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RESEARCH AND EDUCATION

Determining color difference thresholds in denture base acrylic resin

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ABSTRACT

Statement of problem. In restorative prostheses, color is important, but the choice of color difference formula used to quantify color change in acrylic resins is not straightforward.

Purpose. The purpose of this in vitro study was to choose a color difference formula that best represented differences between the calculated color and the observed imperceptible to unacceptable color and to determine the corresponding perceptibility and acceptability threshold of color stability for denture base acrylic resins.

Material and methods. A total of 291 acrylic resin denture base plates were fabricated and subjected to radiation tests from zero to 42 hours in accordance with ISO 7491:2000. Color was measured with a portable spectrophotometer, and color differences were calculated with 3 International Commission on Illumination (CIE) formulas: CIELab, CMC(1:1), and CIEDE2000. Thirty-four observers with no deficiencies in color perception participated in psychophysical perceptibility and acceptability assessments under controlled conditions in vitro. These 2 types of assessments were regressed to each observer by each formula to generate receiver operator characteristic (ROC) curves. Areas under the curves (AUCs) were then calculated and analyzed to exclude observers with poor color discrimination. AUCs were subjected to 1-way ANOVA (α=.05) to deter the statistical significance of discriminability among the 3 formulas in terms of perceptibility and acceptability judgments. Student-Newman-Keuls tests (α=.05) were used for post hoc comparison.

Results. CMC(1:1) and CIEDE2000 formulas performed better for imperceptible to unacceptable color differences, with corresponding CMC(1:1) and CIEDE2000 values for perceptibility of 2.52 and 1.72, respectively, and acceptability thresholds of 6.21 and 4.08, respectively.

Conclusions. Formulas CMC(1:1) and CIEDE2000 possess higher discriminability than that of CIELab in the assessment of perceptible color difference threshold of denture base acrylic resin. A statistically significant difference exists between perceptibility and acceptability thresholds for denture base acrylic resin. (J Prosthet Dent 2015;114:702-708)

Acrylic resins have been used extensively in the fabrication of removable dental prostheses, maxillofacial prostheses, and surgical guides since they were first introduced to dentistry in the 1930s.[1,2] However, color changes in acrylic resins during clinical services may result in esthetically displeasing prostheses and necessitate replacements.[1]

Color order systems, such as the Munsell System, Ostwald System, and Natural Color System (NCS), have been developed to specify color and have subsequently had a significant impact on industrial applications.[3] These systems facilitated the communication and reproduction of colors but could not quantitatively describe the difference between 2 colors. CIELab color space[4] can specify colors precisely by using International Commission on Illumination (CIE) L* (lightness), a* (redness-greenness), and b* (yellowness-blueness) scales and quantify color differences using the CIELab color difference formula. However, CIELab is not a uniform color space.[5,6] Thus, to improve the uniformity of color space and the consistency of calculated color differences and visual assessments, the color difference formulas CMC(l:c),[7] CIE94,[8] and CIEDE2000,[4,9] were developed to substitute for the basic CIELab equation.

CIELab and CIEDE2000 are the color difference formulas most widely used in dentistry,[1,10-22] followed by CMC(l:c).[13,20] A strong correlation has been found between calculated CIELab color difference (ΔE^*) and

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Clinical Implications

Color difference formulas CMC(1:1) and CIEDE2000 can be considered for use to quantify color change in denture base acrylic resin from imperceptible to unacceptable during clinical service or in vitro research.

calculated CIEDE2000 color difference (ΔE_{00}).[10-12] However, they are not interchangeable, especially for colors in different chroma and hue sections.[17,23] Furthermore, calculating color difference (ΔE) with a formula for achieving the best fit with visual color difference (ΔV) remains a problem in dentistry.[10,13,20] It is therefore necessary to evaluate the performance of the color difference formulas in denture base acrylic resins, because a higher fit between ΔE and ΔV might provide a higher level of interpretation for clinical discoloration.

Color differences of dental materials are assessed primarily by means of 2 thresholds: the perceptibility threshold (PT) and the acceptability threshold (AT).[14] Perceptibility assessments are usually conducted by asking observers whether they can see a color difference between the specimens, and the PT is then determined at the color difference point consisting of 50% positive answers and 50% negative answers. Acceptability assessments are conducted by asking whether the color difference is acceptable, if the observer answered yes in the previous perceptibility experiment. Similarly, the AT is set at a 50% acceptable to 50% unacceptable color difference.

There is no universally accepted PT or AT in dentistry, nor have they been well studied for the color stability of acrylic resins.[14-18] The purpose of the present study was to find a color difference formula that performed well from imperceptible to unacceptable color changes and to establish the corresponding PT and AT for denture base acrylic resins under controlled viewing conditions in vitro. The null hypothesis was that equations CIELab, CMC(1:1), and CIEDE2000 all possess the same ability to discriminate both perceptibility and acceptability judgments.

MATERIAL AND METHODS

Plate-shaped specimens were fabricated with a chemically polymerized denture base acrylic resin of shade 3 (Self-cure Denture Base Material Series; Shanghai New Century). The powder-to-liquid was mixed in a 2.2:1 g ratio in accordance with the manufacturer's instructions. Material at the dough stage was placed in metal molds, and excess materials were pressed out with a dental hydraulic press (Model C; Fred S. Carver Inc). Thickness was measured with a digital micrometer (model ID-C1012C, Mitutoyo), and diameter was measured with a digital caliper (model 111-101V-10G, GuangLu), and only specimens 50 ±1 mm in diameter and 0.5 ±0.1-mm thick were selected. After careful examination, specimens with visible pores or rough surfaces were discarded, resulting in a total of 291 specimens.

Half of each of the 291 specimens was covered with aluminum foil, and the specimens were placed in an accelerated aging chamber (Suntest XLS+; Atlas) under the conditions stipulated by ISO 7491:2000.[24] Specimens were placed in a bath containing 37°C circulating deionized water at a depth of 1 cm under a xenon lamp with irradiance of 765 W/m^2 and an average radiant exposure of 2754 kJ/m^2 per hour. Their exposure time varied from 0 to 42 hours. The half covered by aluminum foil was used as the control. With these specimens and different exposure times, a large color pool from imperceptible to unacceptable was created.

A white background with spectral reflectance above 90% in 400 to 700 nm was used. A reflectance spectrophotometer (SP62; X-rite) set to CIE D65 standard illuminant, specular excluded, 4-mm measurement area with a 6.5-mm target window was used. Spectral reflectance values were recorded in increments of 10 nm from 400 to 700 nm and converted to L*a*b* values and XYZ tristimulus values under the CIE D65 illuminant and 10-degree observer (CIE 1964 Supplementary Standard Colorimetric Observer). Five fixed points were measured on each half, and their mean values were calculated as the final values. Color differences (ΔE) on each specimen between the control half and experimental half was calculated using the CIELab equations CMC(1:1) and CIEDE2000. CIELab color differences (ΔE^*) were calculated as follows: $\Delta E^*=[(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2]^{1/2}$, where L* represents lightness, a* represents redness-greenness, and b* represents yellowness-blueness. The CMC(l:c) color differences (ΔE_{CMC}) were calculated using

$$\Delta E_{CMC}=\left[\left(\frac{\Delta L^*}{lS_L}\right)^2+\left(\frac{\Delta C^*_{ab}}{cS_c}\right)^2+\left(\frac{\Delta H^*_{ab}}{S_H}\right)^2\right]^{1/2}.$$

Weighting functions for lightness, chroma, and hue (S_L, S_C, S_H, respectively), and weighting factors for lightness (l) and chroma (c) were also introduced. For CMC(1:1), l and c were both set to one.

CIEDE2000 (ΔE_{00}) were calculated using

$$\Delta E_{00}=\sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2+\left(\frac{\Delta C'}{k_C S_C}\right)^2+\left(\frac{\Delta H'}{k_H S_H}\right)^2+R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}.$$

This formula introduced different weighting functions from CMC(l:c), a scaling factor to advance the CIELab a* scale, and a rotation item between chroma and hue to improve its predictability in blue areas.

Thirty-four dental professionals participated; individuals with deficient color vision were excluded by means of a color vision test.[25] Visual tests were approved by the relevant ethics committee, and all observers

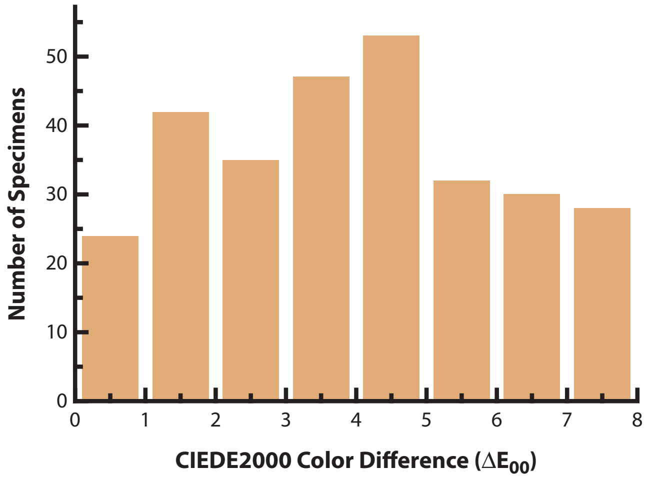

Figure 1. Histogram of CIEDE2000 color difference distributions of 291 specimens. CIE, International Commission on Illumination.

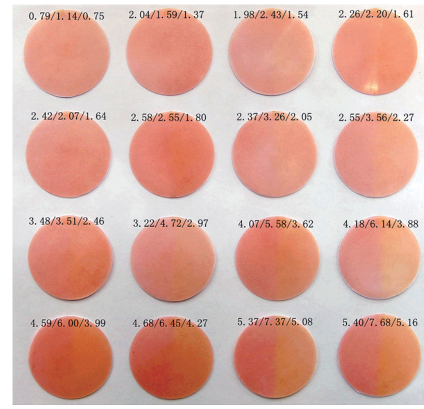

Figure 2. Specimens with invisible to unacceptable color differences between 2 halves (annotations are CIELab, CMC(1:1), and CIEDE2000 color differences). CIE, International Commission on Illumination.

signed informed written consent. The visual assessment was conducted in a dark room under a CIE D65 illuminant in a viewing cabinet with neutral walls and floor. Specimens were placed on the cabinet floor at a fixed viewing distance of 30 cm and a viewing angle of 45 degrees. All specimens were backed with the same size white paper and randomly placed according to a random number table generated by software (MATLAB v8.0; MathWorks). To prevent fatigue, each observer conducted assessments for 15 min/day over 4 successive days to complete all 291 assessments. All observers were asked the following question: "Could you see any color difference between the two halves?" If their answer was "yes," they were then asked the following: "Were the color differences clinically acceptable?"

Observers were given 2 seconds to assess each specimen, and all recording work was performed by 1 assistant. A total of 291×34=9894 evaluations were conducted.

Visual assessment data were converted to 2 binary variables: perceptibility (PER) judgments and acceptability (ACC) judgments, as suggested by Paravina et al,[16] where PER of 1 signified perceptible answers, PER of 0 signified imperceptible answers; and ACC of 0 signified acceptable answers, and ACC of 1 signified unacceptable answers.

PER and ACC judgment data were then analyzed with receiver operating characteristic (ROC) curve analysis. Each observer has his or her own psychophysical threshold point (TP) for PER and ACC judgments. In PER judgments, the observer tends to respond positively to a color difference above his/her PER threshold point (PTP) and vice versa; however, incorrect responses sometimes occur. At each possible PTP, the accuracy of judgment can be measured by sensitivity (true positive rate) and 1-specificity (true negative rate).[26] The ROC curve reflects sensitivity plotted against 1-specificity as the PTP runs through every possible calculated ΔE value. Because 3 color difference formulas were used to calculate ΔE, we obtained 3 ROC curves for each observer in PER judgments. The same was true for ACC judgments, with 3 ROC curves plotted for each observer.

The area under the curve (AUC) for each observer in both PER and ACC judgments was then calculated. The AUC is a measure of the fit of binary judgments (perceptible-imperceptible, acceptable-unacceptable) to the 3 color difference formulas.[20] An AUC higher than 0.900 represents higher sensitivity and specificity and correlates with higher discriminatory ability. Thus, observers whose mean AUCs for the 3 formulas were lower than 0.900 were excluded.

One-way ANOVA and Student-Newman-Keuls (SNK) post hoc comparisons were then used to determine whether the AUCs differed significantly with different formulas and to determine which formula performed best (α=.05) The statistical analysis of the ROC curves and AUC were conducted with software (SPSS v20.0; IBM Corp).

In addition, a structural analysis of the 3 formulas was undertaken to justify their performance in PER and ACC judgments. The weighting functions of each formula were plotted against lightness, chroma, and hue and then compared. Logistic analysis was used to determine PT and AT. Percentages of "perceptible" and "unacceptable" relative to CIELab, CMC(1:1), and CIEDE2000 color difference were designated P. A general model, [lg(P/1–P)=B+Ax], was fitted; "x" represents color difference values and B and A are parameters needing to be fitted through successive iterations.

RESULTS

The color change span is from imperceptible to unacceptable. Because of the degree of unacceptability changes within each individual, we tended to cover the AT that had been previously reported.[18] Further, the

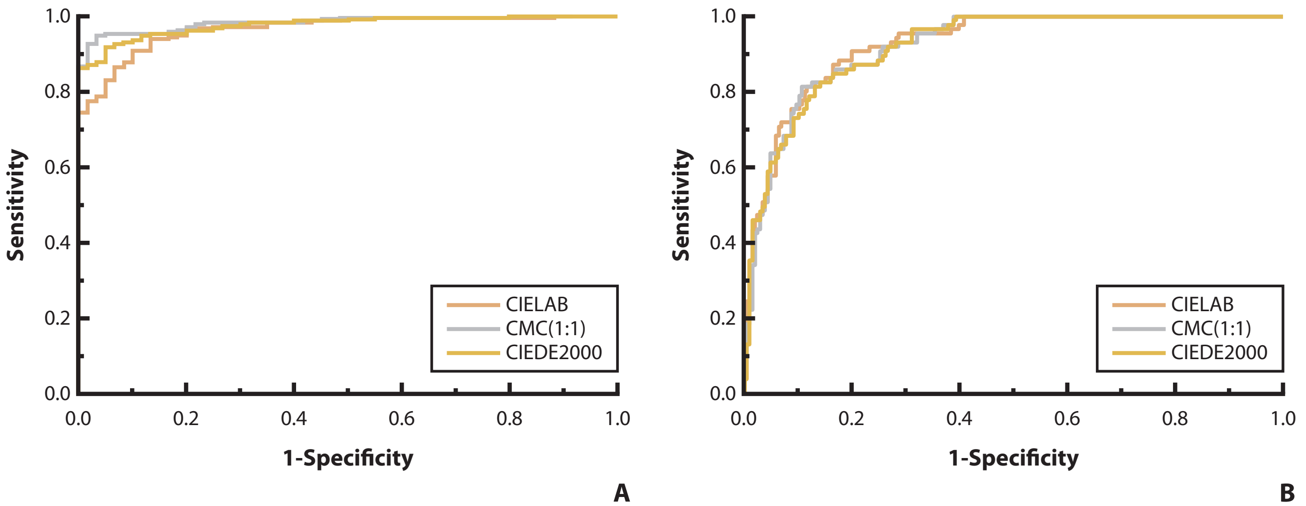

Figure 3. Receiver operating characteristic (ROC) curves for 1 observer using CIELab, CMC(1:1), and CIEDE2000: A, Perceptibility judgments; B, acceptability judgments. CIE, International Commission on Illumination.

coverage was of a high density, as shown in Figure 1. There was virtually more than 1 specimen every 0.1 ΔE_{00} interval. Figure 2 shows several specimens with increasing color difference between the 2 halves (from invisible to unacceptable).

Figure 3A shows the ROC curves for 1 observer under the 3 formulas in PER judgments, whereas Figure 3B shows the ROC curves under the 3 formulas in ACC judgments. AUCs of each observer under the 3 formulas were also calculated. Virtually all observers had their mean AUC above 0.900 in both PER and ACC judgments, except for 2 in ACC judgments. An AUC above 0.900 suggests the higher accuracy and specificity of observer judgment under each formula. Consequently, for an observer, 1 specific AUC value below 0.900 may be attributable to poor formula performance, but having all AUC values below 0.900 signifies lower accuracy and specificity. Thus, the 2 observers with a mean AUC below 0.900 in the ACC group were excluded from both PER and ACC to ensure higher evaluation sensitivity and accuracy. The visual assessments data for the remaining 32 observers were used in formula evaluation and threshold determination.

Figure 4 shows the mean AUC under 3 formulas in PER and ACC judgments. A significant statistical difference was found in the degree of fit among the 3 formulas in PER judgments (F=17.69, P<.001), with their performances ranking as follows: CMC(1:1) = CIEDE2000 > CIELab. Conversely, no statistically significant differences (F=0.19, P=.83) were found in ACC judgments. Because the CMC(1:1) and CIDE2000 equations demonstrated a higher degree of fit in both PER and ACC judgments, they were used to determine PT and AT.

Figure 5A-D shows the weighting functions for lightness, chroma, and hue (S_L, S_C, S_H, respectively) in CMC(1:1) and CIEDE2000. For CIELab, no such corrections were made; thus they could be taken as 1. S_L is lightness-dependent and S_C is chroma-dependent, whereas S_H in CMC(1:1) and CIEDE2000 is both chroma- and hue-dependent. The 3 attributes on the horizontal axes of CMC(1:1) were calculated differently from those in CIEDE2000. Table 1 shows the range and mean of each attribute of all specimens in CIELab, CMC(1:1), and CIEDE2000. The average chroma and hue (C'=19, C^*_S=15, h'=38 degrees, h^*_S=40 degrees) under each formula was selected (Fig. 5C, D) to represent the average performance of the chroma- and hue-dependent S_H function. In general, the weighting function for lightness in CIEDE2000 is a V-shaped curve, whereas in CMC(1:1), it is a monotonically increasing function (Fig. 5A). They have similar increasing weighting functions for chroma (Fig. 5B). The chroma-dependent S_H functions

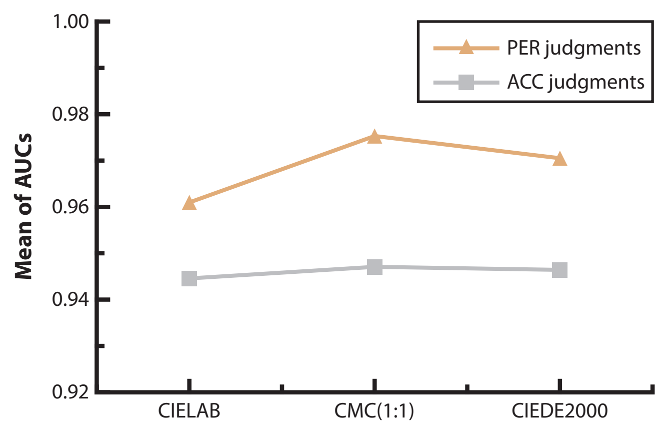

Figure 4. Mean values of area under curve (AUC) of receiver operating characteristic curves for 32 observers with CIELab, CMC(1:1), and CIEDE2000 in perceptibility (PER) judgments and acceptability (ACC) judgments. CIE, International Commission on Illumination.

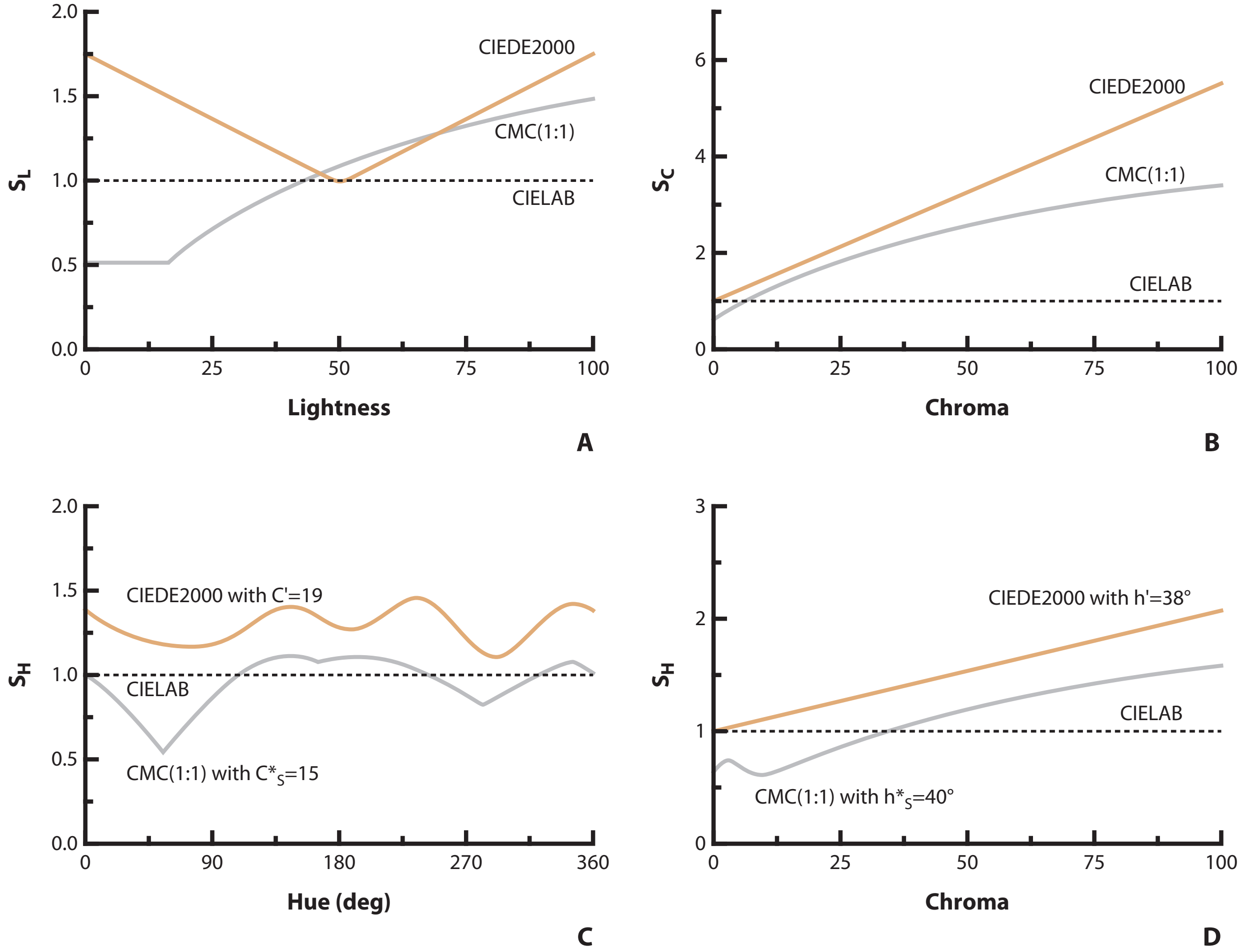

Figure 5. Weighting functions in CMC(1:1) and CIEDE2000. A, Weighting function for lightness compared to lightness. B, Weighting function for chroma compared to chroma. C, Weighting function for hue compared to hue [with chroma fixed at average chroma values for both CMC(1:1) and CIEDE2000]. D, Weighting function for hue compared to chroma [with hue fixed at average hue for both CMC(1:1) and CIEDE2000]. CIE, International Commission on Illumination.

in CMC(1:1) and CIEDE2000 show large differences, and there are 2 clear minimums for CMC(1:1), whereas CIEDE2000 has 3 maximums and 3 minimums (Fig. 5C); similar increasing functions were found for hue dependence (Fig. 5D). However, within the range of the lightness, chroma, and hue of the specimens, virtually similar increasing functions for S_L, S_C, and chroma-dependent S_H and decreasing curves for hue-dependent S_H are to be found in both CMC(1:1) and CIEDE2000.

Values for the percentages of "perceptible" and "unacceptable" relative to CMC(1:1) and CIEDE2000 color differences were analyzed using logistic analysis. For CIEDE2000 in PER judgments, after 23 iterations, the optimal parameters were B=–3.532, A=2.053; for CMC(1:1) in PER, the parameters were B=–3.509, A=1.395; for CIEDE2000 in ACC judgments, the parameters were B=–5.352, A=1.313; and for CMC(1:1) in ACC, the parameters were B=–5.375, A=0.866. Table 2 shows the CIELab, CMC(1:1), and CIEDE2000 color differences

Table 1. Range and mean of lightness, chroma, and hue that weighting functions in CIELab, CMC(1:1), and CIEDE2000 depend on

Function	Color Attributes	Maximum	Minimum	Mean
CIELab	Lightness (L*)	84.15	76.10	79.52
	Chroma (c*)	19.06	10.62	15.79
	Hue (h*)	57.27	32.02	47.27
CMC(1:1)	Lightness (L*$_S$)	84.19	76.56	79.61
	Chroma (C*$_S$)	17.81	9.93	14.90
	Hue (h*$_S$)	47.30	31.38	40.35
CIEDE2000	Lightness (L′)	84.15	76.10	79.52
	Chroma (C′)	21.72	13.15	18.85
	Hue (h′)	48.81	23.24	38.26

CIE, International Commission on Illumination.

with 95% confidence intervals at 5%, 50%, 70%, and 95%, respectively, "perceptible" and "unacceptable" possibility. The result of a paired *t* test showed significant differences between the CMC(1:1) PER and ACC thresholds in all the above confidence levels, with *P*=.006, significant differences were also found between the CIEDE2000 PER

Table 2. Predicted CIELab, CMC(1:1), and CIEDE2000 color difference at different percentages of perceptibility and acceptability

		Perceptibility				Acceptability		
			95% CI				95% CI	
Formula	Probability (%)	Estimate	Lower	Upper	Probability (%)	Estimate	Lower	Upper
CIELab	5	0.26	-0.02	0.49	5	2.23	1.98	2.44
	50	2.08	1.96	2.19	50	4.64	4.54	4.75
	70	2.60	2.49	2.72	70	5.34	5.22	5.47
	95	3.89	3.70	4.12	95	7.06	6.83	7.32
CMC(1:1)	5	0.40	0.19	0.59	5	2.81	2.48	3.09
	50	2.52	2.42	2.61	50	6.21	6.07	6.35
	70	3.12	3.03	3.22	70	7.19	7.03	7.35
	95	4.63	4.46	4.82	95	9.61	9.32	9.94
CIEDE2000	5	0.29	0.12	0.43	5	1.83	1.62	2.02
	50	1.72	1.65	1.79	50	4.08	3.98	4.17
	70	2.13	2.06	2.21	70	4.72	4.62	4.83
	95	3.15	3.03	3.30	95	6.32	6.12	6.54

CI, confidence interval; CIE, International Commission on Illumination.

and ACC thresholds in all the above confidence levels, with P=.006. The corresponding 50:50% CMC(1:1)/CIEDE2000 PT was 2.52/1.72 and AT was 6.21/4.08.

DISCUSSION

The results indicate that the CMC(1:1) and CIEDE2000 equations offer a better fit than CIELab in assessing the PT of denture base acrylic resin and play a similar role for AT. Therefore, the null hypothesis that they all possess the same ability to discriminate both PT and AT evaluations was partially rejected.

Recent studies have shown a higher predictability by CIEDE2000 in both PER and ACC judgments.[17] As CIEDE2000 was derived from a combined dataset with small color differences (mean: 2.6 ΔE CIELab units), it is reasonable that it gives a better performance for PER judgments (also small color differences with PT=2.52ΔE_{CMC}/1.72ΔE_{00}). However, for ACC judgments, discrepancies in the magnitude of color differences might be the main cause. Other factors, such as different illuminating and viewing conditions, known as "parametric effects," the size of stimuli, background colors, and separations might also play a part.[27,28] The finding of better performance by CMC(l:c) than with CIELab is consistent with previous studies,[13,20] which also concluded that altering the l:c ratio may produce even better results.

Discrepancies in performance may originate primarily from the way color difference is calculated. Both CMC(l:c) and CIEDE2000 are CIELab advanced color difference formulas and share the same structure[9]: $\Delta E=\sqrt{\left(\frac{\Delta L^*}{K_L S_L}\right)^2+\left(\frac{\Delta C^*}{K_C S_C}\right)^2+\left(\frac{\Delta H^*}{K_H S_H}\right)^2+\Delta R}$. They have 2 characteristics in common. First, total color difference is composed mainly of 3 parts: ΔL^*, ΔC^*, and ΔH^* (lightness, chroma, and hue differences, respectively) of CIELab. Conversely, for CIEDE2000, a scaling factor was introduced to adjust the a* scale, thereby differentiating the calculations of ΔC^* and ΔH^*. Furthermore, CIEDE2000 added a rotation item to adjust its predictability in the blue region. In this study, ΔR was virtually zero; thus, its contribution to total color difference could be neglected. Second, these advanced versions of CIELab were modified, and 2 types of variables were introduced to weight the three parts, ΔL^*, ΔC^*, ΔH^*, in total color ΔE differences. The 2 variables are the weighting functions (S_L for lightness, S_C for chroma, S_H for hue) and the parametric factors (k_L for lightness, k_C for chroma, k_H for hue).

Parametric factors were introduced to adjust the influence of different experimental conditions on perceived color difference. In this study, they were all set to 1, but optimizing them further may provide a better fit. Weighting functions are meant to improve the perceptual uniformity of CIELab. This study compared the S_L, S_C, and S_H functions in CIEDE2000 with those in CMC(1:1). The general differences in weighting functions between CMC and CIEDE2000, along with the overall change in the span of lightness, chroma, and hue, and especially the important qualitative discrepancies in S_L and hue-dependent S_H, may lead to overall discrepancies in their performance through the entire color space. This may help to explain why this finding is different from that of the previous study based on tooth-colored porcelain evaluation.[13] However, within the range of lightness, chroma, and hue in this pink region, the similarity of weighting function dependencies may account for their comparable performances in this study. Further, the question of how these functions can be modified to adjust the computed color difference with perceived color difference is precisely the heart of all efforts to improve the perceptual uniformity of CIELab.

In this study, the 50% PT was 2.52 ΔE_{CMC} or 1.72 ΔE_{00} and 50% AT was 6.21 ΔE_{CMC} or 4.08 ΔE_{00}, larger than the PT=1.30 and AT=2.25 based on CIEDE2000 that Ghinea et al[17] reported. This may be because of the discrepancies in visual color tolerance of different regions in the CIELab color space,[6,9] resulting from the different sensitivity of the human eye to chroma, hue, and lightness differences.[29] Participants showed more tolerance for discoloration in pink acrylic resin than color change in tooth restorative materials.

An appropriate instrumental color analysis would overcome the subjectivity of visual color assessments. To establish reliable color difference thresholds in dentistry, some prerequisites such as standard viewing conditions, color difference formulas possession of higher discriminability, precise and accurate color measuring devices, and visual assessments with higher sensitivity and specificity should all be met. In future, with the accumulation of reliable visual assessments datasets in dentistry, weighting functions S_L, S_C, and S_H could be adjusted to provide better fit in dental applications. In addition, the recently developed color difference formulas CAM02-SCD and CAM02-UCS based on color appearance model CAM02 could be compared with our present findings to determine whether they can prove statistically significant improvements or not. This study suffered from edge-loss effects caused by the beam light being scattered to the edge of the specimen without being detected when the contact-measuring spectrophotometer was measuring the color of translucent specimens. In future, a noncontacting measuring system will be used to avoid this effect.

CONCLUSIONS

Within the limitations of this study, the following conclusions can be drawn:

The CMC(1:1) and CIEDE2000 color difference formulas provide a better fit with visual assessments than CIELab in the evaluation of perceptibility threshold of discoloration of denture base acrylic resin under controlled conditions in vitro.

A statistically significant difference was found between the perceptibility threshold and acceptability threshold for denture base acrylic resin.

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