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Correlations between Color Differences Based on Three Color-Difference Formulas Using Dental Shade Guide Tabs

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Abstract

Purpose: The purpose of this study was to determine the correlation among color-difference values based on three formulas between shade tab pairs from two shade guides [Vita Lumin (VITA) and Chromascop (CHRO)].
Materials and Methods: The color of shade tabs was measured relative to the standard illuminant D_{65} under the 8° standard observer function, and distributions for CIE L^*, a^*, and b^* values were compared. One hundred and twenty shade pairs from VITA and 190 shade pairs from CHRO were used to calculate color differences using CIELAB, DIN99, and CIEDE2000 formulas (ΔE^*_{ab}, ΔE_{99}, and ΔE_{00}, respectively). A paired t-test was used to determine the difference between each pair of the three color-difference values ($\alpha = 0.01$). Regression analysis was used to determine the correlations between the color differences ($\alpha = 0.01$).
Results: For both shade guides, there were significant differences between ΔE^*_{ab} and ΔE_{00}, ΔE^*_{ab} and ΔE_{99}, and ΔE_{99} and ΔE_{00} ($p < 0.01$). ΔE^*_{ab} and ΔE_{00}, and ΔE^*_{ab} and ΔE_{99} were strongly correlated ($r^2 = 0.90$ to 0.94, $p < 0.05$). Although a simplified a^* rescaling function of the CIE a^* axis has been added in the CIEDE2000 formula, the influence of the opposite signs in the a^* value were found to be irrelevant to the ΔE_{00} value.
Conclusion: ΔE^*_{ab}, ΔE_{99}, and ΔE_{00} can be used interchangeably for the evaluation of color difference of shade tabs.

Acceptability of color matching is perceived visually or measured with a color-measuring instrument. The accuracy of an instrumental method with which color measurement can be made varies with the geometry of the instrument and the surface properties of the object.[1] After measurement of color, the usefulness of a measurement system depends on the color-difference formula to generate values that correlate well with the visual response of the observers.

Results based on an instrumental color measurement are presented by the use of symbols for color notation systems, in which items represented by the symbols are supposed to correlate with visual findings.[2] The Commission Internationale de l'Eclairage (CIE) has recommended several color notation systems, among which the most frequently used is the CIELAB or CIE76 system.[3]

The color coordinates of the CIELAB system are CIE L^* (lightness, achromatic coordinate, ranging from black to white), CIE a^* ($-a^*$ = green, $+a^*$ = red), and CIE b^* ($-b^*$ = blue, $+b^*$ = yellow); polar coordinates, such as C^*_{ab} (chroma) and H^*_{ab} (hue), are calculated from the measured values of the chromatic coordinates such as CIE a^* and b^*. Color difference is calculated as $\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ in the CIELAB system.[3] Although the CIELAB color-difference formula has been widely used in the dental field, several advanced color-difference formulas have been developed to make a single-number shade pass/fail equation for evaluation of color differences. The first modified formula was based on the Adams–Nickerson Color Scale (ANLAB) as $\Delta E_a = \Delta E_{ANLAB}/(1 + 0.0275\ C_{ANLAB})$, where C_{ANLAB} was the ANLAB chroma, which made a significant improvement.[4] CMC (l:c) (Color Measurement Committee of the Society of Dyers and Colorists), CIE94, BFD (Bradford), and LCD (Leeds Color difference) were also developed.[5,6]

Recently, a color-difference formula based on the CIELAB system, CIEDE2000, was developed following the procedure agreed to by CIE TC1-47.[7] It includes not only the lightness, chroma, and hue weighting functions but also an interactive term between the chroma and hue differences for improving the performance for blue colors and a scaling factor for the CIELAB a^* scale for improving the performance for gray colors.[7] This

formula performed better than the CMC and CIE94 formulas[7] and has been officially adopted as the new CIE color-difference formula.[8]

Although advanced formulas such as CMC, CIE94, and CIEDE2000 were developed by modifying the CIELAB system, none of these has an associated uniform color space (UCS). Therefore, color difference based on these formulas cannot be expressed as a vector in a UCS, which is a severe disadvantage of these formulas. The need for a UCS is demonstrated by the widespread use of the CIE a^*–b^* diagram, although this diagram is not uniform.[9,10]

The definition of a UCS is a geometrical representation of color perceptions by points in a 3D space in which the distance between any two points can be taken as a measure of the magnitude of the difference between two color perceptions represented by two given points, in which equal distances represent equal visually perceived color differences.[11] For any proposed UCS in which a (red–green parameter) is plotted against b (yellow–blue parameter) with L (lightness) as a third axis, the color difference (ΔE) can be calculated from $\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$.

Deutsches Institut fur Normung (DIN) 99 color-difference formula has an associated UCS, of which the space is similar to that of the CIELAB. This formula predicted experimental datasets better than CMC and CIE94 formulas and was only slightly worse than the CIEDE2000.[12,13] The DIN99 formula is an improved development based on the CIELAB in that it has a better correlation to the visual impression of small color differences.[13]

According to previous studies in which the color differences after polymerization or thermocycling of the same shade of dental resin composites were compared, three color-difference values (ΔE^*_{ab}, ΔE_{99}, ΔE_{00}) were correlated to one another.[14-17] Paravina et al reported that there was a very strong correlation ($r > 0.97$) between the ΔE^*_{ab} and ΔE_{00} values, indicating that the limitations of the CIELAB system do not appear to be a problem in the evaluation of polymerization-dependent color changes of dental resin composites.[14] Significant correlations between ΔE^*_{ab} and ΔE_{00}, ΔE^*_{ab} and ΔE_{99}, and ΔE_{99} and ΔE_{00} were also reported between the various shades of resin composites ($r^2 = 0.90$ to 0.99), in which the color distribution ranges were -4.3 to -0.8 for the CIE a^* and -7.9 to 7.4 for the CIE b^*.[15] It was suggested that two color-difference values (ΔE^*_{ab}, ΔE_{00}) can be used interchangeably for the evaluation of color difference after polymerization and thermocycling of resin composites.[16] After polymerization and thermocycling of resin composites, significant correlations between ΔE^*_{ab} values and ΔE_{99} values were reported ($r = 0.68$ to 0.77).[17] In the evaluation of color-difference formulas in previous studies[14-17] in the dental field, the shades investigated were limited to those of resin composites with the same shade designation (same hue), or the same CIE a^* signed pairs.

The Vita Lumin Vacuum shade guide (VITA Zahnfabrik, Bad Säckingen, Germany) is divided into four series designated by the letters A, B, C, and D. According to the manufacturer, each series has brown, yellow, gray, and red hue, respectively. Shade tabs of a specific letter group have the same hue, and each hue group includes several tabs of increasing chroma and decreasing value (lightness) designated in numerical order such as A1, A2, and A3;[18] however, others have concluded that the visual distinction between Vita Lumin shade tabs was primarily due to a difference in luminance or brightness.[19] The Chromascop (Ivoclar Vivadent, Schaan, Liechtenstein) shade guide is divided into five series (100, 200, 300, 400, 500). According to the manufacturer, each series has white, yellow, light yellow, gray, and dark brown hue, respectively. Within each series, the chroma increases and the value decreases as the second designation number increases.

In this study, shade tab pairs from the two shade guides were used to evaluate the correlations of three color-difference values based on the CIELAB, DIN99, and CIEDE2000 formulas. In contrast to the same shade designated resin composites or the same signed pairs in the CIE a^* values of previous studies,[14-17] color-difference calculation between pairs of shade tabs, which have wide ranges (positive and negative) in CIE a^* values, could confirm a scaling factor for the CIE a^* scale, improving the performance for gray colors in the CIEDE2000 formula.[7]

The null hypothesis of the present study was that CIELAB-, DIN99-, and CIEDE2000-based color difference values were not correlated to one another when color differences were calculated between the pairs of shade tabs. The purpose of this study was to evaluate the correlation among color-difference values based on three color-difference formulas such as the CIELAB, DIN99, and CIEDE2000 using shade tab pairs from two shade guides.

Materials and methods

The color of shade tabs from two shade guides [Vita Lumin Vacuum shade guide (VITA); and Chromascop (CHRO)] was measured after polishing the approximately 4-mm-wide middle portion of the labial surface of each shade tab with up to #2400 silicon carbide papers (Buehler Ltd, Lake Bluff, IL) to make the measuring surface flat. The color for the middle site of the shade tab was measured, because the translucency of the incisal edge would make the measured color background-dependent, and cervical measurement would reflect the dark color.[20]

External light was excluded by covering with a zero calibration box (Zero Calibration Standard, GretagMacbeth Instruments Corp., New Windsor, NY). CIE L^*, a^*, and b^* values were measured according to the CIELAB color scale relative to the standard illuminant D_{65} on a reflection spectrophotometer (Color-Eye 7000A, GretagMacbeth Instruments Corp.) with specular component excluded (SCE) geometry. A UV filter was positioned to a 100% UV-including position. The aperture size was 3×8 mm^2, and illuminating and viewing configuration was CIE diffuse/8° geometry.[21] Measurements were repeated three times for each tab.

The photometric range for this instrument is 0 to 175% and the resolution is 0.01%. The repeatability in spectral reflectance is within 0.20% standard deviation, and the chromaticity is within ΔE^*_{ab} 0.05 standard deviation when the white calibration plate is measured 30 times at 10-second intervals after white calibration has been performed, as reported by the manufacturer.

One hundred and twenty shade pairs from 16 tabs of the VITA guide ($_{16}C_2 = 120$) were prepared to calculate the ΔE^*_{ab}, ΔE_{99}, and ΔE_{00} color differences. Likewise, 190 shade pairs from 20 tabs of the CHRO guide ($_{20}C_2 = 190$) were prepared to calculate the color differences. The ΔE^*_{ab}, ΔE_{99}, and ΔE_{00} values were compared within each shade guide.

Color difference by the CIELAB formula was calculated with the following equation:[3]

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

Color difference by the CIEDE2000 formula was calculated as

$$\Delta E_{00} = \{[\Delta L^*/(k_L S_L)]^2 + \left[\Delta C^*_{ab}/(k_C S_C)\right]^2 + \left[\Delta H^*_{ab}/(k_H S_H)\right]^2 + \Delta R\}^{1/2},$$

where ΔL^*, ΔC^*_{ab}, ΔH^*_{ab} are the differences in the CIELAB lightness, chroma, and hue, respectively; ΔR is an interactive term between the chroma and hue differences; $\Delta R = R_T[\Delta C^*_{ab}/(k_C S_C)][\Delta H^*_{ab}/(k_H S_H)]$; S_L, S_C, and S_H are the weighting functions; and k_L, k_C, and k_H are the parametric functions to be adjusted according to different viewing parameters. S_L, S_C, and S_H are the factors for adjusting the relative weights in changes of color parameters, and the values calculated for these functions vary according to the pairs being considered in the CIELAB space.[7] In these formulas, weighting functions of color parameters are included. Therefore, the determination of the correlation between color differences calculated by advanced formulas and those calculated with the CIELAB formula, which does not contain a weighting function, as a function of the range of differences in color parameters or color coordinates between the compared pairs can provide the relative involvement of weighting functions in the new formulas. In the present study, weighting and parametric functions were set to 1.

Color difference by the DIN99 formula was calculated as:

$$\Delta E_{99} = [(\Delta L_{99})^2 + (\Delta a_{99})^2 + (\Delta b_{99})^2]^{1/2}/K_E,$$

where

$$L_{99} = 105.51 \ln;(1 + 0.0158L^*),$$
$$e = a^*\cos(16^\circ) + b^* \sin(16^\circ),$$
$$f = 0.7[b^* \cos(16^\circ) - a^* \sin(16^\circ)], \quad G = (e^2 + f^2)^{1/2},$$
$$C_{99} = \ln(1 + 0.045G)/0.045, \quad H_{99} = \arctan(f/e),$$
$$a_{99} = C_{99}\cos(h_{99}), \quad b_{99} = C_{99}\sin(h_{99}).$$

In this formula, e is a temporary variable for redness, f is a temporary variable for yellowness, and G is a temporary variable for chroma. K_E is a changeable factor allowing the ΔE_{99} values to be changed depending on the circumstances.[12] This formula applies logarithmic transformation and rescaling of the CIELAB variables L^* and C^*, and calculates new basic coordinates using the CIELAB hue angle h_{ab} before applying the same formula used by the CIELAB for calculating a color difference. The great advantage of this formula is that it uses the CIELAB formula. In this formula, the size of the perceived color differences can be influenced by external factors. The K_E factors can be used for this purpose; however, it is not recommended to use factors different than 1.[12] In the present study, K_E was set to 1. As for the hue angle (h_{99}), since h_{ab} (CIE 1976 a^*–b^* hue angle) is defined as $\arctan(b^*/a^*)$,[3] the same formula was applied in DIN99.

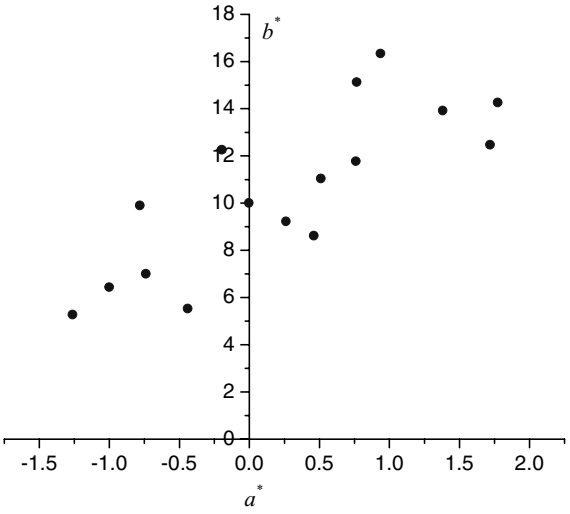

Figure 1 Distribution of CIE a^* and b^* values of the VITA shade guide.

A paired t-test was used to determine the difference between each pair of the three color-difference values ($\alpha = 0.01$). Regression analysis was used to determine the correlation between color differences ($\alpha = 0.01$).

Results

Distributions of the CIE a^* and b^* values of the two shade guides are presented in Figures 1 and 2. For VITA, the range of CIE L^* value was 47.4 to 61.0, that of CIE a^* was −1.3 to 1.8, and that of CIE b^* was 5.3 to 16.3. For CHRO, the range of CIE L^* value was 53.5 to 67.9, that of CIE a^* was −0.7 to 6.0, and that of CIE b^* was 8.6 to 21.4. In the VITA guide, the C4

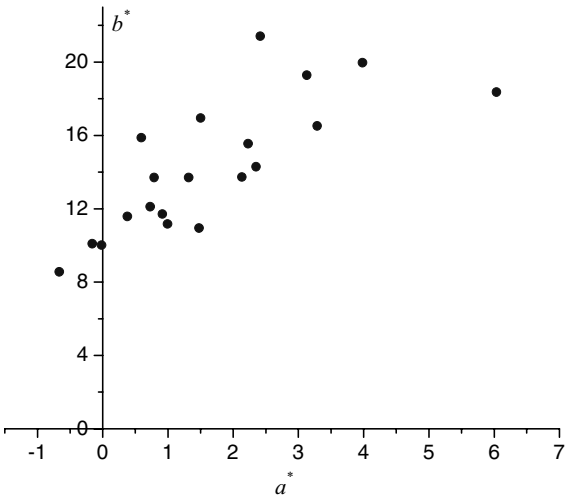

Figure 2 Distribution of CIE a^* and b^* values of the CHRO shade guide.

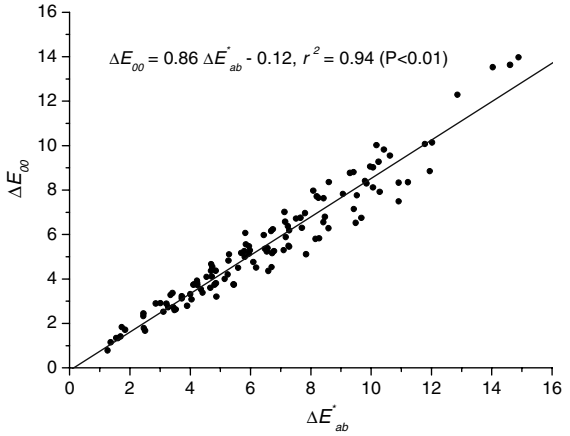

Figure 3 A scatter plot of ΔE^{*}_{ab} and ΔE_{00} values between shade tabs for the VITA shade guide.

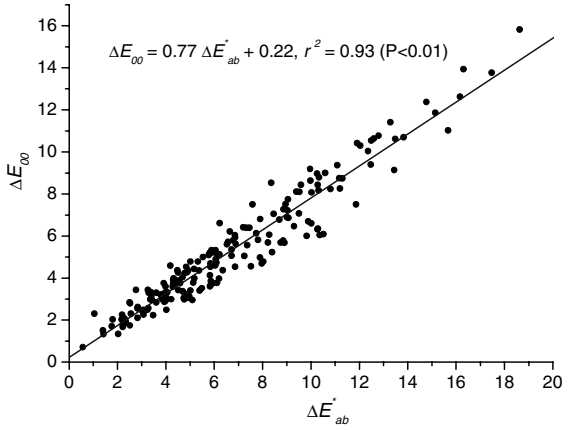

Figure 5 A scatter plot of ΔE^{*}_{ab} and ΔE_{00} values between shade tabs for the CHRO shade guide.

tab showed the lowest value, and the B1 tab showed the lowest chroma. In the CHRO guide, the 540 tab showed the lowest value, and the 110 tab showed the lowest chroma.

Based on a paired *t*-test for the VITA guide, there were significant differences between ΔE^{*}_{ab} and ΔE_{00}, ΔE^{*}_{ab} and ΔE_{99}, and ΔE_{99} and ΔE_{00} ($p < 0.01$). Based on linear regression, a scatter plot of ΔE^{*}_{ab} and ΔE_{00} for the VITA guide is shown in Figure 3. A regression equation ($\Delta E_{00} = 0.86\Delta E^{*}_{ab} - 0.12$) was obtained, and the coefficient of determination (r^2) was 0.94 ($p < 0.01$). A scatter plot of ΔE^{*}_{ab} and ΔE_{99} for the VITA guide is shown in Figure 4. A regression equation ($\Delta E_{99} = 0.78\Delta E^{*}_{ab} - 0.24$) was obtained, and the coefficient of determination (r^2) was 0.90 ($p < 0.01$). Based on linear regression between the difference in the CIE a^* values (Δa^*) of the compared pairs and the difference in color difference values, $\Delta E_{00} - \Delta E^{*}_{ab}$, $\Delta E_{00} - \Delta E_{99}$, and $\Delta E^{*}_{ab} - \Delta E_{99}$ did not have significant correlation with the Δa^* value ($p > 0.01$).

Based on a paired *t*-test for the CHRO guide, there were significant differences between ΔE^{*}_{ab} and ΔE_{00}, ΔE^{*}_{ab} and ΔE_{99}, and ΔE_{99} and ΔE_{00} ($p < 0.01$). Based on linear regression, a scatter plot of ΔE^{*}_{ab} and ΔE_{00} for the CHRO guide is shown in Figure 5. A regression equation ($\Delta E_{00} = 0.77\Delta E_{ab} + 0.22$) was obtained, and the coefficient of determination (r^2) was 0.93 ($p < 0.01$). A scatter plot of ΔE^{*}_{ab} and ΔE_{99} for the CHRO guide is shown in Figure 6. A regression equation ($\Delta E_{99} = 0.71\Delta E^{*}_{ab} - 0.09$) was obtained, and the coefficient of determination (r^2) was 0.92 ($p < 0.01$). Based on linear regression between the difference in the CIE a^* values (Δa^*) of the compared pair and the difference in color difference values, $\Delta E_{00} - \Delta E^{*}_{ab}$ did not have significant correlation with the Δa^* value ($p > 0.01$), but $\Delta E_{00} - \Delta E_{99}$ showed significant correlation ($r = -0.507$, $p < 0.01$), as did $\Delta E^{*}_{ab} - \Delta E_{99}$ ($r = -0.255$, $p < 0.01$).

A scatter plot of the Δa^* value and $\Delta E_{00} - \Delta E_{99}$ values for the CHRO guide is presented in Figure 7. The values showed a quadratic regression ($\Delta E_{00} - \Delta E_{99} = 0.42 + 0.02\Delta a^* +$

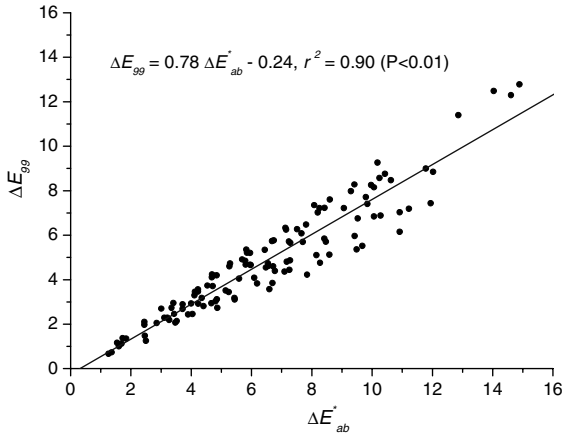

Figure 4 A scatter plot of ΔE^{*}_{ab} and ΔE_{99} values between shade tabs for the VITA shade guide.

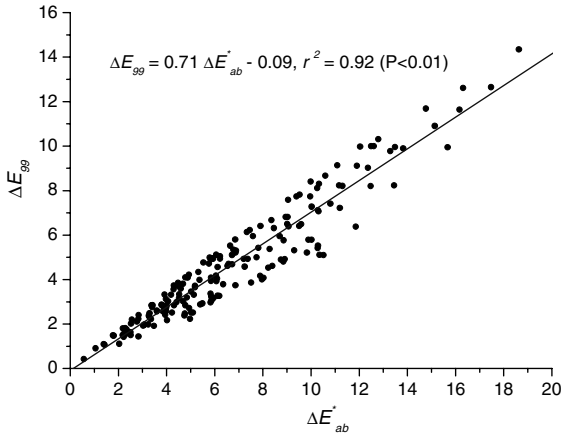

Figure 6 A scatter plot of ΔE^{*}_{ab} and ΔE_{99} values between shade tabs for the CHRO shade guide.

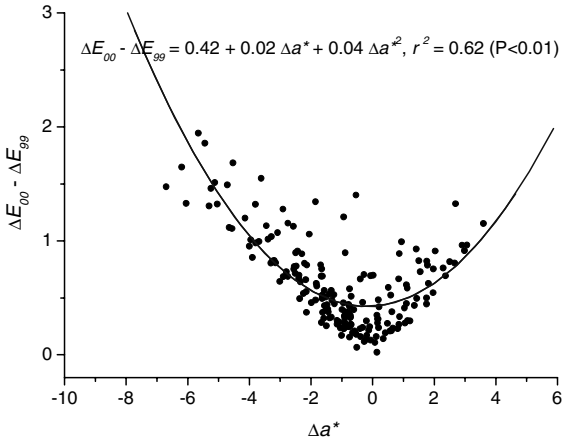

Figure 7 A scatter plot of the Δa^* value between shade tabs and the ΔE_{00}–ΔE_{99} value for the CHRO shade guide with quadratic regression.

$0.04\Delta a^{*2}$), and the coefficient of determination (r^2) was 0.62 ($p < 0.01$).

Discussion

Based on the results of the present study, ΔE^*_{ab} and ΔE_{00} values between the shade tab pairs were correlated in the two shade guides, VITA and CHRO. There was significant correlation in each shade guide, in which the coefficients of determination (r^2) were 0.94 and 0.93, respectively. ΔE^*_{ab} and ΔE_{00} were correlated regardless of the signs of the CIE a^* value of the compared pairs, as in previous studies.[14-17] In other words, ΔE_{00} values between shade tabs of different signs of the CIE a^* value were correlated to ΔE^*_{ab} and to ΔE_{99} values. To confirm the results of the present study, as an example, ΔE^*_{ab}, ΔE_{99}, and ΔE_{00} values between the A1 tab and other tabs in VITA and between the 110 tab and other tabs in CHRO were calculated (Tables 1 and 2). The parts where the signs of the CIE a^* values compared are different are shaded in gray. But even in these pairs,

Table 1 Color differences between the VITA A1 tab (CIE $L^* = 60.8$, $a^* = -1.0$, $b^* = 6.4$) and other tabs for the VITA shade guide

Shade tab	L^*	a^*	b^*	ΔE_{00}	ΔE^*_{ab}	ΔE_{99}
A2	59.8	0.3	9.2	2.9	3.2	2.3
A3	57.5	0.8	11.8	5.4	6.6	4.5
A3.5	55.4	1.4	13.9	7.8	9.5	6.7
A4	52.4	1.8	14.3	10.1	11.9	9.0
B1	59.8	−1.2	5.2	1.3	1.6	1.2
B2	61.0	−0.7	9.9	2.6	3.5	2.1
B3	55.6	0.8	15.1	7.9	10.3	6.9
B4	55.9	0.9	16.3	8.3	11.2	7.2
C1	56.0	−0.7	7.0	4.4	4.8	4.2
C2	53.9	0.0	10.0	7.0	7.8	6.5
C3	51.7	0.5	11.1	9.4	10.4	8.6
C4	47.4	1.7	12.47	14.0	15.0	12.8
D2	55.2	−0.4	5.5	5.2	5.7	4.9
D3	54.6	0.5	8.6	6.2	6.7	5.8
D4	52.9	−0.2	12.3	8.5	9.9	7.7

Table 2 Color differences between the CHRO 110 tab (CIE $L^* = 67.9$, $a^* = -0.7$, $b^* = 8.6$) and other tabs for the CHRO shade guide

Shade tab	L^*	a^*	b^*	ΔE_{00}	ΔE^*_{ab}	ΔE_{99}
120	66.1	0.0	10.0	1.9	2.3	1.8
130	61.8	−0.2	10.1	5.1	6.2	5.1
140	62.1	0.7	12.1	5.6	6.9	5.3
210	60.6	0.8	13.7	7.2	9.0	6.8
220	61.8	2.1	13.7	7.0	8.5	6.3
230	57.0	2.4	14.3	10.6	12.6	10.0
240	59.3	3.3	16.5	10.0	12.4	9.0
310	59.3	0.6	15.9	8.7	11.3	8.2
320	57.5	1.5	17.0	10.6	13.5	10.0
330	59.4	2.4	21.4	11.0	15.7	10.0
340	55.5	4.0	20.0	13.8	17.5	12.7
410	59.0	1.5	10.9	8.1	9.4	7.7
420	58.8	1.0	11.2	8.1	9.5	7.8
430	57.2	0.4	11.6	9.4	11.1	9.1
440	56.3	0.9	11.7	10.3	12.0	10.0
510	56.3	1.3	13.7	10.8	12.8	10.3
520	55.2	2.2	15.6	12.4	14.8	11.7
530	56.4	3.1	19.3	12.6	16.2	11.6
540	53.5	6.0	18.4	15.8	18.6	14.3

the correlations between each pair of color differences were highly correlated. Therefore, the CIEDE2000 color-difference formula can be used interchangeably with other conventional color-difference formulas used in the dental field regardless of the signs of the CIE a^* value of a compared pair, although a scaling factor for the CIELAB a^* scale for improving the performance for gray colors[7] is included in this formula.

To investigate if the sign of the CIE b^* value would influence the correlation based on the results of the present study, color differences (ΔE^*_{ab} and ΔE_{00}) were calculated between the shade tab pairs of opposite signs of the CIE b^* values randomly selected in color space, and the correlation between ΔE^*_{ab} and ΔE_{00} were analyzed. As a result, ΔE^*_{ab} and ΔE_{00} were found to be correlated regardless of the sign of the CIE b^* value compared, although the results are not shown.

A study on the correlation between ΔE^*_{ab} values and human observer responses indicated that a specific relationship existed between the magnitude and direction of the measurements and the average observer responses.[22] Correlations between instrumental and visual assessments of color differences do not agree in all dimensions of color space. Therefore, the relationship between instrumentally measured color differences (ΔE^*_{ab}) and human observer assessment of color differences have been determined. The results showed that the threshold acceptability of color difference was 1.1 ΔE^*_{ab} units for red-varying shades and 2.1 ΔE^*_{ab} units for yellow-varying shades, and the mean value regardless of shade was 1.7 ΔE^*_{ab} units.[23] This indicates that the hue and the chroma influence the perceptibility of color difference, and human observers are more sensitive to color differences in the a^* axis direction than in the b^* axis direction. These results might have implications with the results of the present study. Further study on these subjects is recommended.

In the development of the CIEDE2000 formula, Luo et al reported that all advanced CIELAB-based formulas gave a poor

fit to the chromatic difference close to neutral, because they all assume that the ellipses in the CIE a^*–b^* diagram are circles and developed a simplified a^* function by rescaling the a^* axis, resulting in stretching the a^* scale as is shown in Equation (1):[7]

$$a' = a^*(1 + G), \text{ where } G = 0.5[1 - \{C^{*7}/(C^{*7} + 25^7)\}^{1/2}]. \quad (1)$$

Based on the results of the present study, the G value varied from 0.40 to 0.50 for the VITA guide and varied from 0.26 to 0.48 for the CHRO guide. As a result, a' was always bigger than the CIE a^* in absolute value. When ΔE_{00} is calculated between two colors whose CIE a^* signs are different, positive a^* values become more positive and negative a^* values become more negative; therefore, the discrepancy between ΔE_{00} and ΔE^*_{ab} values might be larger. But based on the results of the present study, the correlation between ΔE_{00} and ΔE^*_{ab} values was very high and the influence of different signs in the CIE a^* values on the correlation between ΔE_{00} and ΔE^*_{ab} values was negligible.

In previous studies, which reported that ΔE_{00} and ΔE^*_{ab} were correlated,[14-17] resin composite was used to compare color differences after polymerization or thermocycling. Because color changes due to polymerization or thermocycling did not influence the sign of the CIE a^* value, ΔE_{00} and ΔE^*_{ab} were highly correlated in the previous studies. But when the signs of the CIE a^* value of compared pairs were different in the present study, the correlations were also very high.

ΔE^*_{ab} and ΔE_{99} were strongly correlated in both shade guides, and the derived regression equations were $\Delta E_{99} = 0.78\Delta E^*_{ab} - 0.24$, $r^2 = 0.90$ ($p < 0.01$) for VITA, and $\Delta E_{99} = 0.71\Delta E^*_{ab} - 0.09$, $r^2 = 0.92$ ($p < 0.01$) for CHRO. In the DIN99 UCS, color coordinates of the CIELAB space are transformed by multiplying sin(16°), cos(16°), and other functions. Therefore, the position of the a^* and b^* values in color space should influence the transformed color coordinates, such as a_{99} and b_{99}. This discrepancy in the shift of color coordinates by the position of a^* and b^* did not show a great enough influence to deviate linear correlation between ΔE^*_{ab} and ΔE_{99} values.

Conclusions

Within the limitations of the present study, there were significant differences between ΔE^*_{ab} and ΔE_{00}, ΔE^*_{ab} and ΔE_{99}, and ΔE_{99} and ΔE_{00} for both shade guides ($p < 0.01$). For the VITA guide, ΔE^*_{ab} and ΔE_{00}, and ΔE^*_{ab} and ΔE_{99} were strongly correlated, and the coefficients of determination were 0.94 and 0.90, respectively. For the CHRO guide, ΔE^*_{ab} and ΔE_{00}, and ΔE^*_{ab} and ΔE_{99} were also strongly correlated, and the coefficients of determination were 0.93 and 0.92, respectively. The influence of the opposite signs in the CIE a^* value was found to be irrelevant to the ΔE_{00} value. Therefore, ΔE^*_{ab}, ΔE_{99}, and ΔE_{00} can be used interchangeably for the evaluation of color difference of shade tabs.

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