Comparison of CIE Lab, CIEDE 2000, and DIN 99 Color Differences Between Various Shades of Resin Composites

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Purpose: In addition to the CIE Lab color-difference formula *(ΔE^*_{ab})*, advanced formulas that include weighting functions have been introduced. The objectives of this study were to determine the correlations in color differences between different shade pairs of resin composites by different color formulas, and to determine whether the weighting functions included in the advanced formulas influenced the color-difference values. **Materials and Methods:** Color was measured after polymerization of two resin composites in 26 shades, and color differences between shades were calculated by ΔE^*_{ab}, CIEDE 2000 *(ΔE_{00})*, and DIN 99 *(ΔE_{99})* formulas. Regression analyses were performed between the color differences calculated by three formulas in each group divided by the differences in color parametric factors between the pairs compared. **Results:** There were significant correlations between ΔE^*_{ab} and ΔE_{00}, ΔE^*_{ab} and ΔE_{99}, and ΔE_{99} and ΔE_{00} (r^2 = .99, .89, and .90, respectively). The weighting functions in the CIEDE 2000 formula had influence on ΔE_{00} values when differences in chroma and hue between compared pairs were great. **Conclusion:** Differences in parametric factors between the pairs compared influenced the correlation between ΔE^*_{ab} and ΔE_{99} values (r^2 = .25 to .97). As the CIEDE 2000 formula has been proven to be better matched to observer responses and showed significant involvement of weighting functions compared to CIE Lab color difference, this formula should be considered for evaluation of the color of resin composites. *Int J Prosthodont 2005;18:150–155.*

Color is perceived visually or measured with photometric instruments. The usefulness of a measurement system becomes dependent on the ability of a color-difference formula to generate values that correlate with the visual responses.[1,2] In many dental color studies, Commission Internationale de l'Eclairage (CIE) Lab color difference *(ΔE^*_{ab})* has been applied.[3] Studies on the correlation between ΔE^*_{ab} values and human observer responses verify a specific relationship between the magnitude and direction of the measurements and the observer responses.[4] The acceptability thresholds are 1.1 ΔE^*_{ab} units for red-varying porcelain crowns and 2.1 ΔE^*_{ab} units for yellow-varying crowns.[5] It was also reported that some shades produce a more reliable and valid match than others.[6] As the magnitude of ΔE^*_{ab} values for perceptible or acceptable difference is dependent on hue and chroma, new color-difference formulas including hue and chroma weighting functions should be applied for color study in dentistry. The magnitude of the distribution range of three color coordinates in shade guides is different,[7] which also suggests that weighting of color coordinates should be considered.

The CIEDE 2000 color-difference formula *(ΔE_{00})* was developed to improve the performance for blue and gray colors and was adopted as a new CIE color-difference equation.[8] However, the CIEDE 2000 formula has no associated uniform color space (UCS). Therefore, this formula violates the vector definition of a color difference in a UCS. For any supposed UCS

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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 as:

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2}$$

The German Society of Color Science and Application (DIN) 99 formula (ΔE_{99}) has an associated UCS, and this formula predicts experimental data sets better than Color Measurement Committee (CMC) and CIE 94 formulas and only slightly worse than CIEDE 2000.[9,10]

A generic color-difference formula represents advanced formulas:

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

where ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab} = differences in CIE Lab lightness, chroma, and hue, respectively; ΔR = interactive term between chroma and hue differences, and $\Delta R = R_T f(\Delta C^*_{ab} \Delta H^*_{ab})$; S_L, S_C, and S_H = weighting functions; and k_L, k_C, and k_H = parametric functions to be adjusted according to different viewing parameters.[11]

In advanced color-difference 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 CIE Lab 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.

The null hypothesis was that there would be no involvement of weighting functions in two advanced formulas—CIEDE 2000 and DIN 99—and therefore there would be significant correlations among the three color differences (CIE Lab, CIEDE 2000, and DIN 99) regardless of the differences in parametric factors. The objectives were to measure the correlation among the color differences of various shades of resin composites calculated by ΔE^*_{ab}, ΔE_{00}, and ΔE_{99} formulas and to determine the dependence of color differences calculated by ΔE_{00} and ΔE_{99} formulas as a function of difference in parametric factors.

Materials and Methods

Two light-cured resin composites were studied. Synergy (Coltène/Whaledent) is composed of 59 vol% strontium-barium-borosilicate filler particles of 0.04 to 2.50 µm (mean 0.60 µm) and resin matrix containing bisphenol-A glycidyl dimethacrylate (bis-GMA), ethoxylated bisphenol-A dimethacrylate (bis-EMA), and triethyleneglycol dimethacrylate (TEGDMA). The shades investigated were N, O, P, Transparent, A1, A2, A3, A3.5, A4, and C2. Vitalescence (Ultradent) is composed of 58 vol% microhybrid particles of mean 0.7 µm and bis-GMA–based resin matrix. The shades investigated were Pearl Frost, Pearl Snow, Trans Gray, Trans Ice, Trans Mist, Trans Yellow, A1, A2, A3, A3.5, B1, B2, B3, C1, C2, and C3.

Resin composites were packed into a polytetrafluoroethylene mold (8 mm in diameter and 2 mm thick). Specimens were light cured for 40 seconds with a light-curing unit (Spectrum 800, Dentsply/Caulk) with an intensity setting of 400 mW/cm^2. Five specimens were made for each shade.

Color was measured according to CIE Lab color scale relative to the standard illuminant D65 over a white background on a reflection spectrophotometer (CM-3500d, Minolta) with specular component–excluded geometry. The aperture diameter of the measuring port was 3 mm. Illuminating and viewing configuration were CIE diffuse/8-degree geometry, and the CIE 1964 supplementary standard colorimetric observer was selected.[3] Color differences between each pair of shades (26 shades) were calculated with three formulas. Color difference according to the CIE Lab formula was calculated as:

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

Color difference according to the CIEDE 2000 formula was calculated as[11]:

$$\Delta E_{00} = \{[\Delta L'/(k_L S_L)]^2 + [\Delta C'/(k_C S_C)]^2 + [\Delta H'/(k_H S_H)]^2 + R_T[\Delta C'/(k_C S_C)] \times [\Delta H'/(k_C S_C)]\}^{1/2}$$

where k_L, k_C, and k_H were set to 1.

Color difference according to the DIN 99 formula was calculated as[9,10]:

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

where k_E was set to 1.

A paired t test was used to determine the difference between each pair of the three color-difference values ($\alpha = .01$). Regression analysis was used to determine the correlation between color differences ($\alpha = .01$). To determine the dependence of new formulas on the difference in parametric factors, the range of differences in color parameters $(\Delta E^*_{ab}$, ΔL^*, ΔC^*_{ab}, ΔH^*_{ab}, Δa^*, and $\Delta b^*)$ between the pairs compared was grouped. Except for Δa^*, the range was grouped into $\Delta x \leqslant 5$; $5 < \Delta x \leqslant 10$; and $10 < \Delta x$. In the case of Δa^*, the range was grouped into $\Delta a^* \leqslant 1$; $1 < \Delta a^* \leqslant 2$; and $2 < \Delta a^*$.

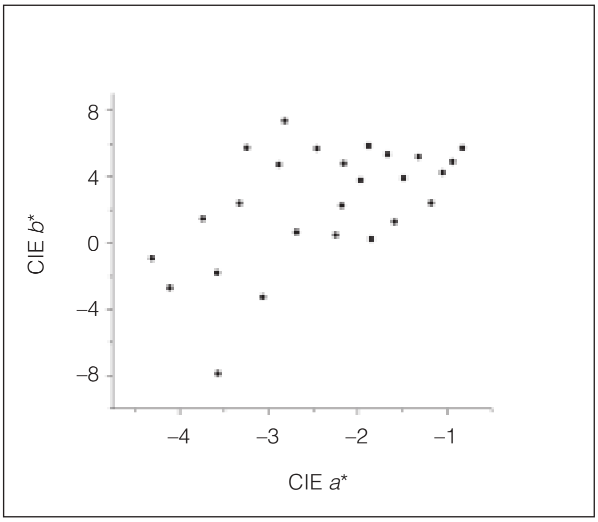

Fig 1a Distribution of CIE a^* and b^* values of resin composite specimens and correlation between color differences.

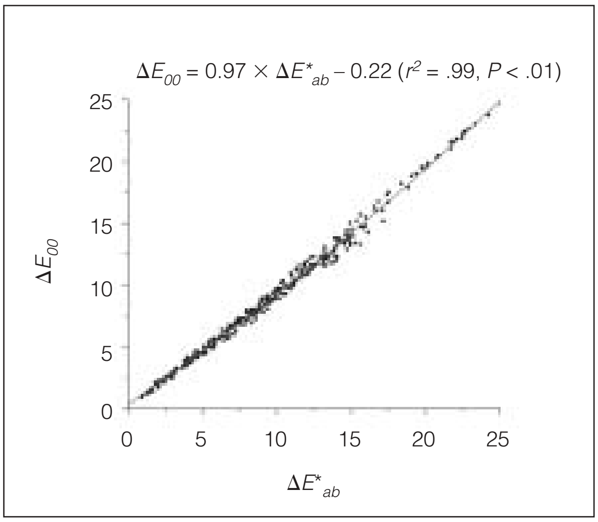

Fig 1b Correlation between ΔE^*_{ab} and ΔE_{00}.

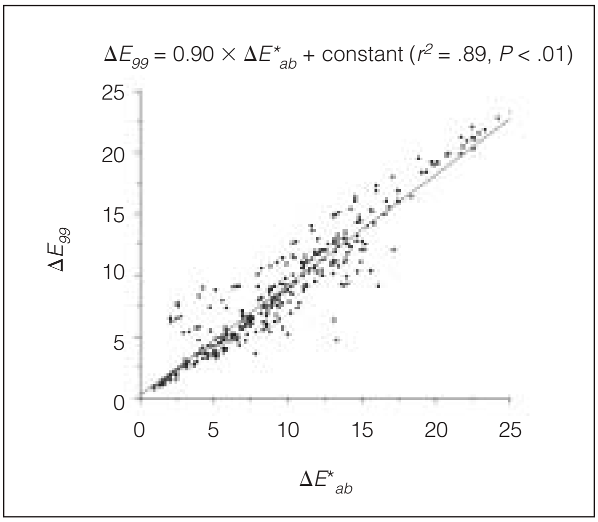

Fig 1c Correlation between ΔE^*_{ab} and ΔE_{99}.

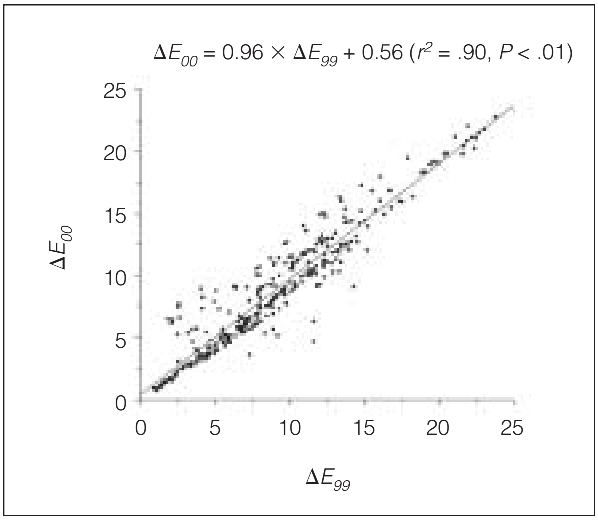

Fig 1d Correlation between ΔE_{00} and ΔE_{99}.

Results

Distribution of CIE a^* and b^* values of the resin composites is presented in Fig 1a. The range of CIE L^* values was 35.7 to 58.9, that of CIE a^* was –4.3 to –0.8, and that of CIE b^* was –7.9 to 7.4.

Based on a paired t test, there were significant differences between ΔE^*_{ab} and ΔE_{00}, ΔE^*_{ab} and ΔE_{99}, and ΔE_{00} and ΔE_{99}, regardless of the range of differences in color parameters ($P < .01$). A scatter plot of ΔE^*_{ab} and ΔE_{00} is presented in Fig 1b. A regression equation ($\Delta E_{00} = 0.97 \times \Delta E^*_{ab} - 0.22$) was calculated, and the coefficient of determination (r^2) was .99 ($P < .01$). Correlations between ΔE^*_{ab} and ΔE_{00} values by the parametric factors are listed in Table 1. The r^2 values were greater than .95, regardless of the parametric factors. In all groups, significant regression equations were derived ($P < .01$). Mean differences between the two values ($\Delta E^*_{ab} - \Delta E_{00}$) were in the range of 0.14 to 1.76. In the highest ranges of ΔC^*_{ab}, ΔH^*_{ab}, and Δb^* values between the pairs compared, these values were greater than 1.00, with the greatest difference being 2.27.

A scatter plot of ΔE^*_{ab} and ΔE_{99} is presented in Fig 1c. A regression equation ($\Delta E_{99} = 0.90 \times \Delta E^*_{ab}$ + constant) was calculated ($r^2 = .89$, $P < .01$); however, the

Table 1 Correlations Between ΔE^*_{ab} (CIE Lab) and ΔE_{00} (CIEDE 2000) Values by Parametric Factors

Parameter	Range	$r^{2\dagger}$	Regression equation‡	$\Delta E^*_{ab} - \Delta E_{00}$ Mean (SD)	Range
Total data		.99	$\Delta E_{00} = 0.97 \times \Delta E^*_{ab} - 0.22$	0.54 (0.46)	–0.32–2.27
ΔE^*_{ab}					
	0.9–5.0	.97	$\Delta E_{00} = 0.92 \times \Delta E^*_{ab} + 0.15$	0.14 (0.21)	–0.32–0.53
	5.1–10.0	.95	$\Delta E_{00} = 0.93 \times \Delta E^*_{ab} - 0.01$	0.52 (0.32)	–0.13–1.33
	10.1–25.1	.98	$\Delta E_{00} = 1.03 \times \Delta E^*_{ab} - 1.22$	0.74 (0.52)	–0.14–2.27
ΔL^*					
	0.0–5.0	1.00	$\Delta E_{00} = 0.85 \times \Delta E^*_{ab} + 0.27$	0.43 (0.50)	–0.32–2.27
	5.1–10.0	.98	$\Delta E_{00} = 0.86 \times \Delta E^*_{ab} + 0.72$	0.61 (0.42)	–0.13–1.82
	10.1–24.0	.99	$\Delta E_{00} = 1.03 \times \Delta E^*_{ab} - 1.06$	0.60 (0.42)	–0.14–1.96
ΔC^*_{ab}					
	0.0–5.0	.99	$\Delta E_{00} = 0.97 \times \Delta E^*_{ab} - 0.19$	0.52 (0.45)	–0.32–2.27
	5.1–6.8	.99	$\Delta E_{00} = 0.88 \times \Delta E^*_{ab} - 0.19$	1.17 (0.28)	0.66–1.69
ΔH^*_{ab}					
	0.0–5.0	.99	$\Delta E_{00} = 0.96 \times \Delta E^*_{ab} - 0.17$	0.43 (0.38)	–0.32–1.29
	5.1–10.0	1.00	$\Delta E_{00} = 1.03 \times \Delta E^*_{ab} - 1.08$	0.68 (0.37)	–0.06–1.69
	10.1–15.3	.96	$\Delta E_{00} = 0.89 \times \Delta E^*_{ab} - 0.16$	1.76 (0.25)	1.26–2.27
Δa^*					
	0.0–1.0	.99	$\Delta E_{00} = 0.93 \times \Delta E^*_{ab} - 0.06$	0.58 (0.42)	–0.15–2.27
	1.1–2.0	.99	$\Delta E_{00} = 0.95 \times \Delta E^*_{ab} - 0.08$	0.52 (0.49)	–0.32–1.93
	2.1–3.5	.99	$\Delta E_{00} = 1.00 \times \Delta E^*_{ab} - 0.42$	0.46 (0.52)	–0.14–1.96
Δb^*					
	0.0–5.0	1.00	$\Delta E_{00} = 0.97 \times \Delta E^*_{ab} - 0.14$	0.40 (0.37)	–0.32–1.20
	5.1–10.0	1.00	$\Delta E_{00} = 1.02 \times \Delta E^*_{ab} - 0.95$	0.69 (0.31)	–0.06–1.33
	10.1–15.3	.98	$\Delta E_{00} = 0.90 \times \Delta E^*_{ab} - 0.28$	1.67 (0.29)	1.14–2.27

†Square of correlation coefficient (coefficient of determination, $P < .01$).
‡All values in equations were significant at the level of $\alpha = .01$.
SD = standard deviation; ΔE^*_{ab} = color difference according to CIE Lab; ΔL^* = difference in CIE L^* value; ΔC^*_{ab} = difference in chroma according to CIE Lab; ΔH^*_{ab} = difference in hue according to CIE Lab; Δa^* = difference in CIE a^* value; Δb^* = difference in CIE b^* value between compared pairs.

intercept constant was not significant ($P > .01$). Correlations between ΔE^*_{ab} and ΔE_{99} by the difference in parametric factors are listed in Table 2. The correlations varied by the differences in parametric factors ($r^2 = .25$ to $.97$, $P < .01$). When ΔH^*_{ab} was higher than 10 units, there was no significant correlation ($P > .01$). In the case of low ΔE^*_{ab} and ΔL^* ranges ($\leqslant 10$), r^2 values were as low as .25 to .52. When pairs were grouped by parametric factors (chroma, hue, and CIE a^* and b^* value), the correlations were high ($r^2 = .88$ to $.97$, $P < .01$), with some exceptions. Mean differences between two values ($\Delta E^*_{ab} - \Delta E_{99}$) ranged between –0.33 and 4.79, with the greatest difference being 8.57.

A scatter plot of ΔE_{99} and ΔE_{00} is presented in Fig 1d. A regression equation ($\Delta E_{00} = 0.96 \times \Delta E_{99} + 0.56$) was calculated ($r^2 = .90$, $P < .01$). The trend between ΔE_{99} and ΔE_{00} was similar to that between ΔE^*_{ab} and ΔE_{99}; therefore, the data are not presented.

Discussion

The hypothesis of the present study was rejected. Compared with the CIE Lab color-difference values (ΔE^*_{ab}), the weighting functions included in the CIEDE 2000 formula had a significant influence on the color-difference values (ΔE_{00}) when ΔC^*_{ab}, ΔH^*_{ab}, and Δb^* values between the compared pairs were high. The color coordinates and color differences with the DIN 99 formula were different from those with the CIE Lab formula. Advanced color-difference formulas gave much better fit than did the ΔE^*_{ab} formula.[9,11,12] In the dental field, color differences based on Munsell parameters, $\Delta E_M = (\text{mean } C \times \Delta H)/5 + 7\Delta V + 4\Delta C$, which included weighting functions, were compared with ΔE^*_{ab}.[13] It was also proposed that color coordinates should be weighted differently, and a modified equation, $\Delta E^*_{ab} = [(0.96\Delta L^*)^2 + (2.34\Delta a^*)^2 + (1.02\Delta b^*)^2]^{1/2}$, yielded a significantly better fit with observer responses.[14]

The CMC formula, which varies the relative contributions of the differences in lightness, chroma, and hue according to the position of the pairs in CIE Lab space, has been applied to dental resin composites.[12] In teeth and dental materials, the distributions of color coordinates are limited compared to the full scale because of the near-neutral hue of teeth. The magnitude of distribution ranges of color coordinates varies among three color coordinates, and the ratio between the ranges for three coordinates (CIE $L^*:a^*:b^*$) is 12.0:2.6:8.3 in the Vita shade guide and 13.1:5.6:12.3 in the Chromascop shade guide.[7] Therefore, different

Table 2 Correlations Between ΔE^*_{ab} (CIE Lab) and ΔE_{99} (DIN 99) Values by Parametric Factors

Parameter	Range	$r^{2†}$	Regression equation‡	$\Delta E^*_{ab} - \Delta E_{99}$ Mean (SD)	Range
Total data		.89	$\Delta E_{99} = 0.90 \times \Delta E^*_{ab} + \alpha$	0.77 (1.73)	–5.22–8.57
ΔE^*_{ab}					
	0.9–5.0	.25	$\Delta E_{99} = 0.82 \times \Delta E^*_{ab} + \alpha$	–0.33 (1.74)	–5.22–1.46
	5.1–10.0	.43	$\Delta E_{99} = 0.85 \times \Delta E^*_{ab} + \alpha$	0.89 (1.46)	–3.71–4.78
	10.1–25.1	.80	$\Delta E_{99} = 0.96 \times \Delta E^*_{ab} + \alpha$	1.19 (1.72)	–2.46–8.57
ΔL^*					
	0.0–5.0	.52	$\Delta E_{99} = 0.49 \times \Delta E^*_{ab} + 1.86$	0.86 (2.18)	–5.52–8.57
	5.1–10.0	.51	$\Delta E_{99} = 0.52 \times \Delta E^*_{ab} + 3.66$	0.84 (1.59)	–2.75–6.99
	10.1–24.0	.89	$\Delta E_{99} = 0.89 \times \Delta E^*_{ab} + \alpha$	0.62 (1.20)	–2.46–5.08
ΔC^*_{ab}					
	0.0–5.0	.89	$\Delta E_{99} = 0.90 \times \Delta E^*_{ab} + \alpha$	0.71 (1.73)	–5.22–8.57
	5.1–6.8	.95	$\Delta E_{99} = 0.93 \times \Delta E^*_{ab} + \alpha$	2.54 (0.47)	1.64–3.27
ΔH^*_{ab}					
	0.0–5.0	.88	$\Delta E_{99} = 0.96 \times \Delta E^*_{ab} + 1.43$	0.19 (1.38)	–5.22–2.77
	5.1–10.0	.97	$\Delta E_{99} = 1.04 \times \Delta E^*_{ab} - 2.75$	2.14 (0.76)	0.86–4.78
	10.1–15.3	$P > .01$	–	4.79 (1.68)	2.73–8.57
Δa^*					
	0.0–1.0	.88	$\Delta E_{99} = 0.90 \times \Delta E^*_{ab} + \alpha$	0.51 (1.49)	–4.94–5.26
	1.1–2.0	.86	$\Delta E_{99} = 0.90 \times \Delta E^*_{ab} + \alpha$	0.70 (1.84)	–5.22–4.61
	2.1–3.5	.88	$\Delta E_{99} = 1.02 \times \Delta E^*_{ab} + \alpha$	1.67 (1.91)	–2.16–8.57
Δb^*					
	0.0–5.0	.93	$\Delta E_{99} = 0.95 \times \Delta E^*_{ab} + \alpha$	0.06 (1.35)	–5.22–1.64
	5.1–10.0	.97	$\Delta E_{99} = 1.02 \times \Delta E^*_{ab} - 2.23$	2.00 (0.74)	0.41–4.78
	10.1–15.3	.43	$\Delta E_{99} = 0.84 \times \Delta E^*_{ab} + \alpha$	4.38 (1.68)	2.25–8.57

†Square of correlation coefficient (coefficient of determination, $P < .01$).
‡All values in equations were significant at the level of $\alpha = .01$.
SD = standard deviation; ΔE^*_{ab} = color difference according to CIE Lab; ΔL^* = difference in CIE L^* value; ΔC^*_{ab} = difference in chroma according to CIE Lab; ΔH^*_{ab} = difference in hue according to CIE Lab; Δa^* = difference in CIE a^* value; Δb^* = difference in CIE b^* value between compared pairs.

weighting of each coordinate seems to be needed because the full scale of UCS for color in dentistry may be within these ranges of shade guides.

In the CIEDE 2000 formula, 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 CIE Lab space.[11] In the present study, the range of S_L, S_C, and S_H was 1.00 to 1.19, 1.12 to 1.40, and 1.05 to 1.18, respectively. The size of the interactive term (ΔR) was small because the range of R_T was –0.050 to –0.001. However, the mean difference between two values ($\Delta E^*_{ab} - \Delta E_{00}$) was great when ΔC^*_{ab}, ΔH^*_{ab}, and Δb^*_{ab} values between the compared pairs were higher than 5 or 10. This means that the discrepancy between two color differences increased as the difference in parameters between the compared pairs increased. However, there was no general trend in r^2 values by the range of parameters.

In modified DIN 99 formulas, a weighting function, k_L, was introduced, allowing weighting of the lightness difference relative to hue and chroma differences. The range of the optimized k_L value with several data sets is 0.99 to 1.75.[9] With the results of the present study, the k_L factor was experimentally applied to evaluate the influence of this factor on the correlation with ΔE^*_{ab} value. Three values—0.90, 1.33, and 1.75—were applied as k_L. When 0.90 was applied, the r^2 value was .89, the same as when k_L was 1. When 1.33 and 1.75 was applied, the r^2 value was .87 and .80, respectively. From this, when k_L was set to 1, the correlation was the highest. Therefore, weighting of the lightness difference influenced the correlation between ΔE_{99} and ΔE^*_{ab}.

However, the practical meaning should be studied further. In the present study, r^2 values between ΔE^*_{ab} and ΔE_{99} varied by the ranges of ΔE^*_{ab} and ΔL^* between the compared pairs. When these ranges were less than 10, r^2 values were lower than .52. This means that the discrepancy between two color-difference values was high when differences in color and lightness were less than 10. Moreover, when the range of color difference is within the threshold value of perceptible or acceptable difference (ΔE^*_{ab}; 0.4 to 3.3), this discrepancy would make for misunderstandings in color determination. The correlation between two color-difference values varied by the parametric differences, which suggests that significant deviations from linear correlation occurred between the color coordinates with CIE Lab and those transformed into DIN 99.

Practical application of color technology requires the establishment of the magnitude that has visual significance. The correlation coefficients between the visual color difference and the corresponding measured values were different; the coefficient for yellow- or pink-pigmented groups is lower than that of gray groups.[4] Observers are more sensitive to dental porcelain crowns whose color differs in redness as opposed to those whose colors differ to the same extent in yellowness.[5] These reports imply that perceptibility of color difference is influenced by hue and chroma and support the weighting of color parameters in advanced color-difference formulas.

As to the size of the perceptible limit, a color difference value of greater than 2 ΔE^*_{ab} units was perceived by the 100% of observers, and between 1 and 2 ΔE^*_{ab} units were not perceived infrequently.[4] Thresholds for perceptibility (mean 0.4 ΔE^*_{ab} units) were significantly lower than thresholds for acceptability (mean 1.7 ΔE^*_{ab} units).[5] As to the acceptability, 50% acceptability was approximately 1 ΔE^*_{ab} unit.[15] ΔE^*_{ab} values of 3.3 were unacceptable according to 50% of the observers.[16] A ΔE_M value of less than 1 was regarded as excellent, and a ΔE_M value of 2 was clinically acceptable.[13] Within the limitations of the present study, the mean difference between two values $(\Delta E^*_{ab} - \Delta E_{00})$ was greater than 1 when ΔC^*_{ab}, ΔH^*_{ab}, and Δb^* ranges were high. Therefore, although the correlation between ΔE^*_{ab} and ΔE_{00} values was high regardless of the difference in parametric factors, the arithmetic difference was also similar to or greater than the perceptible or acceptable limit in some conditions when the difference in chroma (more specifically, CIE b^*) or hue was great.

Although the determination of a proper perceptible or acceptable threshold for the CIEDE 2000 formula with dental materials is necessary, this formula should be considered for the calculation of the color difference when the difference in chroma or hue is the main cause of the color difference. In the case of the DIN 99 formula, significant changes in the transformation of color coordinates from CIE Lab to DIN 99 occurred. Therefore, to allow use of this formula in dentistry, further study is needed.

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