Assessing the accuracy of computer color matching with a new dental porcelain shade system

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Statement of problem. In a previous study, a novel computer color matching system for dental ceramic restoration was developed, and 21 new shades were established. Theoretically, a natural tooth color can be accurately reproduced by combining 2 or 3 ceramic mixtures from the database of 21 new shades.

Purpose. The purpose of this study was to test the use of these shades in conjunction with the computer color matching system to determine their ability to accurately reproduce the body color of 29 shade tabs from a shade guide (VITAPAN 3D-Master).

Material and methods. Disks of 21 reference shades were prepared with porcelain (Cerabien CZR) and polished to 1.0 mm thickness. A spectrophotometer was used to measure the reflectance values from 380 to 780 nm for each disk; the scattering coefficient and absorption coefficient were determined. By using the reflectance values and the scattering and absorption coefficients, the computer color matching program generated porcelain prescriptions incorporating proportions from the 21 reference shades to reproduce the shade tabs. Disks were fabricated from the prescriptions, polished to 1.0 mm thickness, then placed over a zirconia core plate and measured with the spectrophotometer. The color differences (ΔE^*) between the shade tabs and the corresponding ceramic disks were calculated. Statistical analysis was performed with the 1-sample *t* test.

Results. The ΔE^* values between computer color matching specimens and the target shade tabs varied from 0.5 to 1.9, with an average ΔE^* of 1.3, which was significantly less than the clinically detectable ΔE^* threshold of 1.6 ($P<.001$).

Conclusions. The computer color matching system with the established 21 new shades is accurate and effective for reproducing tooth shades. (J Prosthet Dent 2014;111:247-253)

Clinical Implications

The use of a computer color matching system will enable dentists to provide patients with restorations that match a target tooth color more reliably. Laboratory technicians and dentists will be able to measure tooth color and generate a formula that will allow them to reproduce a patient's tooth color.

Color matching a ceramic restoration to a natural tooth is one of the most challenging aspects of clinical dentistry.[1] To emulate the multidimensional character of natural tooth color, the color value, intensity, and translucent properties of a tooth must be captured. Solving the complexity of the optical properties of the natural tooth requires an accurate way of measuring tooth color in a clinical setting. Once the color information has been acquired, it must

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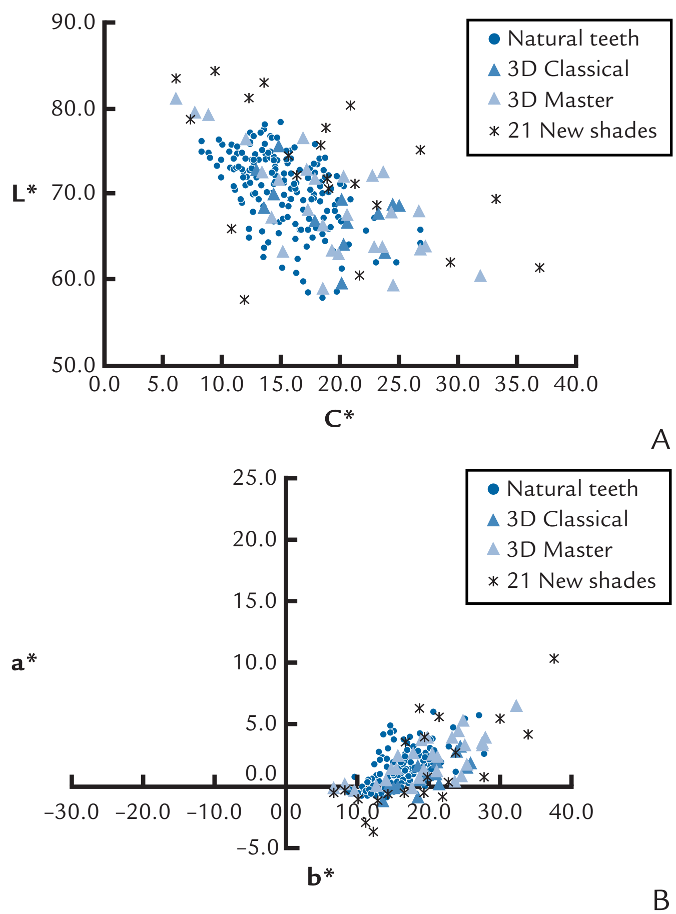
then be effectively communicated to a dental laboratory that will fabricate a ceramic restoration.[2] When matching a natural tooth, dentists rely mostly on visual comparisons with dental shade guides to select the appropriate colors.[3] The accuracy of current shade matching methods is limited by both the clinicians' ability to detect colors precisely[4,5] and the availability of shade guides that represent a complete range of natural tooth color.[6]

Although a number of shade guide systems are available for clinical use, the color space of currently available dental shade guides is limited in that the guides do not represent the full spectrum of color found in natural teeth.[6-8] An individual's perceptual ability is also restricted. Color discrimination ability differs from individual to individual, and visual color selection depends on shape, size, position, surrounding illumination,[9] and background color.[10-12] Variations in any factor may result in an altered perception of color.

A color-measuring instrument with computerized color analysis allows for more standardized and accurate color matching than conventional techniques.[13-15] A spectrophotometer that provides a sufficient 2-dimensional image of the target tooth should theoretically improve tooth color analysis and communication with the dental laboratory for the reproduction of natural tooth color.[16] In a previous study, a computer color matching (CCM) system for dental ceramic restoration was developed. Unlike conventional colorimeters, whose measurements can be less accurate,[17] the CCM system uses a spectrophotometer to improve the system's ability to measure the amount of light reflected from an object.[18] The CCM program interprets the color of the natural tooth measured by a spectrophotometer, and a computer program then generates a formulation for a ceramic mixture (3 to 5 shades and mixing ratios) to match the natural tooth at a specified thickness and over a specific background color. The CCM system has been used in the paint, plastics, printing, and textile industries for several decades and is considered to be the most effective color matching technique.[19] Previous research on the use of the CCM system in matching natural tooth color indicated promising results in ceramic disks and found that the CCM is automated, reliable, and immune to operator error.[18] The CCM system is based on the Kubelka-Munk color theory and the Saunderson correction, which were originally developed to describe the color and translucency of industrial materials mathematically.[20] In dentistry, researchers have worked to apply the Kubelka-Munk color theory to the reproduction of color with dental restorative materials.[21-23] This technique may allow for the objective reproduction of tooth color.

Because the formulations of all target shades are calculated based on the shade database, the breadth of the database is one of the most important components of the CCM system. A useful color space is the International Commission on Illumination (Commission Internationale de l'Éclairage, CIE) L*/a*/b* color space (CIELAB). Ideally, a CCM database would contain layering porcelain shades with CIELAB L*, a*, and b* values that encompass the natural tooth color spectrum (L*=lightness, a*=light blue-black axis, and b*=light blue-dark blue axis), but without the L*, a*, or b* values exceeding those in the basic color database. Therefore, the authors established 21 new custom shades that encompass the entire tooth color spectrum (Fig. 1). Theoretically, a natural tooth color can be accurately reproduced by combining 2 or 3 ceramic mixtures from the database of 21 new shades.

The purpose of this study was to test the ability of the CCM system that incorporates the 21 new shades to



1 Color distributions of the new 21-shade system, comparing natural teeth and 2 commercial shade guides. A, L*-C* map. B, a*-b* map. (L*, lightness; C*, chroma a*, light blue-black axis; b*, light blue-dark blue axis.)

accurately produce a porcelain formula that reproduces a natural tooth color. In this study, the VITAPAN 3D-Master shade guide (VITA Zahnfabrik) provided the target tooth colors to be reproduced. The null hypothesis was that the CCM system using this database of 21 new shades could not accurately reproduce the body color of 29 shade tabs from the VITAPAN 3D-Master shade guide.

MATERIAL AND METHODS

A commercially available shade guide (VITAPAN 3D-Master; VITA Zahnfabrik) consisting of 26 general shades and 3 bleaching shades provided the target colors. CCM prescriptions were determined for each of the target shade guide tabs with a prototype CCM program developed by the authors.[18] Based on this prescription, 3 CCM specimens of 1.0 mm thickness were fabricated for each of the 29 target shade tabs. Each of these CCM specimens was created with the custom shade database, with a ratio of 2 to 3 ceramic shades mixed and layered over the zirconia ceramic substrate. The color of each CCM specimen was then measured and compared with the corresponding target shade tab.

A dental spectrophotometer (Crystaleye; Olympus Corp) (Fig. 2) was used to measure the color. This spectrophotometer uses 7 light emitting diodes as an illumination source with 45°/0° geometry and was calibrated with a calibration plate (Olympus Corp) before data acquisition. The image capture time was 0.2 seconds. The spectral data for each specimen were acquired by the captured image. Reflectance values from 380 to 780 nm, with 1-nm intervals for each pixel, were transferred from the spectrophotometer to a personal computer (ThinkPad T60; IBM Corp). CIELAB color coordinates (L*, a*, and b*) were also provided. Color was measured 3 times for each specimen, and the average was calculated.

A database for the CCM program was established with a newly developed custom shade system (see Fig. 1A,B). Ceramic disks (1.0 mm thick) for each of the 21 new shades were baked in a porcelain oven (FireLite Porcelain Furnace; Whip Mix Corp). The thickness of each disk was adjusted to 1.0 mm with a flat, glossy finish with a polishing machine (Vector Power Head; Buehler Inc) and 600- and 1200-grit emery paper (Buehler Inc). Two sets of reflectance values were collected for each ceramic specimen of the 21 custom shades, one with the specimen against a white backing (Ever-Colors, White 9582; Yoneda Glass Corp) and the other against a black backing (Ever-Colors, Black; Yoneda Glass Corp). The reflectance values of the black and white backings were also measured. The Kubelka-Munk theory was used to calculate the reflectance value from a layer of translucent material with an opaque backing, such as a ceramic dental restoration.[24] The scattering (S) and absorption (K) coefficients for each of the 21 reference shades at each wavelength were determined according to the Kubelka-Munk theory.[20]

To mimic a natural tooth setting, 3 ceramic core plates of differing shades were used as underlying core layers. Reflectance values ranging from 380 to 780 nm were obtained from 0.5-mm thick ceramic cores, shades ZP10, ZP12, and ZP15 (ZirPrime; Noritake Co), and placed on a 5.0-mm-thick, shade A2 composite resin block (Tetric EvoCeram; Ivoclar Vivadent) with glycerin to avoid an air gap that would refract light and change the apparent shade. These reflectance values, along with K and S, for each of the 21 reference shades were entered into the CCM program.

The 29 target shade tabs of the VITAPAN 3D-Master shade guide were placed in an inspection box (Olympus Corp). The color of each shade tab was measured in the body region (3 × 3 mm) with the spectrophotometer, and the reflectance values from 380 to 780 nm were recorded and used as target colors by the CCM calculation.

The CCM program generated prescriptions for each target shade.[25] Each prescription specified the ceramic background (ZP10, ZP12, or ZP15) and a mixing ratio of 2 or 3 ceramic powders from the database of 21 new shades.

2 Spectrophotometer used.

The CCM program also provided the predicted color difference ΔE* between the target tooth color and the expected color of the ceramic specimen calculated with the prescription.

Of the prescriptions generated for each of the 3 shades of zirconia ceramic core, the prescription with the smallest predicted ΔE* was selected to fabricate the ceramic specimen for each target color. By using the selected prescription, ceramic specimens were fabricated for each shade tab, for a total of 29 shade tab/ceramic specimen pairs. An electronic balance (AY 120; Shimadzu) was used to weigh the ceramic powders for the formulations. The ceramic specimens were formed with a precision porcelain mold (Belle de St Claire) and fired according to the manufacturer's directions. The specimens were then adjusted to a thickness of 1 mm, with a flat, glossy surface, by using the polishing machine and 600- and 1200-grit emery paper. Three ceramic disks were made for each target shade.

The CCM specimens were placed over a zirconia core plate chosen by the CCM system (ZP10, ZP12, or ZP15) and measured with the spectrophotometer at the central portion (Fig. 3). All readings were obtained based on an average of triplet measurements. The color values L*, a*, and b* were calculated for the 29 CCM specimens and the 29 target shade tabs. The color difference values ΔE*, ΔL*, Δa*, and Δb* between each of the 29 pairs were calculated by using the following formulas[18]:

$$\Delta L* = L*_{target} - L*_{CCM}$$

$$\Delta a* = a*_{target} - a*_{CCM}$$

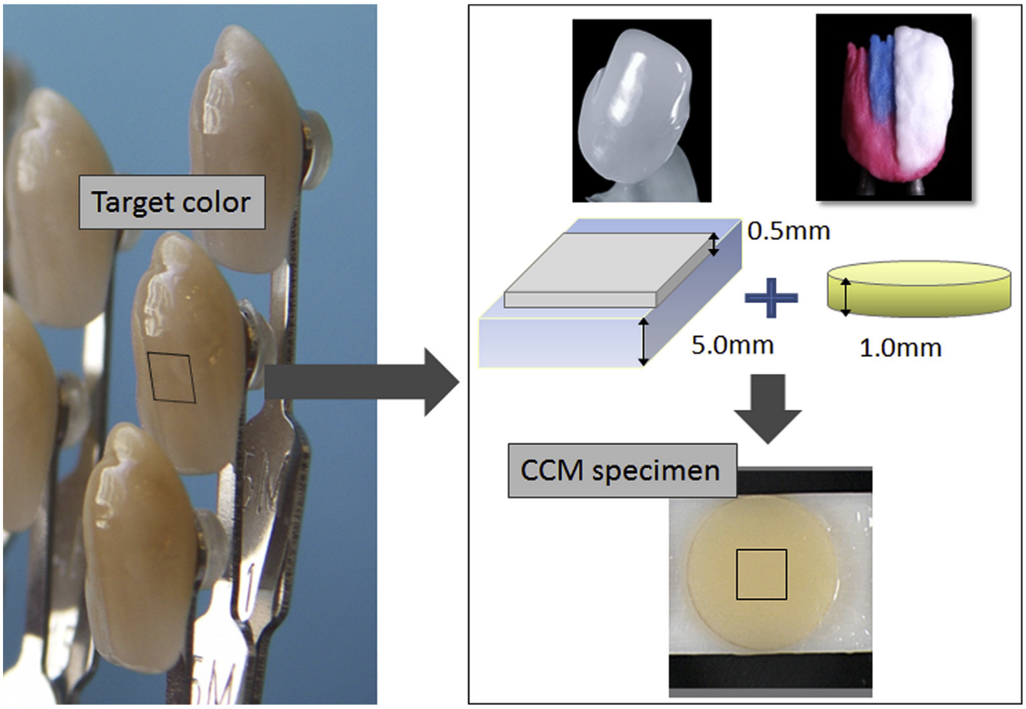
$$\Delta b* = b*_{target} - b*_{CCM}$$

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

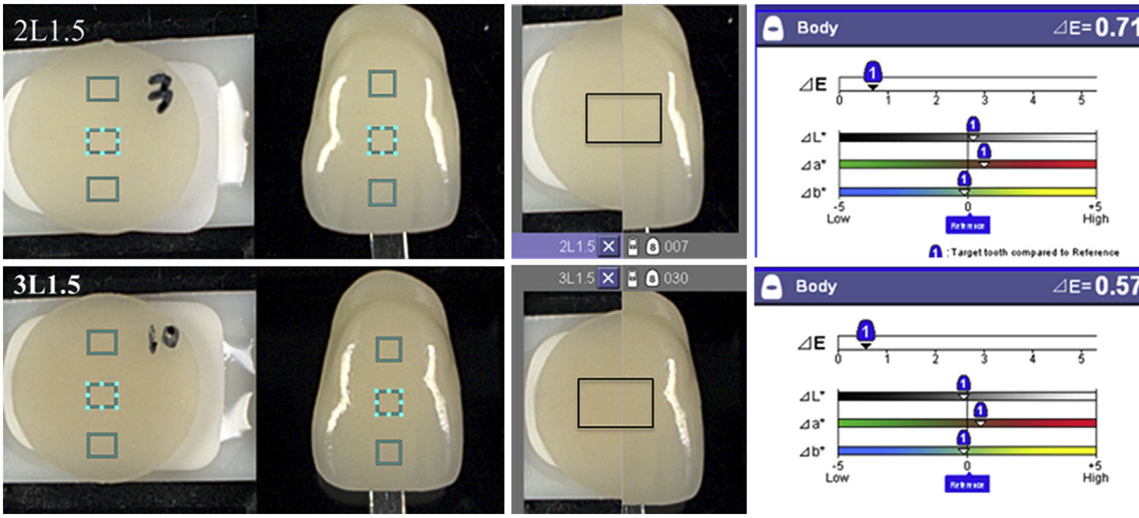
The ability of the new shades of the CCM system to accurately reproduce the color of VITAPAN 3D-Master shade tabs was evaluated based on the ΔE* for each of the 29 CCM target pairs, with a ΔE* <2.69 deemed an acceptable color match[13] and a ΔE* <1.6 deemed a perfect color match.[26] The 1-sample *t* test was used to assess whether there was an acceptable color match (ΔE* <2.69) or a perfect color match (ΔE* <1.6) between the target shade tabs and corresponding ceramic disks. The level of significance was established as α=.05.

RESULTS

The prescriptions for the 29 target shades were generated. The representative comparisons between target shade tabs (2L1.5 and 3L1.5) and CCM specimens are shown in Figure 4. The mean CIELAB color coordinates, L*, a*, and b*, of 29 CCM specimens and target shade tabs and the color difference values ΔL*, Δa*, Δb*, and ΔE* between each of the 29 pairs are tabulated in Table I. The values of ΔL*, Δa*, and Δb* were relatively small, with mean values of −0.36, 0.34, and 0.08, respectively. The ΔE* values between CCM specimens and the target shade tabs varied from 0.51 to 1.88, with an average ΔE* of 1.26 ±0.41. Of the 29 CCM target pairs, 5 were found to have clinically acceptable actual ΔE* values (ΔE* <2.69), and the other 24 pairs had actual ΔE* values <1.6. The 1-sample *t* test revealed that the average ΔE* of the 29 pairs was



3 Scheme of color reproduction by computer color matching.



4 Representative comparisons between target shade tabs (2L1.5 and 3L1.5) and computer color matching specimens.

significantly less than the ΔE* threshold of 1.6 ($P<.001$).

DISCUSSION

The results of this study support the rejection of the null hypothesis, because the average ΔE* value of 1.3 between CCM specimens and the target shade tabs was significantly less than the clinically detectable ΔE* threshold of 1.6 ($P<.001$).

The CCM system used in this study is able to rapidly produce a prescription for the reproduction of a tooth color with ceramics, with reference to the color of the ceramic core and the ultimate thickness of the layered porcelain. One of the most important components of the CCM system is the shade database, because the calculation of the target shade formulation is based on it. In a previous study[18] that used the CCM system for tooth color reproduction, a commercial shade system with 8 dentin body shades and 2 modifiers (Cerabien CZR; Noritake Co) was used. The selection was not evidence based; commonly used colors of shade guide tabs were selected, and gray and pink were chosen to adjust for value and redness. As a result, the average ΔE* value was 2.58 for the ceramic specimen/natural tooth pairs.[18] In contrast, the present study, which used the 21 newly developed custom shades to form the database for the CCM system, indicated a mean ΔE* value of 1.26, which is smaller than in the previous study. This difference in the shade database may explain the difference in values. The new custom shade system for CCM has 3 advantages compared with existing shade guide systems. First, 21 custom shades encompass the natural tooth spectrum. Second, the thickness of porcelain is 1.0 mm, which mimics a ceramic restoration. Third, the specimens were produced layered on a zirconia substrate to account for the influence of the substrate. Therefore, the CCM system can generate prescriptions with a minimum of error during the calculation and processing of specimens.

To date, little agreement has been reached as to the value of the ΔE* threshold for a detectable or unacceptable color difference.[25] In this project, it was predetermined that ΔE* values less than 2.69 were deemed acceptable based on a recent in vivo study using a dental spectrophotometer that evaluated the color match of 72 crowns.[13] This value was also comparable to the range of thresholds of clinical acceptance previously reported.[26-29] Moreover, a ΔE* value of 1.6 was deemed as the perfect color match threshold in this study based on another recent study that measured the color difference between natural intact central incisors and ceramic restorations.[25] In the present study, the ΔE* values between CCM specimens and the target shade tabs varied from 0.51 to 1.88, with an average ΔE* of 1.26, which was less than the ΔE* threshold of 1.6 ($P<.001$). Presently there is no agreed standard for a clinically acceptable ΔE* threshold. The mean ΔE* value of 1.26 found in this study is smaller than previously reported clinically detectable ΔE* thresholds.[25] Considering the relatively small color difference obtained in this study between the CCM specimens and target shade tabs, the newly developed CCM system is able to accurately and effectively reproduce the color of target shade tabs in vitro.

Several dental spectrophotometers are commercially available that should improve tooth color selection, communications, and analysis. However, there is no advantage to these instruments until porcelain formulas can be produced to allow accurate color reproduction. For decades, tooth color reproduction in ceramic restorations has been considered an art. Many presentations have shown beautiful, successful restorations, but they omit the color science and education necessary to achieve the result. Digital cameras have been used to communicate color, but the accuracy of their information is questionable.[30,31] Whereas other

Table I. Color values of CCM specimens and target shade tabs (n=3)

Shade Tab No.	Target Shade Tab L*	a*	b*	CCM Specimen L*	a*	b*	ΔL*	Δa*	Δb*	ΔE*[†]
0M1	80.71	−0.8	5.84	81.11	−0.95	6.73	−0.40	0.15	−0.89	0.99
0M2	79.59	−0.74	6.95	80.31	−0.91	7.99	−0.72	0.17	−1.04	1.28
0M3	78.9	−0.84	8.54	79.88	−1.13	9.41	−0.98	0.29	−0.87	1.34
1M1	76.48	−0.55	12.49	76.79	−0.89	11.7	−0.31	0.34	0.79	0.91
1M2	78.43	−0.85	16.79	77.06	−0.83	16.76	1.37	−0.02	0.03	1.37
2L1.5	73.46	−0.28	16.68	73.17	−0.78	16.87	0.29	0.50	−0.19	0.61
2L2.5	73.21	0.63	21.16	73.03	−0.88	21.42	0.18	1.51	−0.26	1.54
2M1	72.94	−0.97	13.79	72.67	−0.68	12.56	0.27	−0.29	1.23	1.29
2M2	71.27	0.76	17.63	73.05	0.17	17.55	−1.78	0.59	0.08	1.88
2M3	71.83	1.39	22.75	72.93	0.3	23.56	−1.10	1.09	−0.81	1.75
2R1.5	71.36	0.7	16.65	72.6	0.4	15.32	−1.24	0.30	1.33	1.84
2R2.5	72.7	1.13	21.71	72.97	0.7	21.15	−0.27	0.43	0.56	0.76
3L1.5	68	1.03	18.51	67.84	0.55	18.42	0.16	0.48	0.09	0.51
3L2.5	69.59	1.1	22.95	68.71	1.24	23.28	0.88	−0.14	−0.33	0.95
3M1	69.01	1.58	14.91	69.13	0.87	14.38	−0.12	0.71	0.53	0.89
3M2	68.16	2.03	19.51	68.99	1.34	19.55	−0.83	0.69	−0.04	1.08
3M3	69.61	1.99	23.91	69.35	1.85	24.73	0.26	0.14	−0.82	0.87
3R1.5	67.29	2.5	17.46	68.72	1.66	16.63	−1.43	0.84	0.83	1.85
3R2.5	67.26	2.01	22.63	68.36	2.69	23.53	−1.10	−0.68	−0.90	1.58
4L1.5	65.31	1.79	18.27	64.84	1.73	19.32	0.47	0.06	−1.05	1.15
4L2.5	64.18	3.26	25.98	64.1	2.66	26.95	0.08	0.60	−0.97	1.14
4M1	64.22	2.49	16.94	63.97	1.9	15.25	0.25	0.59	1.69	1.81
4M2	64.16	2.96	22.79	64.84	2.89	21.71	−0.68	0.07	1.08	1.28
4M3	64.42	4.41	28.6	64.63	3.98	28.05	−0.21	0.43	0.55	0.73
4R1.5	65.82	3.07	18.76	64.7	3.04	17.85	1.12	0.03	0.91	1.44
4R2.5	63.72	4.44	23.96	64.46	4.51	24.13	−0.74	−0.07	−0.17	0.76
5M1	58.55	3.49	18.24	59.6	3.51	17.05	−1.05	−0.02	1.19	1.59
5M2	59.48	5.63	25.13	60.87	5.32	24.75	−1.39	0.31	0.38	1.47
5M3	60.51	6.28	29.19	61.96	5.61	29.94	−1.45	0.67	−0.75	1.76
Mean	69.32	1.71	18.92	69.68	1.37	18.85	−0.36	0.34	0.08	1.26*
SD	5.97	1.96	5.79	5.86	1.98	5.87	0.81	0.43	0.83	0.41

CCM, computer color matching; SD, standard deviation; L*, lightness; a*, light blue-black axis; b*, light blue-dark blue axis; ΔE*, color difference.
[†]Average ΔE* of the 29 pairs was significantly less than the ΔE* threshold of 1.6 (*P*<.001).

aspects of dentistry have begun to benefit from technology such as digital impressions and restorations fabricated with computer-aided design and computer-aided manufacturing, color science in dentistry is still lagging. Color and esthetic perception are subjective and will be judged as art. Color reproduction and form is critical to clinical success, especially from a patient's perspective. However, it is clear that science, such as optical technology and mathematic calculations, will support clinicians and technicians in the creation of successful art in restorations.[2,32]

One of the limitations of this study is that only the color at the central body area of the target shade tab was matched and replicated by the CCM system. Natural tooth color is not monochromatic, and a tooth may display a number of colors from the incisal to the cervical area.[33] Therefore, future research with the CCM system is needed for ceramic restorations with regard to the accurate reproduction of color gradation from the incisal through the cervical regions. Finally, an in vivo assessment of the CCM study with the newly developed 21 shade database should be performed to test the efficacy of the CCM system on color reproduction.

CONCLUSION

The CCM system using the 21 newly established shades was found to be accurate and effective in reproducing target shades (29 shades of VITAPAN 3D-Master), with an average ΔE* of 1.26.

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