

Perceived color shift of ceramics according to the change of illuminating light with spectroradiometer

Hyun-Suk Cha¹, DDS, PhD, Bin Yu², PhD, Yong-Keun Lee^{3*}, DDS, PhD

¹Department of Dentistry, College of Medicine, University of Ulsan, Asan Medical Center, Seoul, Republic of Korea

²State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing, China

³Institute for Clinical Performance of Biomaterials (ICPB), Seoul, Republic of Korea

PURPOSE. Perceived color of ceramics changes by the spectral power distribution of ambient light. This study aimed to quantify the amount of shifts in color and color coordinates of clinically simulated seven all-ceramics due to the switch of three ambient light sources using a human vision simulating spectroradiometer. **MATERIALS AND METHODS.** CIE color coordinates, such as L^* , a^* and b^* , of ceramic specimens were measured under three light sources, which simulate the CIE standard illuminant D65 (daylight), A (incandescent lamp), and F9 (fluorescent lamp). Shifts in color and color coordinate by the switch of lights were determined. Influence of the switched light (D65 to A, or D65 to F9), shade of veneer ceramics (A2 or A3), and brand of ceramics on the shifts was analyzed by a three-way ANOVA. **RESULTS.** Shifts in color and color coordinates were influenced by three factors ($P < .05$). Color shifts by the switch to A were in the range of 5.9 to 7.7 ΔE^*_{ab} units, and those by the switch to F9 were 7.7 to 10.2; all of which were unacceptable ($\Delta E^*_{ab} > 5.5$). When switched to A, CIE a^* increased (Δa^* : 5.6 to 7.6), however, CIE b^* increased (Δb^* : 4.9 to 7.8) when switched to F9. **CONCLUSION.** Clinically simulated ceramics demonstrated clinically unacceptable color shifts according to the switches in ambient lights based on spectroradiometric readings. Therefore, shade matching and compatibility evaluation should be performed considering ambient lighting conditions and should be done under most relevant lighting condition.

[J Adv Prosthodont 2013;5:262-9]

KEY WORDS: Color shift; Ceramic materials; Illuminating light; Spectroradiometer

INTRODUCTION

Fabrication of a natural looking restoration is one of the challenges in esthetic dentistry because shade matching with natural teeth is a difficult task due to the complicated optical properties of teeth.¹ An esthetic restoration should

reproduce morphologic, optical, and biologic characteristics of teeth under varied clinical conditions. Switches of ambient light sources and condition cause perceived color shifts of restorations and shade guides.^{2,3}

All-ceramic restorations can be made to match natural teeth in terms of color, surface texture, and translucency⁴; therefore, they address the demand for esthetic restorations.^{5,6} Optical properties of zirconia have introduced new opportunities for achieving superior esthetics.¹ Based on a clinical evaluation of shade matching maintenance of an all-ceramic system, 97 to 100% of restorations were rated alfa.⁷ However, one of the clinical problems for all-ceramics is that the allowed thickness for a restoration is limited, which is generally regarded as 1.5 mm.⁴

Shade matching is one of the most pivotal esthetic tasks. Although shade matching is usually performed by visual methods, instrumental color taking enhances the validity of visual shade matching.^{8,9} Shade matching perfor-

Corresponding author:

Yong-Keun Lee
Institute for Clinical Performance of Biomaterials (ICPB)
106-B101, 27 Heukseokhangang-ro, Dongjak-gu, Seoul, 156-070,
Republic of Korea
Tel. 8228161616; e-mail, yklee@icpb.com
Received February 28, 2012 / Last Revision April 26, 2013 / Accepted
May 1, 2013

© 2013 The Korean Academy of Prosthodontics
This is an Open Access article distributed under the terms of the Creative
Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0>) which permits unrestricted non-commercial use,
distribution, and reproduction in any medium, provided the original
work is properly cited.

mance has been improved through the development of new shade guides and electronic color taking devices for dentistry.¹ Electronic color taking devices showed excellent repeatability,¹⁰ and the use of spectrophotometer (SP) allowed accurate color evaluation of teeth and restorations.¹¹ However, color parameters measured by instruments vary by the measurement protocols.¹²

Perceived color of an object is decided by reflected and transmitted visible light, and an object can only reflect and transmit the spectrum of light that shines on it. Since lightings show varied source-dependent spectral power distributions (SPDs), shade matching performance is highly influenced by the light sources.¹³ Therefore, the impact of illuminating lights on the color of dental substances is a significant clinical concern.³ Metameric colors are the color stimuli of identical tristimulus values calculated based on the reflectance values under a particular light source, but have different spectral reflectance values,¹⁴ and metamerism is probably the largest single cause of industrial shade matching problems.¹⁵ Since the SPDs of popular ambient light sources such as incandescent lamp, fluorescent lamp, and daylight differ, color of dental substances showed changes according to the illuminants used in SP or real light sources.^{3,16-18}

It has been confirmed that the instrumental color values of teeth, restoratives, and shade guides vary by standard illuminant used in SP.¹⁹⁻²⁴ It was also reported that color shift of all-ceramics by the switch of illuminants in SP was clinically perceptible.¹⁸ Perceptible color differences were observed in shade guide tabs due to the switch of illuminants in SP.^{8,23,24} As to the observer factor, shade matching performance was affected by the color temperature of illuminated lights; lower color temperature light decreased correct shade matching.²⁵ Therefore, careful control of lighting conditions is essential to achieve an optically pleasing restoration.²⁶

Although the daylight is regarded as an ideal light source, it cannot be easily standardized because of its variability by weather, time of the day, and season of the year. Therefore, the Commission Internationale de l'Éclairage (1) mathematically defined ambient lights. CIE standard illuminant D65 is defined to represent a phase of the daylight with a color temperature of 6,500°K, illuminant A is defined to represent an incandescent light (2,856°K), and illuminant F9 is defined to represent a fluorescent lamp light (4,150°K).²⁷

If teeth and restorations are opaque, influences of the type of instrument, illuminating and measuring configuration, and the kind of illuminant or light source on the color determination should have been limited.²⁸ However, color taking of translucent substances by SP results in deviated color values compared with the real color perceived by naked eyes.²⁹ These deviations are mainly caused by edge-loss effect due to small measurement aperture of SP,^{12,30} thickness of translucent layer, and background conditions.³¹ These distortions in color values measured by SP would decrease when color is taken by a spectroradiometer (SR).

SR does not show edge-loss effect, and the illuminating configuration is similar to that of ambient lighting condition; therefore, simulation of human color vision in this kind of instrument is higher than that in conventionally used SP. Light source-dependent color shifts of a shade guide were determined by SR.³ However, properties of light sources used in SR should be further specified,³²⁻³⁴ because the CIE illuminants are mathematically defined,²⁷ whereas the SPDs of real light sources vary by the type, brand, and configuration of the source.

Visual thresholds for color differences are applied to correlate the instrumental color values with the clinical evaluation. Although the threshold for acceptability was reported to be 3.5 color difference (ΔE^*_{ab}) units and that for perceptibility was 1.8 ΔE^*_{ab} units based SP readings,³⁵ 2.6 ΔE^*_{ab} units was considered the clinically perceptible, while 5.5 ΔE^*_{ab} units was considered the clinically acceptable threshold based on SR readings.³⁶ Human color vision is categorized into colorimetry, sensation, perception, and visualization.³⁷ Since the instrumental color taking is in the colorimetry domain and the perceptible/acceptable thresholds are in the perception domain, correlating two domains needs careful interpretation.

Although there have been reports on the influence of illuminants on the SP-based color shifts of dental substances,^{16-18, 38-40} limitations in SP color taking might have distorted the experimental results of those studies. Moreover, the illuminating configuration in the SP instrument is different from that in clinical condition. Therefore, the purpose of this study was to determine the influence of the switch of real light sources, simulating the CIE standard illuminants D65, A, and F9, on the SR-based color shift of clinically simulated ceramics. The null hypothesis assumed was that the shifts in color and three color coordinates (CIE L^* , a^* , and b^*) would not be influenced by the switched light, shade of veneer ceramics, and brand of ceramics.

MATERIALS AND METHODS

Specimens of seven core ceramics were fabricated, 11 mm in diameter, following the manufacturers' instructions. VITA Lumin A2 shade (VITA Zahnfabrik, Bad Säckingen, Germany) was selected. Thickness of the specimens was controlled with a polishing machine (AM Technology, Asan, Chungnam, Korea) to the manufacturers' recommended thickness required to mask a discolored abutment (Table 1). A sintering ceramic (VITA VM 7; VITA Zahnfabrik) was used as a reference core material.

Veneer ceramics were prepared for each core material (Table 1 and Table 2), with the final thickness of layered specimen of 1.5 mm.⁴ Two shades corresponding to A2 and A3 shades (VITA Zahnfabrik) were selected. Thus, layered specimens were divided into A2- and A3-veneered groups. Seven specimens were made for each brand of the core and veneer ceramics. The number of specimens was determined based on previous color studies, in which generally five specimens were investigated.⁴¹⁻⁴³ Detailed specimen

Table 1. Ceramic materials investigated

Group and Type	Code	Brand (Shade)	Batch number	Thickness (mm)	Manufacturer		
Slip-cast block	ICS	In-Ceram Spinell Blanks	7951	0.5	VITA Zahnfabrik, Bad Säckingen, Germany		
	ICA	In-Ceram Alumina Blanks	7502				
Core Zirconia block	AZC	AdensZi-Ceram	122005	0.4	ADENS, Seoul, Korea Digident GmbH, Pforzheim, Germany		
	DIZ	Digizon HIP	22				
	VIZ	VITA 2000 YZ Cubes	7412				
	VITA 2000 YZ Cubes	7412					
Feldspathic block	MK2	Vitablocs	7920	0.7	VITA Zahnfabrik		
Heat pressed	EM2	IPS Empress 2	H22609	0.8	IvoclarVivadent AG, Schaan, Liechtenstein		
Sintering (reference)	VM 7	VITA VM 7	7550	0.5	VITA Zahnfabrik		
	V7-2	VITA VM 7 (2M2)	7550	1.0			
	V7-3	VITA VM 7 (2M3)	7360				
	V91-2	VITA VM 9 (2M2)	7480	0.8			
	V91-3	VITA VM 9 (2M3)	7605				
	V92-2	VITA VM 9 (2M2)	7480	1.1			
	V92-3	VITA VM 9 (2M3)	7605				
	Veneer	ER-2	IPS ERIS (120)	H13505		0.7	IvoclarVivadent AG
		ER-3	IPS ERIS (210)	H03466			
		OM-2	Omega 900 (2M2)	7910		1.0	
OM-3		Omega 900 (2M3)	7967				

Table 2. Combinations of core and veneer ceramics to make clinically relevant thickness-based specimens

Code for layered specimens		Code for core and veneer	
A2 veneer	A3 veneer	Core	Veneer (A2/A3)
ICS2	ICS3	ICS	V7-2, V7-3 (2M2/2M3)
ICA2	ICA3	ICA	V7-2, V7-3
AZC2	AZC3	AZC	V92-2, V92-3 (2M2/2M3)
DIZ2	DIZ3	DIZ	V92-2, V92-3
VIZ2	VIZ3	VIZ	V92-2, V92-3
MK22	MK23	MK2	V91-2, V91-3 (2M2/2M3)
EM22	EM23	EM2	ER-2, ER-3 (120/210)
VM72	VM73	VM7	V7-2, V7-3 (2M2/2M3)

preparation procedures have been reported previously.³¹

When the color of layered specimens was measured (Table 2), corresponding veneer specimen was laid over a core specimen. In this layering procedure, one veneer specimen for each material, representing the mean color value of seven specimens, was used. When layering, a drop of optical fluid (refraction fluid, 1.5 index; Cargille Lab, Cedar Grove, NJ, USA) was applied between the veneer and core specimens for an optical connection.³¹

Color of the layered specimens were taken according to the CIE $L^*a^*b^*$ color scale over a white tile (CIE $L^* =$

94.4, $a^* = -0.1$, and $b^* = 0.6$) under each of three light sources. A spectroradiometer (PR-670 SpectraScan; Photo Research, Chatsworth, CA, USA), equipped with a lens (MS-75 MacroSpectar Lens; Photo Research), was fixed vertically over the upper part of a light-tight box (Color Sense II; Sungjin Hitech, Gunpo, Kyunggi-do, Korea) with a vertical distance of 355 mm from the specimen.³ A measurement spot size of 5.25 mm in diameter was selected by setting the automated aperture opening to 1 degree, which was prescribed by the manufacture. Two lamps that simulate the illuminant D65 (GretagMacbeth F20T12/65 6500

K lamp; X-Rite, Grand Rapids, MI, USA), one lamp that simulates the illuminant A (JD 100W/M2; Iwasaki Electric, Tokyo, Japan), and one lamp that simulates the illuminant F9 (F20T12/CW; Osram, Sylvania, Mississauga, Ontario, Canada) were installed on the inner top surface of the light-tight box by the manufacturer to illuminate the inside of the light-tight box with a similar light intensity regardless of the light source.³

Spectral reflectance values were obtained from 380 to 780 nm with 2 nm intervals (Spectrawin 2.0; Photo Research), which were converted to the CIE L^* , a^* , and b^* values. Chroma was calculated as $C_{ab}^* = (a^{*2} + b^{*2})^{1/2}$, and color shift was calculated as $\Delta E_{ab}^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$.²⁷

Vectorial shifts of lightness and chroma, and those of CIE a^* and b^* from the values under D65 simulator to those under A, or F9 simulators were determined. Amounts of shifts in color, lightness (CIE L^*), CIE a^* and b^* , and also chroma, by the switch of lights were calculated. Influence of the kind of switched light (A or F9), shade of veneer ceramics (A2 or A3), and brand of core ceramics (n=8) on the shifts in color and color coordinates was evaluated with a three-way analysis of variance (ANOVA, $\alpha=.05$). Brand was used as a factor instead of type of ceramics because ceramics in the same type could not be regarded as acting the same pattern by the switch of lights.

RESULTS

Amounts of shifts by the switch of lights are listed in Table 3 and Table 4. The range of shifts in color by the switch from D65 to A was 5.9 to 7.7 (mean \pm standard deviation: 6.7 ± 0.6), that of lightness (the value under A simulator minus that under D65) was -1.3 to 1.6 (0.1 ± 0.8), that of CIE a^* was 5.6 to 7.6 (6.5 ± 0.6), that of CIE b^* was -0.1 to 1.3 (0.7 ± 0.4), and that of chroma was 1.1 to 2.6 (1.9 ± 0.4). The range of shifts in color by the switch to F9 was 7.7 to 10.2 (9.2 ± 0.8), that of lightness was 5.9 to 7.0 (6.4 ± 0.4), that of CIE a^* was -0.9 to 0.1 (-0.4 ± 0.2), that of CIE b^* was 4.9 to 7.8 (6.5 ± 0.9), and that of chroma was 4.9 to 7.7 (6.5 ± 0.9).

Vectorial shifts of lightness and chroma are presented in Fig. 1 and Fig. 2. In Fig. 1 to Fig. 4, 2M2 (A2) and 2M3 (A3) indicate the corresponding shifts of Vitapan 3D-Master shade guide (VITA Zahnfabrik) tabs under the same light switching conditions reported in a previous study.³ The ranges of lightness and chroma for the A2-veneered ceramics under D65 were 81.4 to 83.4 and 18.2 to 24.0, respectively, which shifted to 81.8 to 84.6 and 19.7 to 25.5 under A, and to 87.4 to 89.9 and 23.4 to 30.4 under F9. Those for the A3-veneered ceramics showed similar shifts.

Vectorial shifts of CIE a^* and b^* are presented in Fig. 3 and Fig. 4. The ranges of CIE a^* and b^* for the A2-veneered

Table 3. Amount of shifts in color and color parameters of A2-veneered ceramics by switch of lights (D65 to A, D65 to F9)

Code	Light Shift ^a	ΔE_{ab}^*	ΔL^*	Δa^*	Δb^*	ΔC_{ab}^*
ICS2	A-D65	5.9 (0.2)	1.1 (0.7)	5.7 (0.2)	0.5 (0.7)	1.5 (0.7)
	F9-D65	7.7 (1.0)	5.9 (0.8)	0.1 (0.2)	4.9 (0.8)	4.9 (0.8)
ICA2	A-D65	5.9 (0.2)	1.6 (0.8)	5.6 (0.1)	-0.1 (0.4)	1.1 (0.4)
	F9-D65	8.0 (0.4)	5.9 (0.4)	-0.5 (0.1)	5.4 (0.4)	5.3 (0.4)
AZC2	A-D65	6.0 (0.1)	0.2 (1.2)	5.8 (0.1)	0.7 (0.4)	1.9 (0.4)
	F9-D65	8.3 (0.6)	6.4 (0.7)	-0.5 (0.1)	5.3 (0.2)	5.3 (0.2)
DIZ2	A-D65	6.0 (0.2)	0.4 (0.4)	5.9 (0.2)	1.0 (0.5)	2.2 (0.6)
	F9-D65	8.5 (0.6)	6.3 (0.6)	-0.6 (0.1)	5.7 (0.4)	5.7 (0.4)
VIZ2	A-D65	6.1 (0.2)	0.2 (0.6)	5.9 (0.2)	1.3 (0.4)	2.6 (0.4)
	F9-D65	9.0 (0.7)	6.5 (0.7)	-0.9 (0.1)	6.1 (0.3)	6.1 (0.3)
MK22	A-D65	5.9 (0.2)	0.2 (0.6)	5.8 (0.1)	0.8 (0.5)	1.8 (0.5)
	F9-D65	9.3 (0.4)	6.8 (0.4)	-0.7 (0.0)	6.3 (0.2)	6.3 (0.2)
EM22	A-D65	6.6 (0.3)	0.6 (0.5)	6.5 (0.3)	0.4 (0.5)	1.5 (0.5)
	F9-D65	8.7 (0.3)	6.0 (0.3)	-0.3 (0.1)	6.4 (0.3)	6.3 (0.3)
VM72	A-D65	6.9 (0.2)	1.0 (0.6)	6.6 (0.1)	1.3 (0.5)	2.5 (0.5)
	F9-D65	9.9 (1.0)	6.9 (0.6)	-0.5 (0.1)	7.1 (1.0)	7.0 (1.0)

^a Values were calculated by subtracting the values under D65 from those under A or F2.

^b Standard deviations are in parentheses.

Table 4. Amount of shifts in color and color parameters of A3-veneered ceramics by switch of lights (D65 to A, D65 to F9)

Code	Light Shift ^a	ΔE^*_{ab}	ΔL^*	Δa^*	Δb^*	ΔC^*_{ab}
ICS2	A-D65	6.9 (0.1)	-0.5 (0.4)	6.9 (0.1)	0.6 (0.5)	1.6 (0.5)
	F9-D65	9.7 (0.4)	6.4 (0.3)	-0.2 (0.0)	7.2 (0.3)	7.2 (0.3)
ICA2	A-D65	7.2 (0.1)	-0.5 (0.4)	7.1 (0.1)	1.0 (0.4)	2.3 (0.5)
	F9-D65	9.5 (0.5)	5.9 (0.5)	-0.5 (0.1)	7.4 (0.4)	7.4 (0.4)
AZC2	A-D65	7.1 (0.3)	0.1 (1.0)	7.0 (0.2)	0.9 (0.8)	2.1 (0.8)
	F9-D65	9.7 (1.2)	6.7 (1.1)	-0.5 (0.1)	6.9 (0.6)	6.9 (0.6)
DIZ2	A-D65	7.1 (0.2)	0.3 (1.2)	7.0 (0.2)	0.8 (0.4)	2.1 (0.5)
	F9-D65	10.0 (1.2)	6.9 (1.1)	-0.5 (0.1)	7.2 (0.6)	7.2 (0.6)
VIZ2	A-D65	7.2 (0.2)	-0.3 (1.5)	7.0 (0.1)	0.9 (0.5)	2.3 (0.5)
	F9-D65	10.0 (1.2)	7.0 (1.1)	-0.6 (0.1)	7.2 (0.7)	7.1 (0.7)
MK22	A-D65	6.8 (0.1)	0.1 (0.4)	6.8 (0.1)	0.7 (0.2)	1.8 (0.2)
	F9-D65	10.1 (0.3)	6.8 (0.4)	-0.4 (0.1)	7.5 (0.2)	7.4 (0.2)
EM22	A-D65	7.1 (0.2)	-1.3 (0.4)	7.0 (0.2)	0.1 (0.4)	1.2 (0.4)
	F9-D65	8.6 (0.5)	5.9 (0.5)	-0.1 (0.1)	6.4 (0.3)	6.4 (0.3)
VM72	A-D65	7.7 (0.1)	-1.1 (0.5)	7.6 (0.1)	0.9 (0.4)	2.2 (0.4)
	F9-D65	10.2 (0.4)	6.6 (0.5)	-0.3 (0.1)	7.8 (0.4)	7.7 (0.4)

^a Values were calculated by subtracting the values under D65 from those under A or F2.

^b Standard deviations are in parentheses.

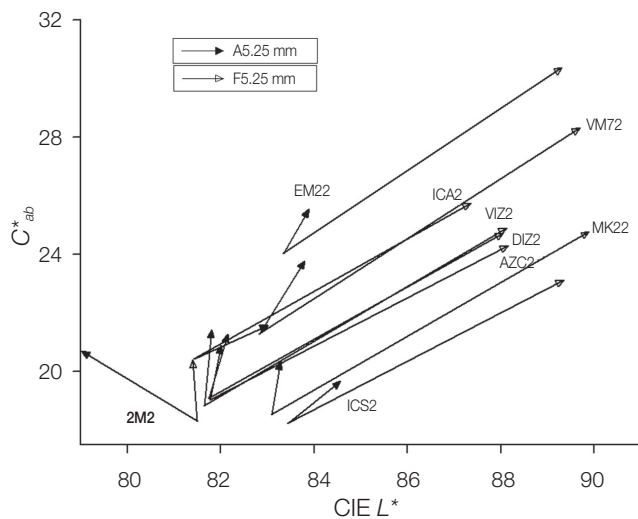


Fig. 1. Vectorial shifts of lightness (CIE L^*) and chroma for A2-veneered ceramics by switch of lights.

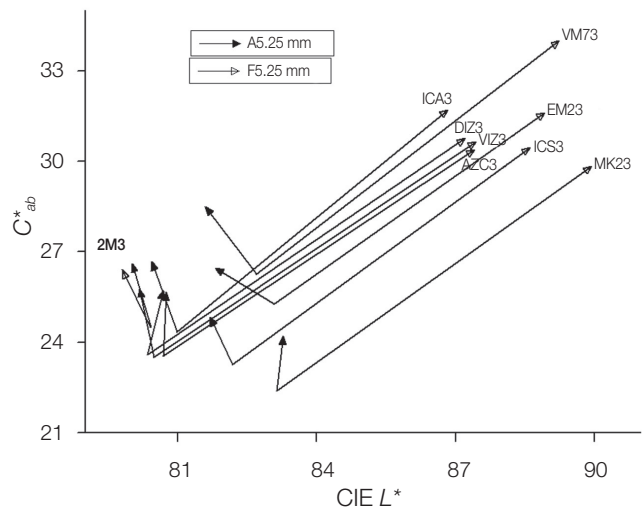


Fig. 2. Vectorial shifts of lightness (CIE L^*) and chroma for A3-veneered ceramics by switch of lights.

ceramics under D65 were 0.3 to 1.7 and 18.2 to 24.0, respectively, which shifted to 5.9 to 7.7 and 18.8 to 24.4 under A, and to -0.1 to 1.2 and 23.1 to 30.4 under F9. Those for the A3-veneered ceramics were showed similar shifts.

Based on a three-way ANOVA, the shifts in color and three color coordinates were influenced by the kind of switched light, shade of veneer, and brand of ceramics ($P < .05$).

DISCUSSION

The null hypothesis of the present study was rejected because all the color values were influenced by three factors. Regarding the shifts of color coordinates by the switch of lights, CIE L^* values under F9 were higher than those under D65 (Fig. 1 and Fig. 2), which might be caused by the difference in the light intensities of two simulators. However, it was confirmed that all the three simulators irra-

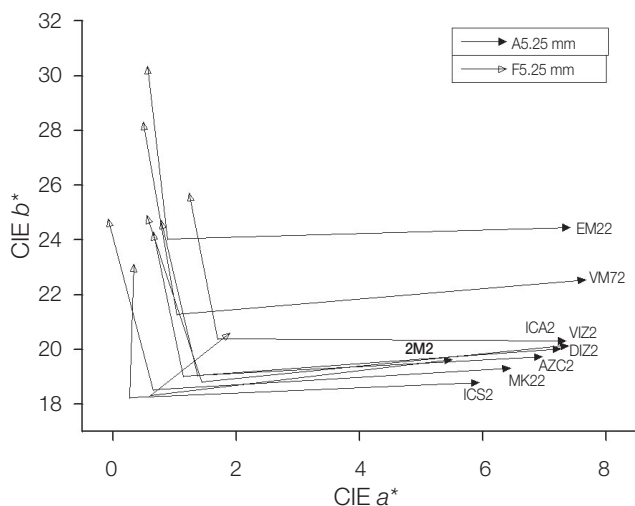


Fig. 3. Vectorial shifts of CIE a^* and b^* values for A2-veneered ceramics by switch of lights.

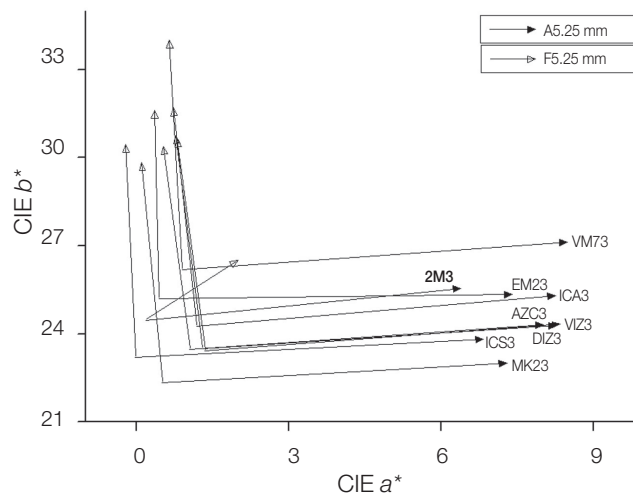


Fig. 4. Vectorial shifts of CIE a^* and b^* for A3-veneered ceramics by switch of lights.

diated similar light intensities.³ Therefore, these shifts seem to reflect the light-switch induced lightness changes, which might be partially caused by fluorescent emission or other optical phenomena. As to the shifts in CIE a^* and b^* (Fig. 3 and Fig. 4), these shifts clearly reflected the SPDs of the switched lights. Fluorescent light tends to accentuate blue color, whereas incandescent light accentuates yellow-red range.¹³ In the present study, when light was switched from D65 to A, red and yellow hue increased (Fig. 3 and Fig. 4). When switched from D65 to F9, yellow hue and small amount of green hue increased (increased CIE b^* and decreased a^*).

With dental ceramics, acceptability thresholds in color parameters were determined.³⁵ As results, the acceptability threshold was $\Delta L' = 2.4$, $\Delta C' = 3.2$, and $\Delta H' = 3.2$. These parameters are used in the CIEDE 2000 color difference formula,⁴⁴ and indicate the differences in the CIE $L^*a^*b^*$ lightness, chroma, and hue. Therefore, the thresholds for $\Delta L'$ and $\Delta C'$ were compared with lightness and chroma shifts of the present study. Lightness shifts by the switch from D65 to A (range: -1.3 to 1.6) were in the acceptable range ($\Delta L' < 2.4$), while those from D65 to F9 (5.9 to 7.0) were not acceptable (Table 3 and Table 4). Chroma shifts by the switch from D65 to A (1.1 to 2.6) were in the acceptable range, while those from D65 to F9 (4.9 to 7.7) were not acceptable. Therefore, the shifts in color, lightness, and chroma by the switch to F9 could be regarded as visually higher compared with those by the switch to A. As to the threshold ΔE^*_{ab} values, the thresholds based on SR readings³⁶ were referenced in the present study. Although experimental methods were not the same, when the visually acceptable threshold ($\Delta E^*_{ab} < 5.5$) are applied, color shifts in all specimens by both A and F9 switches were unacceptable ($\Delta E^*_{ab} = 5.9$ to 7.7, and 7.7 to 10.2, respectively).

Influence of illuminant-dependent color shifts of shade guide tabs based on SP readings was determined, and the color differences between the values relative to the illuminants A and D65 were in the range of 0.9 to 2.7 ΔE^*_{ab} units.²⁰ In the present study with ceramics, the corresponding values were in the range of 5.9 to 7.7 (Table 3 and Table 4), which were higher than those of the shade guide tabs. The shifts in color, lightness, and chroma of simulated all-ceramic specimens relative to three standard illuminants of SP were compared.¹⁸ As results, the range of color shifts was in the range of 1.5 to 3.6 ΔE^*_{ab} units by the switch from D65 to A and that from D65 to F2 switch was 1.3 to 3.0. Lightness shifts (ΔL^*) were 0.6 to 1.2 by A switch and 0.5 to 0.9 by F2 switch. Chroma shifts (ΔC^*_{ab}) were 0.5 to 1.4 by A switch and 1.2 to 2.3 by F2 switch. Comparing with the results of the present study, the amounts of SP-based shifts were smaller than those measured by SR in the present study. Plausible causes for these discrepancies might be in the differences 1) of the measurement geometries of SP and SR, 2) in the illuminants and real light sources although the SPDs of the F2 and F9 simulators are similar, and 3) in the illuminating configuration. We think that the amounts of shift measured by SR of the present study are more clinically relevant than those determined by SP. Anyway, the color shifts by the switch of real light sources in ceramic materials are higher than those previously reported based on SP readings.

Color shifts of a shade guide due to the switch of three light sources were determined by SR.³ As results, the range of color shifts by the switch from D65 simulator to A simulator was 4.0 to 9.1 ΔE^*_{ab} units, and that from D65 to F9 switch was 3.2 to 8.5 ΔE^*_{ab} units. Comparing with the ceramics of the present study, color shifts in the corresponding shade guide tabs showed a similar trend, but were

not the same (2M2 and 2M3 in Fig. 1 to Fig. 4). Based on these, it was confirmed that the shifts in color and color coordinates in clinically simulated ceramics are not the same to those of the corresponding shade guide tabs; therefore, matched color with a shade guide under a particular light source could be mismatched under a different light source.

Core and veneer specimens were optically connected by an optical fluid instead of firing together, which is a limitation of the present study. Besides, the shape and size of clinical restorations are different from columniform specimens used in the present study, which might have caused discrepancy. Further *in vivo* studies carried under clinical conditions should be performed.

CONCLUSION

Within the limitations of this study, perceptible color shifts of clinically simulated ceramics under different ambient light sources were confirmed by spectroradiometer readings. Color shifts under different light sources were in clinically unacceptable range ($\Delta E^*_{ab} > 5.5$), which should be considered together with the inconsistencies in light-dependent color shifts among shade tabs, teeth, and restorations. Color matching and shade compatibility evaluation should be performed under optimal lighting conditions that simulate the light source, which is most relevant to the patient.

REFERENCES

- Vichi A, Louca C, Corciolani G, Ferrari M. Color related to ceramic and zirconia restorations: a review. *Dent Mater* 2011;27:97-108.
- Barão VA, Gennari-Filho H, Goiato MC, dos Santos DM, Pesqueira AA. Factors to achieve aesthetics in all-ceramic restorations. *J Craniofac Surg* 2010;21:2007-12.
- Lee YK, Yu B, Lim JI, Lim HN. Perceived color shift of a shade guide according to the change of illuminant. *J Prosthet Dent* 2011;105:91-9.
- Rosenstiel SF, Land MF, Fujimoto J. *Contemporary fixed prosthodontics*. 4th ed. St. Louis; Mosby; 2006. p. 774.
- Anusavice K. *Philips' science of dental materials*. 11th ed. St. Louis; Saunders; 2003. p. 655-719.
- Zhang Y, Kim JW. Graded zirconia glass for resistance to veneer fracture. *J Dent Res* 2010;89:1057-62.
- Barnes D, Gingell JC, George D, Adachi E, Jefferies S, Sundar VV. Clinical evaluation of an all-ceramic restorative system: a 36-month clinical evaluation. *Am J Dent* 2010;23:87-92.
- Park JH, Lee YK, Lim BS. Influence of illuminants on the color distribution of shade guides. *J Prosthet Dent* 2006;96:402-11.
- Judeh A, Al-Wahadni A. A comparison between conventional visual and spectrophotometric methods for shade selection. *Quintessence Int* 2009;40:e69-79.
- Lehmann KM, Igiel C, Schmidtman I, Scheller H. Four color-measuring devices compared with a spectrophotometric reference system. *J Dent* 2010;38 Suppl 2:e65-70.
- Ishikawa-Nagai S, Yoshida A, Da Silva JD, Miller L. Spectrophotometric analysis of tooth color reproduction on anterior all-ceramic crowns: Part 1: analysis and interpretation of tooth color. *J Esthet Restor Dent* 2010;22:42-52.
- 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.
- Yap AU, Sim CP, Loh WL, Teo JH. Human-eye versus computerized color matching. *Oper Dent* 1999;24:358-63.
- Wyszecki G, Stiles WS. *Color science - Concepts and methods, quantitative data and formulae*. 2nd ed. New York; John Wiley and Sons; 2000.
- Marcus RT. The measurement of color. In: Nassau K, editor. *Color for science, art and technology*. Amsterdam; Elsevier; 1998. p. 48-9.
- Lee YK, Lim BS, Kim CW, Powers JM. Color characteristics of low-chroma and high-translucence dental resin composites by different measuring modes. *J Biomed Mater Res* 2001;58:613-21.
- Lee YK, Powers JM. Color difference of four esthetic restorative materials by the illuminant. *Am J Dent* 2005;18:359-63.
- Yu B, Lee YK. Color difference of all-ceramic materials by the change of illuminants. *Am J Dent* 2009;22:73-8.
- van der Burgt TP, ten Bosch JJ, Borsboom PC, Plasschaert AJ. A new method for matching tooth colors with color standards. *J Dent Res* 1985;64:837-41.
- Lee YK, Yoon TH, Lim BS, Kim CW, Powers JM. Effects of colour measuring mode and light source on the colour of shade guides. *J Oral Rehabil* 2002;29:1099-107.
- Kim SH, Lee YK, Lim BS, Rhee SH, Yang HC. Metameric effect between dental porcelain and porcelain repairing resin composite. *Dent Mater* 2007;23:374-9.
- Volpato CA, Monteiro S Jr, de Andrada MC, Fredel MC, Petter CO. Optical influence of the type of illuminant, substrates and thickness of ceramic materials. *Dent Mater* 2009;25:87-93.
- Corcodel N, Helling S, Rammelsberg P, Hassel AJ. Metameric effect between natural teeth and the shade tabs of a shade guide. *Eur J Oral Sci* 2010;118:311-6.
- Cha HS, Lee YK. Difference in illuminant-dependent color changes of shade guide tabs by the shade designation relative to three illuminants. *Am J Dent* 2009;22:350-6.
- Gokce HS, Piskin B, Ceyhan D, Gokce SM, Arisan V. Shade matching performance of normal and color vision-deficient dental professionals with standard daylight and tungsten illuminants. *J Prosthet Dent* 2010;103:139-47.
- Carsten DL. Successful shade matching--what does it take? *Compend Contin Educ Dent* 2003;24:175-82.
- Commission Internationale de l'Eclairage (CIE) Colorimetry - technical report. CIE Pub. No. 15. 3rd ed. Vienna; Bureau Central de la CIE; 2004.
- Lee YK, Yu B, Lee SH, Cho MS, Lee CY, Lim HN. Variation in instrument-based color coordinates of esthetic restorative materials by measurement method-A review. *Dent Mater* 2010;26:1098-105.
- van der Burgt TP, ten Bosch JJ, Borsboom PC, Kortsmits WJ.

- A comparison of new and conventional methods for quantification of tooth color. *J Prosthet Dent* 1990;63:155-62.
30. Bolt RA, Bosch JJ, Coops JC. Influence of window size in small-window color measurements, particularly of teeth. *Phys Med Biol* 1994;39:1133-42.
 31. Lee YK, Cha HS, Ahn JS. Layered color of all-ceramic core and veneer ceramics. *J Prosthet Dent* 2007;97:279-86.
 32. Gozalo-Diaz D, Johnston WM, Wee AG. Estimating the color of maxillary central incisors based on age and gender. *J Prosthet Dent* 2008;100:93-8.
 33. Bayindir F, Bayindir YZ, Gozalo-Diaz DJ, Wee AG. Coverage error of gingival shade guide systems in measuring color of attached anterior gingiva. *J Prosthet Dent* 2009;101:46-53.
 34. Li Q, Yu H, Wang YN. In vivo spectroradiometric evaluation of colour matching errors among five shade guides. *J Oral Rehabil* 2009;36:65-70.
 35. Ghinea R, Pérez MM, Herrera LJ, Rivas MJ, Yebra A, Paravina RD. Color difference thresholds in dental ceramics. *J Dent* 2010;38 Suppl 2:e57-64.
 36. Douglas RD, Steinhauer TJ, Wee AG. Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch. *J Prosthet Dent* 2007;97:200-8.
 37. Davis S. Color perception - philosophical, psychological, artistic, and cognitive perspectives. New York; Oxford University Press; 2000. p.88-90.
 38. O'Brien WJ, Groh CL, Boenke KM. One-dimensional color order system for dental shade guides. *Dent Mater* 1989;5:371-4.
 39. Ferreira D, Monard LA. Measurement of spectral reflectance and colorimetric properties of Vita shade guides. *J Dent Assoc S Afr* 1991;46:63-5.
 40. Lee YK, Powers JM. Metameric effect between resin composite and dentin. *Dent Mater* 2005;2:971-6.
 41. Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all-ceramic systems. Part I: core materials. *J Prosthet Dent* 2002;88:4-9.
 42. Paravina RD, Westland S, Kimura M, Powers JM, Imai FH. Color interaction of dental materials: blending effect of layered composites. *Dent Mater* 2006;22:903-8.
 43. Lee YK, Yu B, Lim HN. Lightness, chroma, and hue distributions of a shade guide as measured by a spectroradiometer. *J Prosthet Dent* 2010;104:173-81.
 44. Kim JG, Yu B, Lee YK. Correlations between color differences based on three color-difference formulas using dental shade guide tabs. *J Prosthodont* 2009;18:135-40.