

Reproducibility of tooth color gradation using a computer color-matching technique applied to ceramic restorations

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Statement of problem. To reproduce tooth color precisely, an objective methodology based on color science is required. However, perception-based techniques are still the primary method for color matching in restorative dentistry.

Purpose. This study evaluated the accuracy of reproduction of color gradation for ceramic restorations using a Computer Color Matching (CCM) technique employing a prototype program and spectrophotometric data measurements.

Materials and methods. The colors of 10 target-shade tabs of the Vitapan 3D Master shade guide were measured at 4 regions of crowns from the cervical to the incisal area using a spectrophotometer. Tooth-shaped CCM ceramic specimens (30 specimens; 3 specimens for each of 10 target-shade tabs), the same size and shape as target-shade tabs, were fabricated according to the CCM prescriptions calculated using a prototype CCM program. The colors of CCM ceramic specimens and target-shade tabs were compared in 10 incremental areas from gingival to incisal (each measuring 1 mm high $\times$ 3 mm wide). The color differences, ΔE , ΔL^* , Δa^* , and Δb^* , were calculated. The color difference ΔE values were analyzed by a repeated measures analysis of variance ($P < .0001$). Three prosthodontists evaluated CCM specimens by perception techniques.

Results. The mean color difference (ΔE) values were clinically acceptable (below 3.6) for incremental areas 3 through 10 and unacceptable for areas 1 and 2 (gingival area). Highly significant differences in the mean of ΔE values among target-shade tabs ($P < .0001$), areas ($P < .0001$), and target-shade tab-by-area interaction effects ($P < .0001$) were noted. However, perceptual evaluation indicated "Definitive match" or "Approximate match" for all CCM specimens.

Conclusion. The CCM technique tested in this study utilizing 4 measurements on target-shade tabs could reproduce tooth color gradation from incisal to precervical regions with clinically acceptable results. (J Prosthet Dent 2005;93:129-37.)

CLINICAL IMPLICATIONS

An originally developed Computerized Color Matching (CCM) technique applied to 4 regions of a shade guide reproduced color in 8 incremental areas out of 10 (incisal to precervical) with clinically acceptable results. CCM may be an objective technique for dental color matching.

Color matching of teeth is a complex process, and shade selection errors can result.^{1,2} Empirical comparison using a dental shade guide is the accepted method for evaluating and reproducing natural tooth color for ceramic restorations. However, the use of shade guides

is highly subjective.³ Most existing commercial shade guides do not represent the entire spectrum of tooth color,⁴⁻⁶ and the lack of a standard color order may render this method of shade determination inconsistent. Also, this matching method depends on the clinician's color perception, ambient light conditions, and the background against which the tooth is compared,² all of which are subject to variance. Yet despite these limitations, the technology for dental color matching has changed little over the past several decades.

In recent years, investigators have attempted to utilize color science and color theory to devise a standard that will allow expression of colors numerically, in much the same way length and weight are expressed, for easier and more precise transfer and communication of color in restorative dentistry.⁷⁻¹³ The Kubelka-Munk

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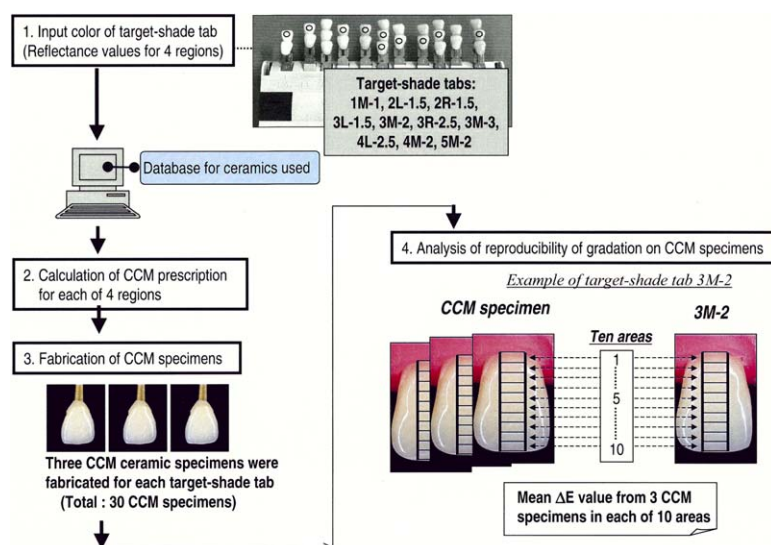


Fig. 1. Study design.

theory (K-M)¹⁴ is a popular color theory and has been utilized for the calculation of scattering and absorption coefficients, as well as the prediction of stratiform layered color for various dental materials. However, while Kubelka's work explicitly described the aspects of the relationship between reflectance and opacity of colorant layers, the interrelation between reflectance and opacity/translucency remains a subject of theoretical studies. Color formulation using the K-M theory has been evaluated, with the goal being enhanced color matching and color prediction for a variety of esthetic dental materials. One of the first studies to apply the Kubelka-Munk theory to color prediction in dentistry was performed on layered composite specimens.¹⁵ From this study, it was concluded that there were no significant differences between color coordinate values of composite specimens calculated using K-M and observed values and that the color of composite specimens in a range of thicknesses could be successfully predicted.¹⁶

Color matching methodology employing spectrophotometer and computer calculations based on color theory has been widely used in the paint, plastics, printing ink, and textiles industries for several decades and continues to be the most efficient method for color matching.¹⁴ In dentistry, however, visual color matching is still the primary method for selecting and evaluating the color of teeth and restorations and may create dissatisfying results. The major difference between color matching based on perception techniques and based on the use of a modern Computer Color Matching (CCM) technique lies in the level of accuracy. Recently, dental shade guides have been improved,¹⁷ but the color range is still not sufficient to cover the color space of natural teeth.¹⁸ Computer Color Matching methodology is intended to provide ceramic prescriptions to create any

type of tooth color without the need for dental shade guides. Therefore, the CCM technique may be a more effective method for reproducing a tooth color than an existing dental shade guide system.

The Computer Color Matching (CCM) technique was used to create metal-ceramic crown specimens utilizing the Kubelka-Munk theory (K-M).^{19,20} It was demonstrated that the CCM technique could reproduce the target opaque color with ΔE values less than 0.95 and with ΔE values less than 1.22 in various thicknesses of layered ceramic of dentin and enamel. To evaluate color difference, there are 2 methods: the perceptual method and the instrumental measuring method. The perceptual method relies on color perception by human eyes, which varies by person and is affected by many factors: surrounding light condition, size of objects, background, and eye fatigue. In contrast, instrumental color measurement has the advantage of objective evaluations. In this study, both perceptual and instrumental color evaluations were performed. For the initial evaluation of color gradation across small and different tooth regions, instrumental color measurements were made according to the color difference value ΔE and color coordinates ΔL^* , Δa^* , and Δb^* (Commission Internationale de l'Eclairage $L^*a^*b^*$ color system¹⁴). Although there are several studies suggesting clinically acceptable ΔE values in vivo,^{13,21} a ΔE of 3.6 was selected as the threshold value for clinical acceptability in this study.

The final decision on the color of crowns is left to patients; therefore, perceptual evaluation is also an important factor. A perceptual evaluation was performed on the color of each crown obtained in this study as a final verification. Using the instrumental as well as the perceptual methodology allows the accuracy in

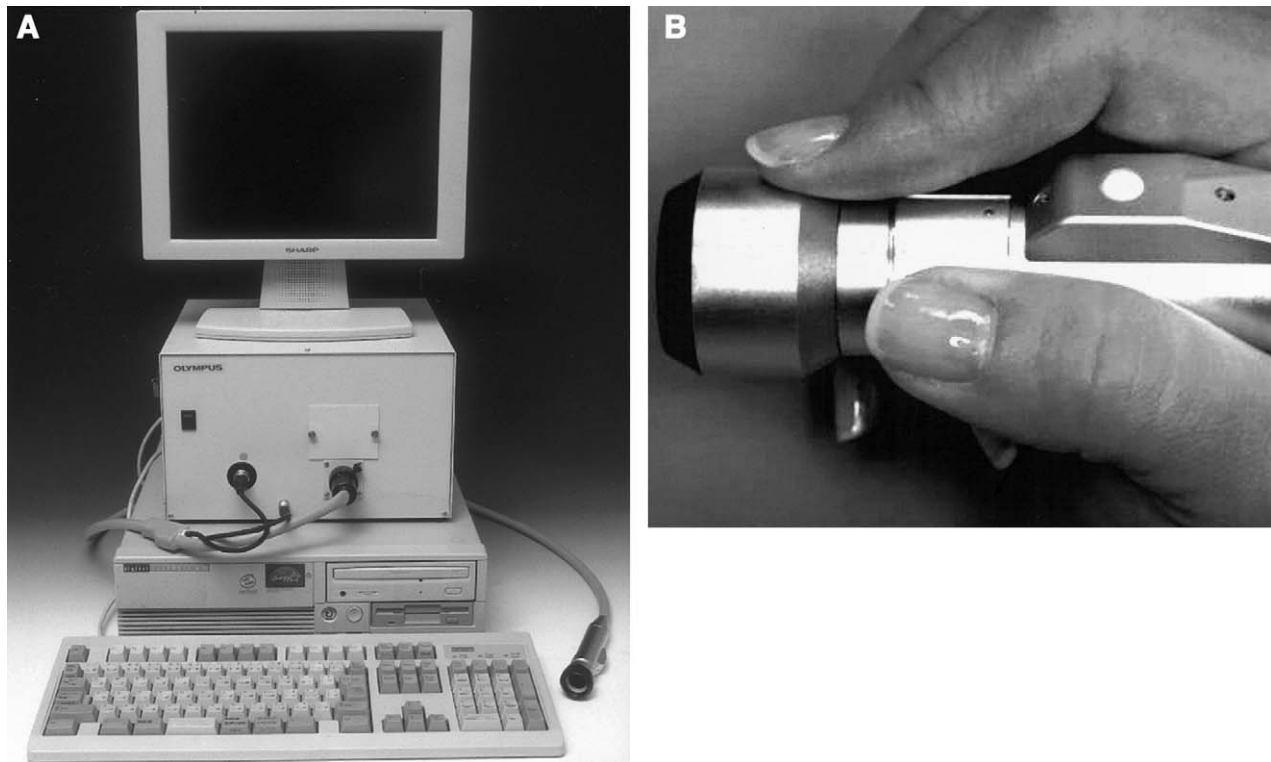


Fig. 2. A, Spectrophotometer used in study. **B,** Measurement probe of spectrophotometer.

color gradation reproduced by the CCM technique to be better evaluated according to clinically applicable standards.

The ultimate goal of work in this area is the creation of an automated and reliable color matching process immune to operator error. To apply the CCM technique for ceramic restorations, the complexity of natural tooth color gradation²² must be considered. The purpose of the present study was to test a newly developed Computer Color Matching (CCM) program based on the Kubelka-Munk theory for ceramic restorations with regard to accuracy in reproducibility of color gradation across different tooth regions from the incisal through the cervical regions of ceramic specimens.

MATERIAL AND METHODS

CCM prescriptions were determined for each of 10 target-shade guide tabs using a prototype CCM program developed by the authors, and 3 tooth-shaped ceramic specimens (CCM specimens) consisting of layers of enamel, dentin, ceramic core, and die material were fabricated for each tab. Three CCM specimens were fabricated for each of the 10 target-shade tabs, for a total of 30 CCM specimens. The colors of target-shade guide tabs and CCM specimens were compared visually and color difference values ΔE , ΔL^* , Δa^* , and Δb^* between CCM specimens and target shade tabs were analyzed. The experimental protocol is shown in Figure 1.

Color measuring instrument

Spectrophotometric measurements were made using a multispectral camera system (MSC-2000; Olympus, Tokyo, Japan) as shown in Figure 2. A 100W halogen lamp (Olympus) was shone through filters to provide an approximately 25W light source onto a 20-mm-diameter illuminating area and 15-mm-diameter measuring area for a measuring time of 8 seconds. The spectrophotometer used in this study utilized 45/0-degree geometry and was accurate to less than 0.2 ΔE for repeated measurements. Prior to specimen color measurement, a calibration was performed with a standardized calibration tile (Ever-Colors, White; Yoneda Glass Co, Osaka, Japan). The probe was placed on the surface of the object, and the display confirmed the object and the area to be measured. This machine generates a multispectro image, that is, a digital image of an entire object that features spectral data for each pixel, and saves it to a computer (Sony Vaio PCV-R538DS; Sony, Tokyo, Japan) to be used for measurements. The image is expanded on the computer, and the measurement area is determined to be a smaller section of the larger image on the display. Actual measurement is performed for each area chosen from the display image. Reflectance values ranged from 400 nm to 700 nm at 20-nm intervals. CIELAB color coordinates, L^* (Lightness), a^* (Redness), and b^* (Yellowness), were provided. Color measurement was performed 3 times for each specimen

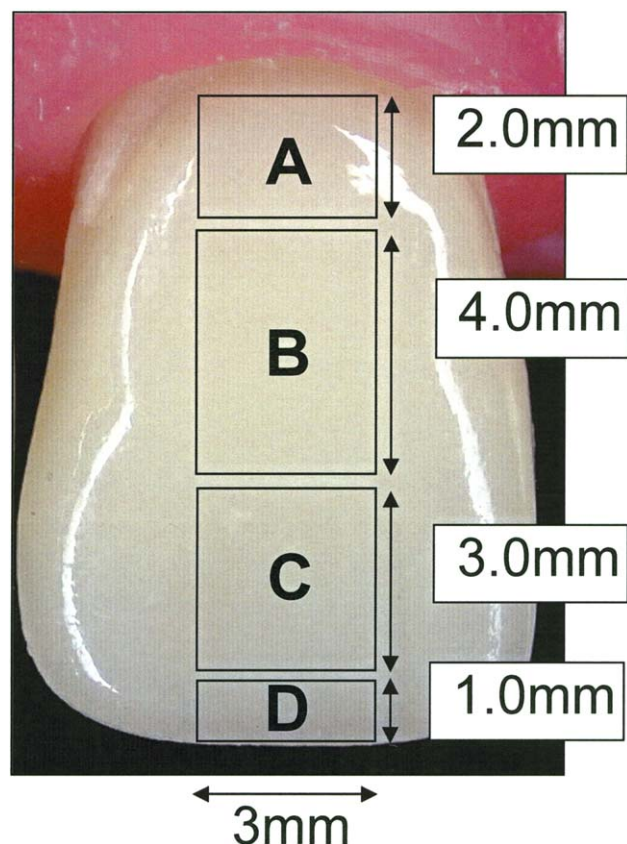


Fig. 3. Regions for measurement of target-shade tab.

and for each shade tab. The average of these measurements was considered as the measured data.

Establishment of database for CCM program

An all-ceramic crown system (IPS Empress 2; Ivoclar Vivadent, Schaan, Liechtenstein) was used for this study. Six shades of incisal ceramics (IC: TN, E4, OD1, E5, TB, and pink), 6 shades of layering ceramics (LC: 010, 140, 310, 440, 540, and pink), and 3 shades of dentin ingots (IN: 100, 200, 300) were selected to fabricate ceramic specimens for baseline measurements. IN specimens, 5.0 mm thick (simulating the tooth abutment), were fabricated from the dentin ingots. LC specimens, 1.0 mm thick (considered to be the thickness for the layering dentin ceramic), and IC specimens, 2.0 mm thick (considered to be the thickness of the incisal edge), were fabricated according to the manufacturer's recommendations. The surface of each specimen was adjusted with a sheet of emery paper (no. 800; Riken Corundum Co Ltd, Konosu City, Japan) to prepare a flat surface. Specimens were then polished using a sheet of emery paper (no. 1200; Riken Corundum Co Ltd) to obtain a fine, smooth surface. LC and IC specimens were measured with a white backing (Ever-Colors, White 9582; Yoneda Glass Co) and a black backing (Ever-Colors,

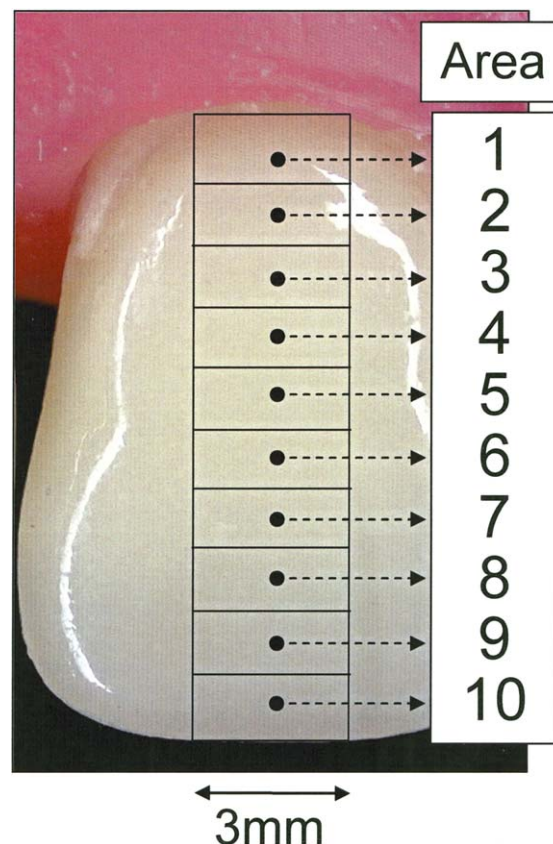


Fig. 4. Incremental areas for measurement of CCM ceramic specimens and target-shade tabs.

Black; Yoneda Glass Co). Scattering coefficients (S) and absorption coefficients (K) for LC specimens and IC specimens were calculated using the Kubelka-Munk theory.¹⁴ The scattering coefficient is defined as the rate of increase of reflectance with a thickness of a very thin layer for diffusely incident radiant energy, and the absorption coefficient refers to the rate of decrease of transmittance with a thickness of a very thin layer for diffusely incident radiant energy.¹⁶ L^* , a^* , and b^* values of IN specimens, and Scattering coefficients (S) and absorption coefficients (K) for LC and IC specimens were used for CCM calculation. Three specimens were fabricated for each shade of LC, IC, and IN. The average reflectance values from the 3 specimens of each shade at wavelengths ranging from 400 nm to 700 nm measured at 20-nm intervals were used to calculate scattering coefficients (S), absorption coefficients (K), and L^* , a^* , and b^* .

Color measurement of target colors and fabrication of ceramic core

Ten target-shade tabs of 1M-1, 2L-1.5, 2R-1.5, 3L-1.5, 3M-2, 3R-2.5, 3M-3, 4L-2.5, 4M-2, and 5M-2 from a shade guide (Vitapan 3D Master; Vita

Zahnfabrik, Bad Sackingen, Germany) were placed in the maxillary left central incisor area of a typodont (D18D-EP; Nissin, Tokyo, Japan). The typodont was fixed in a plastic box, painted black, to simulate the oral cavity and avoid back lighting. Against this background, colors of 4 regions of each tab including the cervical, body, incisal, and gingival (Fig. 3) were measured under 3 conditions. The colors at region A (2 mm high $\times$ 3 mm wide), B (4 mm high $\times$ 3 mm wide), C (3 mm high $\times$ 3 mm wide), and D (1 mm high $\times$ 3 mm wide) were measured without any backing (freestanding). Region D was additionally measured with a white backing (Fit Checker; GC Corp, Tokyo, Japan) and with a black backing (Impression Compound; Kerr, Orange, Calif). The color measurement was performed 3 times for each condition, and average reflectance values were used for subsequent procedures.

The data obtained from black backing and white backing measurements were used to calculate the hiding power. Hiding power refers to a specific parameter of translucency relevant to this study.^{14,23} The hiding power of a layer is correlated with its luminous transmittance; that is, a layer that does not transmit any incident light will completely hide the colors of any structures beneath.¹⁴ In this study, hiding power was determined using the ratio R_b/R_w (R_b is the reflectance of the ceramic layer over a black backing, R_w is the reflectance of the ceramic layer over a white backing). If there is a 1:1 ratio, the object being measured is said to be opaque. The data from freestanding trials were used to calculate predicted color difference (ΔE) for CCM prescription. Color differences between 3 shades of IN (100, 200, 300) and color at region B were calculated. Ceramic cores were then fabricated on a prepared maxillary left central incisor abutment, with 1 shade having the smallest ΔE value out of 3 shades, according to the manufacturer's standards.

Calculation of CCM prescription and fabrication of CCM ceramic specimens

Three CCM specimens were fabricated for each of the 10 target-shade tabs, for a total of 30 CCM specimens. Reflectance values in the middle third of a ceramic core filled with composite (IPS Empress 2 Die Material ST-1; Ivoclar) were considered as a background for the prototype CCM program using Kubelka-Munk theory.¹⁴ Prescriptions for layering ceramic (1.0-mm thickness) over the ceramic core consisted of 4 dentin shades out of 6 selected. The mixing ratio was calculated for each region A, B, and C according to the CCM program.

For an incisal prescription, the translucency parameter hiding power^{14,23} was calculated for 4 shades of IC (TB, pink, OD1, and E5) and was adjusted to equal the hiding power of region D using TN (Clear) and E4 (Opaque white), according to the CCM program.



Fig. 5. Target-shade tab 3M-2 and corresponding CCM ceramic specimens. (Left: Target-shade tab 3M-2, Right: CCM specimen)

Then, mixing ratios for all 6 shades were calculated to reproduce the color of region D. Three tooth-shaped layered IPS Empress 2 (Ivoclar Vivadent) ceramic specimens featuring a ceramic ingot base overlaid with LC and IC were fabricated for each of the 10-target-shade tabs (total 30 CCM specimens) by the same dental technician. An electronic balance (AY 120; Shimadzu, Kyoto, Japan) was used for weighing the formulated ceramic powders. Then 3 formulated layering ceramics were applied to region A, B, and C of the ceramic core and blended at the interfaces for shade continuity. The thickness of layering ceramics was adjusted after firing. Formulated incisal ceramic was applied to incisal region D, slightly overlapping with region C, and thickness in this region was adjusted as well. CCM specimens were then completed with a glazing.

Evaluation of reproducibility of target color on CCM ceramic specimens

The tooth-shaped CCM specimens were filled with die material (IPS Empress 2 Die Material ST-1; Ivoclar Vivadent) and placed in the maxillary left central incisor area of a typodont (D18D-EP; Nissin). The color of CCM specimens was measured at 10 incremental areas (each 1.0 mm high $\times$ 3.0 mm wide, Fig. 4). The values of L^* , a^* , and b^* for the 3 CCM specimens of each of the 10 target-shade tabs at each of the 10 incremental areas were measured. The values of ΔL^* , Δa^* , Δb^* , and color difference ΔE were then calculated according to the following equation¹⁴:

$$\Delta L^* = L^*_{\text{target}} - L^*_{\text{CCM}(1-3)}$$

$$\Delta a^* = a^*_{\text{target}} - a^*_{\text{CCM}(1-3)}$$

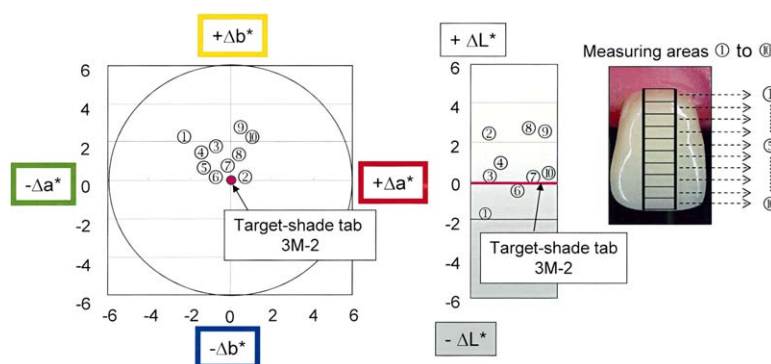


Fig. 6. The mean ΔL^* , Δa^* and Δb^* values between target-shade tab 3M-2 and corresponding CCM ceramic specimens in 10 incremental areas.

Table I. Mean color difference ΔE values between target-shade tab and CCM specimen

Area	Corresponding target-shade tab for CCM specimen									
	1M-1	2L-1.5	2R-1.5	3L-1.5	3M-2	3R-2.5	3M-3	4L-2.5	4M-2	5M-2
1	6.5*	3.4	3.8*	5.9*	4.0*	3.7*	3.4	3.9*	5.9*	3.0
2	4.8*	4.5*	2.5	3.7*	3.9*	4.1*	4.1*	4.1*	4.5*	2.7
3	3.4	1.1	4.2*	3.6	2.4	2.8	2.5	4.1*	4.9*	3.3
4	4.4*	0.6	2.6	3.5	1.9	2.4	2.7	4.2*	6.2*	4.0*
5	4.5*	1.2	3.3	3.6	1.6	1.8	2.4	4.9*	6.9*	3.7*
6	4.2*	2.0	2.8	3.5	1.5	1.4	1.9	5.2*	7.1*	3.9*
7	3.8*	3.2	3.0	3.1	1.7	1.4	1.7	5.1*	6.2*	2.0
8	4.1*	4.7*	2.4	2.9	2.4	2.8	1.6	4.3*	4.5*	2.4
9	5.3*	3.5	1.2	1.9	4.1*	6.0*	1.7	2.9	2.6	3.4
10	3.9*	5.8*	1.2	2.9	2.1	3.0	2.5	1.0	2.3	4.5*

*Clinically not acceptable ΔE .

$$\Delta b^* = b^*_{\text{target}} - b^*_{\text{CCM}(1-3)}$$

$$\Delta E = \{(L^*_{\text{target}} - L^*_{\text{CCM}(1-3)})^2 + (a^*_{\text{target}} - a^*_{\text{CCM}(1-3)})^2 + (b^*_{\text{target}} - b^*_{\text{CCM}(1-3)})^2\}^{1/2}$$

Thus, for each shade, the mean values of ΔE , ΔL^* , Δa^* , and Δb^* were calculated at each of the 10 incremental areas on each of the 3 specimens fabricated.

A repeated measures analysis of variance was performed to evaluate the effects of target-shade tabs, areas, and tab-by-area interactions on the accuracy of ΔE values. Target-shade tabs were evaluated as a blocking factor, with 3 specimens nested within each of the 10 tabs. Repeated measures of ΔE were made at 10 areas across each specimen, constituting a repeated measures factor. The analysis was implemented using statistical software (SAS/STAT system; SAS Institute, Cary, NC).

The accuracy of color reproducibility on CCM specimens was evaluated using ΔE values, with ΔE values less

than 3.6 considered clinically acceptable.¹³ Three prosthodontists (excluding authors) evaluated CCM specimens by perception techniques and divided specimens into 4 categories: “Definitive match,” “Approximate match,” “Poor match,” and “No match.”

RESULTS

The representative comparison between target-shade tab 3M-2 and CCM specimens is shown in Figures 5 and 6. The similar color produced indicated ΔE values of less than 3.6 for areas 3 through 10. However, the ΔE value in area 1 was 4.0 and the ΔE value in area 2 was 3.9. These ΔE values were greater than 3.6, indicating a clinically unacceptable color difference. The values of Δa^* and ΔL^* did not display a specific trend and instead indicated negative values in some areas and positive values in other areas. In contrast, Δb^* values were positive for all 10 incremental areas. These results were observed for other pairs as well.

Table II. Repeated measures analysis of variance

Source	df	Type III SS	Mean square	F value	P > F
Tests of hypotheses for between subjects effects					
Tabs	9	197.02	21.89	549.24	<.0001
Error	20	0.79	0.03	—	—
Univariate tests of hypotheses for within subject effects					
Areas	9	43.70	4.85	240.50	<.0001
Areas*Tabs	81	363.44	4.48	222.19	<.0001
Error(Areas)	180	3.63	0.02	—	—

The mean ΔE values between CCM specimens and target-shade tabs varied from 0.6 to 7.1 (Table I). The repeated measures analysis of variance (Table II) indicated highly significant differences in the mean accuracy of ΔE values between tabs ($P < .0001$), highly significant differences between areas ($P < .0001$), and a highly significant tab and area interaction effect ($P < .0001$).

Of particular interest is the very small mean square for Errors(Areas) = 0.02, reflecting a very high degree of agreement for the 3 specimens with respect to the ΔE values obtained for a given tab and area. The perceptual evaluation revealed that all CCM specimens were categorized as “Definitive match” or “Approximate match.”

DISCUSSION

The CCM technique has been applied for dental porcelain^{19,20} and tested for metal-ceramic crowns. In these studies, CCM prescriptions were calculated for opaque porcelain underlying dentin and enamel porcelain. However, to apply the CCM technique to all-ceramic crowns having no opaque or metal substructure, CCM prescriptions must be determined for layered ceramic, such as enamel and dentin. Also, the influence of reflectance from the prepared tooth color should be accounted for when considering the color background. The present research was designed according to clinical application and lab procedures for all-ceramic crowns. These procedures include the following: (1) the use of shade guide tabs for determination of target color, (2) measurement of color at 4 regions to account for tooth color gradation related to tooth anatomy, (3) fabrication of a ceramic core on a typodont tooth, prepared for an all-ceramic crown, and (4) the designation of background color being the color of the ceramic core filled with die material.

In the present study, Vitapan 3D master shade tabs were used as target color and were reproduced with the IPS Empress all-ceramic crown system. CCM calculations were based on the data (scattering coefficient

[S] and absorption coefficient [K] for ceramic materials used). Another benefit of the CCM technique used is that prescriptions obtained using these data can reproduce any target color located within the color space of the original colorants. Natural tooth color is not monotone, and it has been reported that the color of natural teeth differs with tooth region, ranging from incisal to cervical.²² In the present study, the colors of 4 regions were measured for CCM prescriptions, considering tooth anatomy and color gradation of shade guide for regions including cervical, body, incisal, and incisal edge. Although working from fewer prescriptions simplifies CCM-based porcelain lab work, there may be a need to calculate prescriptions for more than 4 regions depending on the color gradation of a natural tooth. Four formulated ceramics, 3 for the dentin layer and 1 for the enamel layer, were applied to create a tooth color gradation. The formulated ceramics were applied to the corresponding regions of ceramic cores and blended at the interfaces for shade continuity. Thus, the 4 formulated porcelains can be used to create more than 4 individual colors on the CCM specimen. In this manner, the colors of 10 incremental areas of 1-mm height from the cervical region to the incisal edge were compared to the target-shade tab.

To analyze the CCM technique clinically, CCM-formulated porcelains were applied on ceramic cores fabricated on a prepared abutment for an all-ceramic crown. The color of a ceramic restoration will be affected by porcelain thickness and also the color of the background, consisting of the abutment and the ceramic core. As the purpose of the present study was to examine the accuracy of the CCM technique for clinical application, it was essential that the tooth-shaped ceramic specimens have the same structure as all-ceramic crowns. CCM prescriptions can be calculated to reproduce the target color on the individual background color. In the present study, 1 color of die material, ST1, was chosen to represent the color of the abutment tooth, and the color of ceramic core filled with ST1 was considered the background color for CCM calculation of each target color.

In determining translucency, previous research has used the color difference of ΔE values between specimens measured with a white backing and a black backing.^{11,18} The hiding power was used as the translucency parameter in this study. The Kubelka-Munk equation was used to compute a scattering coefficient as part of the hiding-power calculation,²³ and CCM prescriptions for the incisal edge were calculated to match a hiding power of region D (incisal). As the hiding power of 4 IC ceramics (chromatic ceramic) was adjusted to equal the hiding power of target-shade by mixing with TN and E4 (nonchromatic IC ceramic) on computer calculation, the final prescription for

region D, including 6 IC shades, could have the same translucency of the incisal edge.

Mean values of ΔE between CCM ceramic specimens and target-shade tabs in each of the 10 incremental areas varied from 0.6 to 7.1 with a mean value of 3.2. Considering that a ΔE value of less than 3.6 is considered a clinically acceptable color difference,¹³ reproducibility of color gradation using this CCM technique in areas 1 and 2 (gingival), and also overall CCM specimens for tabs 1M-1, 4L2.5, and 4M-2 indicated a clinically unacceptable color difference. Possible explanations for this include the following: (1) these 3 target-shade tabs may have a greater color gradation than other target-shade tabs, and (2) as the measurement area of target-shade tabs in the cervical region was 2.0 mm high, as in this area, there may be a greater range of color gradation, especially close to the gingival tissues. Considering the anatomical characteristics of the cervical region such as the emergence profile and narrow tooth width, color in the cervical area should be measured by examining narrower bands of the region rather than considering the cervical region as a whole.

The color measurement results were the same using data obtained from multispectro images centered on the cervical area and from images in which the cervical area was positioned in the upper portion of the display. While this suggests that the position of the measured specimen does not affect results, the effect of gingival color on the cervical region requires consistency across each measured cervical region.

Additionally, where areas of measurement were identical to the target-shade measurement, all ΔE values for regions A, B, C, and D were below 2.1. This finding implies that the CCM technique could reproduce target tooth color accurately in these regions. Therefore, in order to reproduce the tooth color gradation precisely in a narrow band, the area of the target measurement is the critical issue. In fact, there is no scientific data available describing the color gradation of natural teeth. Some teeth may display weaker gradation and others stronger gradation than shade guides. To determine the area of a target measurement for natural teeth, it would be important to analyze color gradation beforehand. To prepare the CCM technique for clinical use, systematic data analysis of individual target tooth color is essential.

A CCM technique requires a spectrophotometer and computer with a compatible CCM program. Spectrophotometers are available commercially; however, they are expensive and require significantly more space than a digital camera. To establish a CCM technique for widespread dental clinic use, it will be necessary to develop a spectrophotometer with a lower cost and more compact size. Until such developments in the market are realized, the results of this study may be of limited application.

CONCLUSION

The CCM technique tested in this study using 4 measurements on target-shade tabs could reproduce tooth color gradation from incisal to precervical regions with clinically acceptable results. It was suggested that the color measurements of target-shade tabs should be made in narrower bands in the cervical area where there is a strong gradation towards the cervical margin.

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REFERENCES

1. Sproull RC. Color matching in dentistry. 3. Color control. *J Prosthet Dent* 1974;31:146-54.
2. Preston JD. Current status of shade selection and color matching. *Quintessence Int*; 1985:47-58.
3. Miller L. Organising color in dentistry. *J Am Dent Assoc* 1987; Spec No: 26E-40E.
4. Sproull RC. Color matching in dentistry. 1. The three-dimensional nature color. *J Prosthet Dent* 1973;29:416-24.
5. Ribino, Garcia A, Jimenez del Barco, Romero J. Colour measurement of human teeth and evaluation of colour guide. *Color Res Appl* 1994;19: 19-22.
6. O'Brien WJ, Boenke KM, Groh CL. Coverage errors of two shade guides. *Int J Prosthodont* 1991;4:45-50.
7. O'Brien WJ, Johnston WM, Fanian F. Double-layer color effects in porcelain systems. *J Dent Res* 1985;64:940-3.
8. Ma T, Johnston WM, Koran A 3rd. The color accuracy of the Kubelka-Munk theory for various colorants in maxillofacial prosthetic material. *J Dent Res* 1987;66:1438-44.
9. Rugh EH, Johnston WM, Hesse NS. The relationship between elastomer opacity, colorimeter beam size, and measured colorimetric response. *Int J Prosthodont* 1991;4:569-76.
10. Davis BK, Johnston WM, Saba RF. Kubelka-Munk reflectance theory applied to porcelain veneer systems using a colorimeter. *Int J Prosthodont* 1994;7:227-33.
11. Johnston WM, Ma T, Kienle BH. Translucency parameter of colorants for maxillofacial prostheses. *Int J Prosthodont* 1995;8:79-86.
12. Johnston WM, Hesse NS, Davis BK, Seghi RR. Analysis of edge-losses in reflectance measurements of pigmented maxillofacial elastomer. *J Dent Res* 1996;75:752-60.
13. Johnston WM, Kao EC. Assessment of appearance match by visual observation and clinical colorimetry. *J Dent Res* 1989;68:819-22.
14. Judd DB, Wyszecki G. *Color in business, science and industry*. 3rd ed. New York: John Wiley & Sons; 1975. p. 281-341, 420-38, 446-61.
15. Miyagawa Y, Powers JM, O'Brien WJ. Optical properties of direct restorative materials. *J Dent Res* 1981;60:890-4.
16. Miyagawa Y, Powers JM. Prediction of color of an esthetic restorative material. *J Dent Res* 1983;62:581-4.
17. Paravina RD, Powers JM, Fay RM. Color comparison of two shade guides. *Int J Prosthodont* 2002;15:73-8.
18. Hasegawa A, Ikeda I, Kawaguchi S. Color and translucency of in vivo natural central incisors. *J Prosthet Dent* 2000;83:418-23.
19. Ishikawa-Nagai S, Sato R, Furukawa K, Ishibashi K. Using a computer color-matching system in color reproduction of porcelain restorations. Part 1: Application of CCM to the opaque layer. *Int J Prosthodont* 1992; 5:495-502.
20. Ishikawa-Nagai S, Sawafuji F, Tsuchitani H, Sato RR, Ishibashi K. Using a computer color-matching system in color reproduction of porcelain restorations. Part 2: color reproduction of stratiform-layered porcelain samples. *Int J Prosthodont* 1993;6:522-7.
21. Ruyter IE, Niler K, Moller B. Color stability of dental composite resin materials for crown and bridge veneers. *Dent Mater* 1987;3:246-51.
22. O'Brien WJ, Hemmendinger H, Boenke KM, Linger JB, Groh CL. Color distribution of three regions of extracted human teeth. *Dent Mater* 1997;13:179-85.
23. Mitton PB. Easy quantitative hiding power measurements. *J Paint Technology* 1970;42:159-83.

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