawn for ΔL^* (L^*_{LED}-L^*_{QTH}). Indeed, the variation in L^* strongly depended on the material used, as reflected in Fig. 4.

As for the influence of light curing units, results in the first column of Table 2 showed that samples cured with QTH LCU (BlueLight) yielded a slightly lower range in color difference than those cured with the LED unit. This result agreed with the color results of Usumez *et al.*[31], whereby samples cured with a QTH LCU underwent the lowest color change after polymerization. Despite the slight difference, it should be highlighted that comparable differences existed in the color coordinates between the two LCUs and materials after polymerization. Light-curing of resin composites caused a characteristic shift towards the blue region of color space, augmenting the hue angle, h_{ab}. As a result, there was a perceived decrease in yellow hue, as also indicated in another report[11]. In addition, changes in the L^* parameter were significant and had the greatest influence on the overall polymerization color change[19,32]. Indeed, with reference to the changes proposed in CIEDE2000[18], it could be seen that similar conclusions were drawn for chroma and hue angle (C' and h'), where now $a' = a^*(1+G)$, is the change of the a^* axis of CIELAB proposed in CIEDE2000, where G is a function of the chroma given by the expression $G = 0.5[1-[(\overline{C^*_{ab}}^7/(\overline{C^*_{ab}}^7+25^7)]^{1/2}]$ and where $\overline{C^*_{ab}}$ is the arithmetic mean of the C^*_{ab} for a pair of samples.

After polymerization, the a' coordinate increased slightly while the b' coordinate decreased somewhat more markedly. The samples, being less saturated after polymerization, therefore presented less chroma and greater tone angle (shifting toward the blue region of color space), as reflected in Fig. 5.

As shown in Table 3, $V_{AB}(E)$ and $V_{AB}(O)$ values varied depending on the variables studied as well as the material examined. For example, based on ΔE^*_{ab} and ΔE^*_{00} values calculated for Artemis after polymerization (Column 1 of Table 1), $V_{AB}(E)$ coefficient was found to be lower than 5% for both LCUs, while Esthet-X yielded 17.4% and 16.1% for BlueLight and BluePhase LCUs respectively. In terms of comparison between polymerized samples of different thicknesses cured with different LCUs, similar results were yielded: 4.9% and 11.1% for BlueLight LCU and 10.4% and 20.5% for BluePhase. However, in this case, differences between the coefficients were lower. It is noteworthy that in most cases the value of

V_{AB}(E) exceeded 11%. In other words, the correction terms introduced in CIEDE2000 resulted in greater variations between the two color difference formulas than those found for the inter-observer variability in experiments whereby just-perceptible color differences were evaluated and for which the value of V_{AB}(E) coefficient was 11%[25].

As for the coefficient V_{AB}(O) for ΔE^*_{ab} and ΔE_{00}, it was found to be greater than 0.25 in all cases, indicating that the disagreement between the two formulas was greater than 25%. In particular, Esthet-X registered the greatest color difference variations after polymerization (Column 1 of Table 3), whereby disagreements after curing with two different LCUs approached 60%. Indeed, the sharp differences between V_{AB}(E) and V_{AB}(O) coefficients after polymerization (e.g., 3.2% as opposed to 31.6% for Artemis or 16.1% as opposed to 58.5% for Esthet-X) signified a strong contrast in color difference values determined by the two formulas—with CIEDE2000 yielding consistently lower color difference values, as shown in Fig. 1. As for the rest of the comparisons (namely between two different thicknesses and between two different LCUs), sharp differences in color difference values determined by the two formulas were also observed. Such differences might arise from the weighting functions (S_L, S_C, and S_H) introduced in the CIEDE2000 color difference formula and also from the change of the a* axis of CIELAB, affecting mainly colors with low chroma (neutral colors). For both resin composites, most of the polymerized and unpolymerized samples presented C^*_{ab} values lower than 20. As a result, change in the a* axis, $a'=a^*(1+G)$, for these samples was significant (G varied from 0.5 at C*=0, through G=0.30 at C*=20 to G=0.06 at C*=30). As for the rotation term, R_T, introduced in CIEDE2000 to account for the interaction between chroma and hue differences in the blue region, it was found to be close to zero (in the order of 10^{-9}) in all cases. On this note, it could be said that differences between the two formulas were not due to the rotation term.

Thus far, this study has established that there were significant correlations between ΔE^*_{ab} and ΔE_{00} values in all the three comparisons: after polymerization, between polymerized resin composites of 1-mm and 2-mm thicknesses, and between polymerized resin_composites cured with QTH and LED LCUs ($r^2 > 0.95$ and $p<0.0001$ for all the three cases). However, as can be seen in Figs. 1 to 3, the best-fit straight lines differed according to the parameters studied (especially at the ordinate at the origin), making it impossible to find only one relationship between the two formulas. In any event, our best-fit straight lines also differed from those reported in another study[19], which likewise changed with the parameters analyzed. On the other hand, V_{AB}(E) and V_{AB}(O) coefficients showed significant differences between the two color difference formulas, indicating a significant involvement of weighing functions for the lightness, chroma, and hue components as well as the correction of neutral colors introduced in CIEDE2000. Therefore, based on the results of the present study and as per the recent recommendation of the CIE[15], the CIEDE2000 formula should be used to evaluate the color differences of resin composites.

In addition, variation values between the two formulas depended on factors peculiar to and inherent in the experiment itself, such as the type of material or type of LCU used for polymerization. In particular, these factors seemed to play a prominent role and largely accounted for the differences after polymerization in this study. Having established the significant role played by the weighting functions (S_L, S_C, and S_H), it now warrants a need for future studies to assess the significance of parametric factors (K_L, K_C and K_H) in the evaluation of color differences of resin composites, as well as the relative significance of each correction term introduced in CIEDE2000.

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