Clin Oral Invest (2011) 15:49–56
DOI 10.1007/s00784-009-0366-1

ORIGINAL ARTICLE

Development of digital shade guides for color assessment using a digital camera with ring flashes

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Received: 5 August 2009 / Accepted: 2 December 2009 / Published online: 5 January 2010

Abstract Digital photographs taken with cameras and ring flashes are commonly used for dental documentation. We hypothesized that different illuminants and camera's white balance setups shall influence color rendering of digital images and affect the effectiveness of color matching using digital images. Fifteen ceramic disks of different shades were fabricated and photographed with a digital camera in both automatic white balance (AWB) and custom white balance (CWB) under either light-emitting diode (LED) or electronic ring flash. The Commission Internationale d'Éclairage $L^*a^*b^*$ parameters of the captured images were derived from Photoshop software and served as digital shade guides. We found significantly high correlation coefficients (r^2>0.96) between the respective spectrophotometer standards and those shade guides generated in CWB setups. Moreover, the accuracy of color matching of another set of ceramic disks using digital shade guides, which was verified by ten operators, improved from 67% in AWB to 93% in CWB under LED illuminants. Probably, because of the inconsistent performance of the flashlight and specular reflection, the digital images captured under electronic ring flash in both white balance setups revealed less reliable and relative low-matching ability. In conclusion, the reliability of color matching with digital images is much influenced by the illuminants and camera's white balance setups, while digital shade guides derived under LED illuminants with CWB demonstrate applicable potential in the fields of color assessments.

Keywords Digital camera · White balance · Color difference · Shade guide · Color matching · Illuminants

Clinical relevance Color matching with digital images is much influenced by the illuminants and camera's white balance setups, while digital shade guides built with images under LED illuminants and custom white balance demonstrate applicable potential in the fields of color assessments.

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Introduction

Visual color matching is a challenging procedure in dentistry. Conventional shade matching techniques using different shade guides for comparisons do not render sufficient reliability or reproducibility [1–3]. Instrumental assessment of color is considered to be better than subjective visual color matching methods [4, 5]. However, the high cost hinders their common use. In addition to expensive colorimeters, digital images captured with a digital camera and subsequently analyzed using photo editing software has garnered more attention for color assessment [6–10].

Recent advances in image acquisition and data storage have resulted in the widespread use of digital cameras and ring flashes. Several studies have shown the potential of digital cameras for dental color matching [7, 8, 11–13]. The scene captured by an image sensor of a digital camera can be decomposed into red, green, and blue (RGB) components and translated into digital information by a specific digital signal processor (DSP). These digital RGB signals rendered in a specific color space are then saved in different file formats. However, the color information received from a digital camera is device-dependent. Images produced via a digital camera are usually affected by the light source, absorption–reflection spectra of the objects, the photosensor of the digital camera, and how the image is processed and rendered by the DSP of the digital camera. In general, these captured signals are much influenced by the illumination under which the image is taken.

To compensate for color differences caused by the color cast of various light sources, an automatic white balance (AWB) mechanism is usually employed in most high-end digital cameras. Similar to the human eye, digital cameras provide an AWB function to adjust the color of pixels under different lighting conditions. The most widely used algorithm for AWB is based on the gray world assumption, which seeks to equalize the mean of RGB channels. Another commonly used algorithm incorporates the white world assumption, which states that the RGB values of the brightest point in the image should be the same [14]. However, AWB often fails in situations where the light source has a particular cast or if the captured image does not contain natural white [15–17]. This is especially important in dental color matching, since various illuminants are used in dental clinics, and the captured images are usually focused in small areas composed largely of a tooth's structure. To achieve the optimal white balance setting in different situations, a custom white balance (CWB) can be used by choosing a preset value installed in the digital camera or customizing with neutral targets via adjusting the RGB gains so that white is close to true white. It is obvious that colors will appear in their natural shades in the captured images only if the camera is set to correctly reproduce white.

Since the effect of digital camera's white balance setups on the reliability of digital images was seldom tested, the purpose of this study was to verify the necessity of CWB for the digital camera. We hypothesized that different illuminants and camera's white balance setups shall influence color rendering of digital images and affect the effectiveness of color matching using digital images.

Materials and methods

Fabrication of ceramic specimens

Two sets of ceramic disks consisted of fifteen shades A1–A3, A3.5, A4, B1–B4, C1–C4, D2, and D3 were fabricated with Vita VMK 68 dentin porcelain (Vita Zahnfabrik, Bad Säckingen, Germany) according to the manufacturer's firing protocol. The disks (15 mm in diameter) were polished flat until the desired thickness of 1.0 mm was achieved. All lapping procedures were conducted with a Buehler polishing system (Lake Bluff, IL, USA) and a series of silicon carbide paper from 180 to 600 grit under copious water. The disks were then ultrasonically cleaned for 10 min and stored in a desiccator.

Digital photography with ring flashes

A high-resolution digital single-lens reflex (SLR) camera (Nikon D1, Tokyo, Japan) equipped with a charge-couple device (CCD) was fixed to a copy stand. A 105-mm macro lens (AF Micro-Nikkor, Nikon) attached to the camera was oriented perpendicular to the measuring surface of a sample disk with a fixed 1:1 magnification. One set of porcelain disks were placed on a black cloth backing when the digital images were taken under two white-balance settings of the camera, including AWB and CWB. The programmed auto mode in the camera was used for the AWB. The CWB of the camera was manually preset by shooting a white standard plate (no. 91547, Tokyo Denshoku, Tokyo, Japan) according to manufacturer's instruction.

Two ring flashes were used, including a Nikon ring flash (Nikon Macro Speedlight SB-29 TTL Ring Light Flash, Nikon) and a custom-made LED illuminator, in which 12 white LEDs (SDL-5N3PW-S, Sander Electronic, Taipei, Taiwan) were evenly arranged around a circular frame designed to fit the lens [18]. The characteristics of the light sources (Fig. 1) were analyzed by a spectrophotometer (USB2000, Ocean Optics, Dunedin, FL, USA) and a chroma meter (CL-200, Konica Minolta Sensing). The background lighting in the room was subdued and maintained at a constant level during the entire experiment. To minimize the specular reflection from the flat porcelain disks, a polarizing lens was mounted in front of the macro lens and the scene was checked in the view window of the camera before shooting. The captured images with obvious specular reflection were excluded, and a new image was taken.

Reliability of digital images

Digital images of all 15 master ceramic disks were taken and saved in ISO200 TIF format. The resolution used was 2.62×10^6 ($2{,}000\times1{,}312$) pixels. The images were retrieved on a 24-bit resolution screen and analyzed using Adobe Photoshop 6.0 software (Adobe System, San Jose, CA, USA). The color space of the software was set the same as the default color space of the camera, and the image mode was changed from RGB to $L^*a^*b^*$. A standardized circular area of 10 mm in diameter at the center of each ceramic image was cropped for analysis. The tonal scales of $L^*a^*b^*$ values ($\mathrm{Lab}_{\mathrm{histogram}}$) of these areas were measured three times, and mean values were recorded by applying the histogram function of Adobe Photoshop. To test the

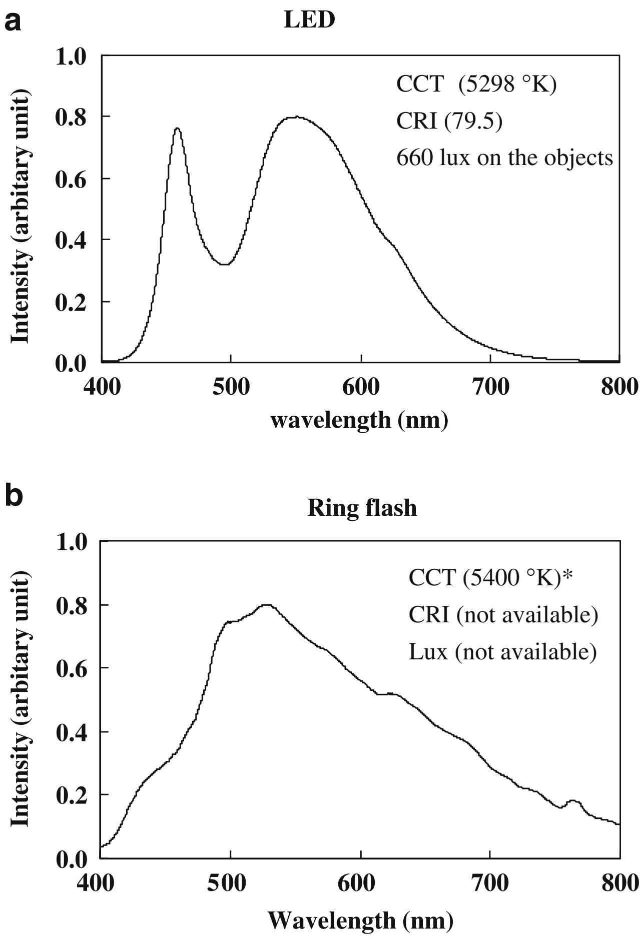

Fig. 1 Spectral radiant power distribution, correlated color temperature (CCT), color render index (CRI), and intensity (lux) of the light sources: **a** LED, **b** ring flash (*The CCT of the ring flash is according to manufacturer's reference)

reliability of the systems, the above procedure was repeated five times, and when starting a new measuring section, the camera was repositioned and the white balance was reset. In total, 15 images were taken of each specimen under each lighting condition by the same operator (Dung).

Validity of digital shade guides

Since the $Lab_{histogram}$ color values obtained directly from the histogram were given on a scale of 0-255 (8 bits), the default color swatches of Photoshop were used as internal standards to characterize and linearize the $Lab_{histogram}$ values into Lab_{adobe} values, and the following equations were derived for data conversion:

$$L_{adobe} = L_{histogram}/2.55 \quad (r^2 = 0.99),$$
$$a_{adobe} = a_{histogram} - 128 \quad (r^2 = 1.00), \text{and}$$
$$b_{adobe} = b_{histogram} - 128 \quad (r^2 = 1.00).$$

The averaged Lab_{adobe} values in the captured images of a set of 15 ceramic disks were served as digital shade guides. To test the validity of the digital shade guide generated in each illuminant/WB setup, a spectrophotometer (CM-508, Konica Minolta Sensing, Osaka, Japan) was used to measure Commission Internationale d'Éclairage $L^*a^*b^*$ color parameters (Lab_{spec}) of each ceramic disk as the gold standards for comparisons.

Applicability of digital shade guides

Ten other operators were asked to match another set of ceramic disks with the help of the digital shade guides in a randomized, blinded trial. Following the same setups, they took images under LED and ring flash lighting conditions, including with both AWB and CWB corrections. The Lab_{adobe} values of each disk image were derived following the same method prescribed, and the proposed shade of each disk was determined, when the least color difference (ΔE) between the test specimen and 15 reference shades in the respective digital shade guide was acquired. Meanwhile, an additional matching test of ceramic disks using a spectrophotometer was undertaken by each operator as well.

The matched ratios of 15 ceramic disks by the digital shade guides and spectrophotometric methods were compared with Kruskal–Wallis and Mann–Whitney tests after Bonferroni corrections (SPSS 10.0, SPSS, Chicago, IL, USA).

Results

The results of measurement variability are summarized in Table 1. The small coefficient of variation of each color

Table 1 The average coefficient of variations (%) of $L^*a^*b^*$ values of 15 ceramic disks measured by digital images with different illuminant/WB setups

Coefficient of Variation (%)	L^*			a^*			b^*		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
LED(CWB)[a]	0.02	0.00	0.04	0.01	0.00	0.02	0.01	0.00	0.02
LED(AWB)[b]	0.06	0.01	0.28	0.11	0.01	0.42	0.10	0.00	0.51
Flash(CWB)	1.42	0.48	2.59	0.20	0.03	0.37	0.15	0.05	0.24
Flash(AWB)	1.28	0.61	1.94	0.21	0.06	0.41	0.12	0.03	0.21

[a] *CWB* custom white balance

[b] *AWB* auto white balance

parameter ($Lab_{histogram}$) in different setups denotes the reproducibility of image analysis for color measurement. In which images taken with electronic flash showed the largest coefficient of variations.

Mean values of the $L^*a^*b^*$ color coordinates of the ceramic disks are plotted in Fig. 2. Lab_{spec} values were used as the gold standards with which the Lab_{adobe} values derived from digital images were compared. The results of the correlation statistics are listed in Table 2. High Spearman correlation coefficient values were found for most comparisons (r^2>0.96, p<0.001), except for the a^* and b^* coordinates measured under the LED with AWB. The b^* coordinate with the LED and AWB showed a moderate correlation (r^2=0.426, p=0.008), while the a^* coordinate with the LED and AWB showed no significant correlation (r^2=0.038, p=0.483) with Lab_{spec} values.

The proposed shades of another set of ceramic disks with the help of the digital shade guides and the spectrophotometer are listed in Table 3. The blind test evaluating the matching ability with different setups revealed that the spectrophotometric method had a greatest mean match of 97% for the ten operators. Image methods using the LED light source with the CWB also showed good matches of 93% (p<0.05). However, images taken with the LED/AWB, flash/CWB, and flash/AWB showed fair matches of 67%, 65%, and 59%, respectively (Table 3).

Discussion

The electronic ring flash units mounted on the digital SLR cameras are commonly used for macro (or close-up) photography in dentistry. The present study revealed that digital images taken with camera in AWB and CWB setups under an electronic ring flash showed fair matching results of 59% and 65%, respectively. The matched ratios are close to those of previous studies [7, 19]. In Jarad et al's study [7], the preset "speed light mode" was chosen for WB setup in the camera and images were taken with an electronic ring flash. They discovered that digital image method showed a 61% correct matches, which was higher than 43% with the conventional visual matching. Schropp [19] selected an AWB mode for the camera and took images with a ring flash. He also experienced a better result with the digital image method compared with the conventional one. However, 59-65% correct matches are considered rather low for practical applications. Although the Lab_{adobe} values of these images showed significantly high correlations to the relative Lab_{spec} values, these parameters might not provide sufficient reliability. Inconsistent flashlight performance and specular reflection in images could be the inherent causes for the unsteady Lab_{adobe} values with the electronic ring flash. In which, the L^* parameter, the major domain in color difference (ΔE), exhibited the highest varieties among measurements (Table 1).

On the other hand, the LED provides the WYSIWYG scene and thus decreases the risk of specular reflection. The reliability of imaging with LED was promising. The average coefficient of variations of $L^*a^*b^*$ values were <0.11%. However, the correlations of respective Lab_{adobe} values of images captured by the camera with the AWB setup did not adequately parallel those measured by the spectrophotometer (Fig. 2). The fairly low correlation coefficients for the a^* and b^* coordinates in LED with AWB could be due to ineffective white balance adjustment and worsened by the low luminance of the LED (660 lux on the objects) used in the present study, which may have generated an inferior signal/noise ratio (SNR) for the installed CCD sensor (Fig. 2). It is believed that digital noise usually occurs when taking low-light photos, in which the amount of light measured by each pixel of the CCD is low and sometimes even close to the level of noise naturally found in the CCD [20]. The rather low intensities of the red (640 nm) and green (525 nm) components in the LED spiky spectrum (Fig. 1) could also explain the reason why the a^* coordinate (red-green) of the LED with the AWB setup had the poorest correlation coefficient (r^2= 0.038, p=0.483). Consequently the accuracy of color matching with LED/AWB was incompetent (Table 3).

Changing the AWB to CWB in the camera effectively resolved the problems from the spiky waves of the LED light sources. The Lab_{adobe} values of the captured images in LED/CWB setup showed significant correlations (r^2>0.96, p<0.001) to the respective Lab_{spec} values and thus lead to significant improvement in color matching to 93% (Table 3). Moreover, some unmatched pairs had a color difference (ΔE) <1 (data not shown). One can assume that the difference might be mathematically significant but not clinically relevant; hence, digital shade guides built with LED/CWB setup are applicable in the clinic. In addition, further studies might be of interest in increasing the light intensity of LED to improve the SNR of the camera, which theoretically shall enhance color matching ability with digital images. Furthermore, the recently marketed LED ring flashes also merit further exploration.

Northern daylight around the noon hour on a bright day was considered the ideal conditions for color matching. But it cannot always be achieved in daily practice. Instead, studio environments equipped with standard color-corrected lighting are recommended in both visual and instrument shade selections. However, the extra investments in room space and facilities sometimes are impossible. The preliminary results of this study indicate that digital images taken with camera and LED ring flash provide potential for color matching, if the white balance (WB) of the camera is properly adjusted. Besides the CWB performed by calibra-

Fig. 2 Scatterplots of $L^*a^*b^*$ values of 15 ceramic disks measured by digital images with different setups and a spectrophotometer (CM-508). *AWB* automatic white balance, *CWB* custom white balance

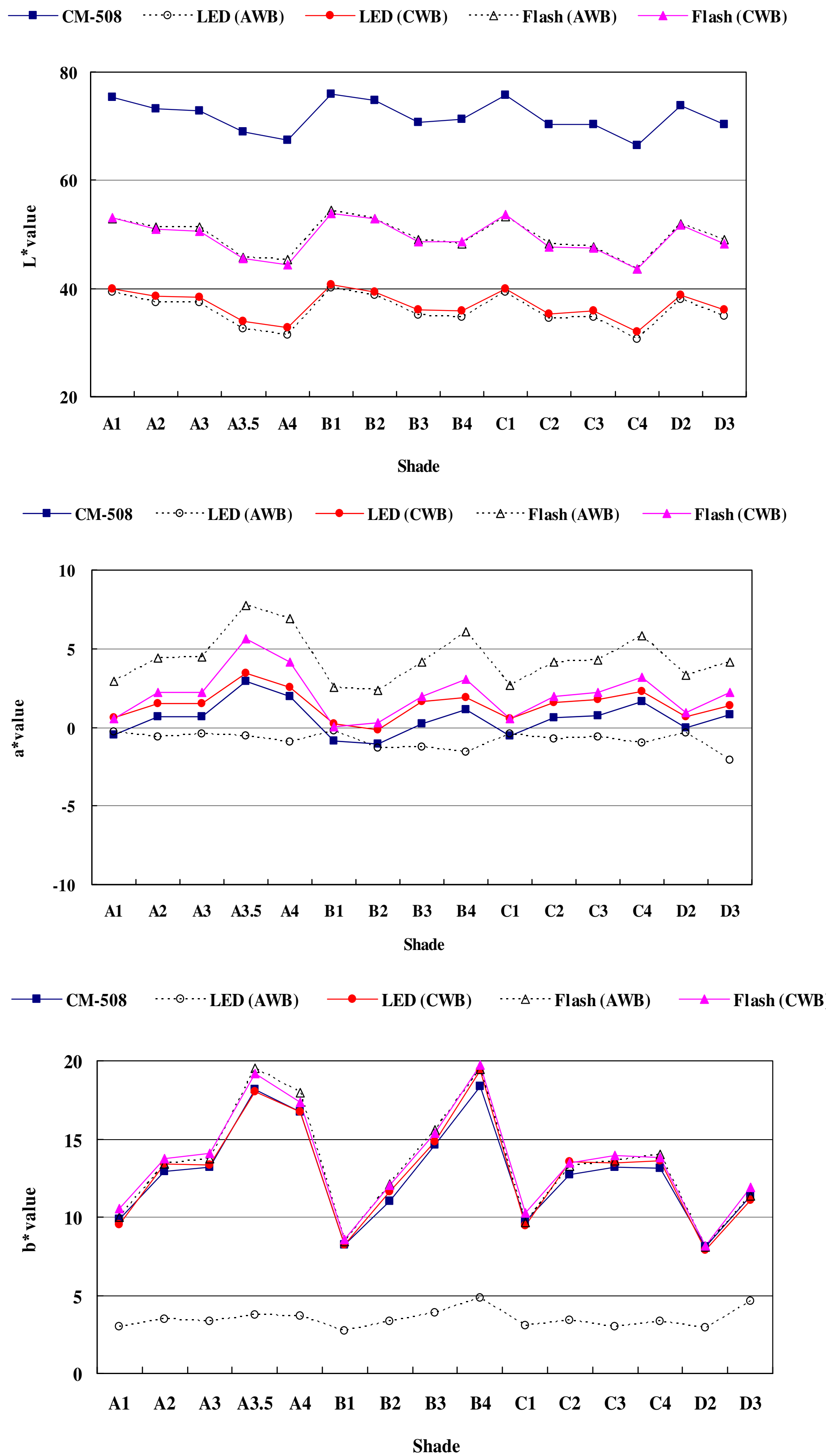

Table 2 Determination coefficients (r^2) of $L^*a^*b^*$ values of 15 ceramic disks measured by digital images with different illuminant/WB setups and a spectrophotometer (CM-508)

	L^*		a^*		b^*	
	r^2	P	r^2	P	r^2	P
CM-508	1.000		1.000		1.000	
LED (CWB)[a]	0.984	0.000	0.964	0.000	0.986	0.000
LED (AWB)[b]	0.990	0.000	0.038	0.483[c]	0.426	0.008
Flash (CWB)	0.992	0.000	0.972	0.000	0.996	0.000
Flash (AWB)	0.974	0.000	0.949	0.000	0.994	0.000

[a] CWB custom white balance

[b] *AWB* auto white balance

[c] All determination coefficients (r^2) were significant at the level of 0.01 except for the a^* parameter of LED (AWB) group

tion with a white standard before the sample images were taken in this study [21], manual WB can also be done by choosing the preset WB protocols installed in the camera [7, 8], in which custom adjustment for the particular light sources are well established by the camera company. In addition, one can include neutral white (or gray) objects in the images as the gold standards for comparison [13], or directly adjust WB of images in raw formats in the computer afterwards [22]. Until the preset WB protocols for the certain LED light sources are preinstalled in the digital cameras, CWB performed in this study can be an efficient method to provide Lab_{adobe} parameters for color matching.

Adobe Photoshop software is a popular and powerful graphics editing program, which can be used to view and measure the color of the captured images in different modes, including Bitmap, RGB, XYZ, $L^*a^*b^*$, etc. In this study, Photoshop's $L^*a^*b^*$ color mode was selected as the standard color space for calculating color differences (ΔE)

Table 3 The proposed shades of each ceramic disk determined with the help of the spectrophotometric and digital shade guides; and the mean matched ratios of 15 ceramic disks detected by ten operators

ceramic shade	Proposed shades by digital shade guides				
	CM-508	LED(AWB)	LED(CWB)	Flash(AWB)	Flash(CWB)
A1	A1(8), C1(2)	A1(4), B1(1), B2(1), C1(4)	A1(6), C1(4)	A1(3), B1(1), B2(1), C1(5)	A1(5), B1(2), B2(1), C1(1), D2(1)
A2	A2(10)	A2(6), A3(4)	A2(9), A3(1)	A2(6), A3(3), D3(1)	A2(0), A3(7), D3(3)
A3	A3(7), A2(3)	A3(5), A2(5)	A3(10)	A3(2), A2(5), A3,5(1), C3(1), B3(1)	A3(9), B3(1)
A3.5	A3.5(10)	A3.5(8), A3(1), A4(1)	A3.5(10)	A3.5(10)	A3.5(10)
A4	A4(10)	A4(9), C4(1)	A4(10)	A4(7), A3.5(3)	A4(6), A3.5(4)
B1	B1(10)	B1(3), A1(4), B2(1), C1(2)	B1(10)	B1(6), A1(2), C1(2)	B1(4), A1(3), C1(1), D2(2)
B2	B2(10)	B2(10)	B2(10)	B2(6), A2(4)	B2(9), C1(1)
B3	B3(10)	B3(5), B4(2), C3(1), D3(2)	B3(10)	B3(6), B4(4)	B3(5), B4(4), C2(1)
B4	B4(10)	B4(9), B3(1)	B4(10)	B4(9), A4(1)	B4(10)
C1	C1(10)	C1(4), A1(2), B1(1), B2(3)	C1(8), A1(2)	C1(4), A1(4), B2(1), D2(1)	C1(8), A1(1), A3(1)
C2	C2(10)	C2(6), A3.5(1), B3(1), C3(2)	C2(8), C3(2)	C2(6), B3(4)	C2(5), B3(3), C3(1), D3(1)
C3	C3(10)	C3(6), B3(1), C2(2), D3(1)	C3(8), C2(2)	C3(4), B3(3), C2(3)	C3(5), B3(3), C2(1), D3(1)
C4	C4(10)	C4(10)	C4(10)	C4(7), A4(3)	C4(9), A4(1)
D2	D2(10)	D2(9), C1(1)	D2(10)	D2(7), A1(1), B1(1), C1(1)	D2(7), B2(1), C1(2)
D3	D3(10)	D3(6), C3(4)	D3(10)	D3(5), A3(1), C2(1), C3(3)	D3(6), A3(1), C3(3)
Unmatched pairs	5	50	11	62	52
Matched pairs	145	100	139	88	98
Matched ratio*	97%[a]	67%[b]	93%[a]	59%[b]	65%[b]

*Groups with different superscript letters significantly differ at $p<0.05$

because it is more perceptually uniform and has excellent applicability for device-independent manipulations of continuous tone images. Moreover, Lab_{adobe} values in separate lightness and chroma channels can easily be derived from Adobe Photoshop software. Once the regions of interest in the images are selected by the marquee tools, the $L^*a^*b^*$ coordinates between 0 and 255 (8 bits) can easily be read in the histogram windows. Several studies also adopted $Lab_{histogram}$ for color analyses; however, they did not provide efficient methods to convert $Lab_{histogram}$ to Lab_{adobe} values [7, 21, 23, 24]. Using default swatches within the software for calibration, the simple formulas for the color space conversion between $Lab_{histogram}$ and Lab_{adobe} were confirmed, which can provide useful tools for further studies using this software.

Although using digital shade guides for color matching takes more time compared with the use of colorimeter, the digital images provide more tooth information in addition to color. In the future, adopting macro functions of open source software for image analysis (e.g., ImageJ from National Institutes of Health, USA) shall not only expedite the color matching with digital shade guides, but also reduce the cost of Adobe Photoshop software.

The concept of digital shade guides proposed in this study can be applied in dental clinics. However, the reliability of digital images of tooth captured in vivo should be verified before those digital shade guides built with the same LED/CWB setup can be applicable. Moreover, due to the inconsistence of the commercial shade guides [6, 19], customized ceramic specimens (custom shade guides) fabricated in affiliated laboratories are suggested to serve as internal standards for each digital shade guide. In addition, different technologies utilized by different digital cameras produce different RGB and $L^*a^*b^*$ values when recording the same image, even under exactly the same conditions [22]. Therefore, the algorithm function of the CWB in different digital cameras should be calibrated before the digital shade guides can be clinically applied. Moreover, future clinical studies are needed to verify the use of digital shade guides and LED for shade matching to natural teeth in the clinical situation [25].

Conclusion

Within the limitations of the present study, the reliability of color matching with digital images is much influenced by the illuminants and camera's white balance setups, digital images captured by a digital SLR camera with CWB setup showed promising correlations to the respective measurements by a spectrophotometer, and the digital shade guides derived under LED illuminants with CWB demonstrate applicable potential in the fields of color assessments.

Acknowledgments This work was supported in part by grant V96C1-045 from Taipei Veterans General Hospital, Taipei, Taiwan.

Conflict of interest The authors declare that they have no conflict of interest.

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