Journal of
Biomedical Optics

BiomedicalOptics.SPIEDigitalLibrary.org

Illuminating light-dependent color shifts in core and veneer layers of dental all-ceramics

Yong-Keun Lee
Hyun-Suk Cha
Bin Yu

SPIE.

Journal of Biomedical Optics 19(9), 095002 (September 2014)

Illuminating light-dependent color shifts in core and veneer layers of dental all-ceramics

Yong-Keun Lee,[a,*] Hyun-Suk Cha,[b] and Bin Yu[c]
[a]Institute for Clinical Performance of Biomaterials (ICPB) and ETN Dental Clinic, 106-B101, 27 Heukseokhangang-ro, Dongjak-gu, Seoul 156-070, Republic of Korea
[b]University of Ulsan, College of Medicine, Department of Dentistry, Asan Medical Center, 388-1, Pungnap-2 dong, Songpa-gu, Seoul 138-736, Republic of Korea
[c]Institute of Process Engineering, Chinese Academy of Sciences, State Key Laboratory of Multiphase Complex Systems, Beijing, China

Abstract. The color of an object is perceived differently depending on the ambient light conditions. Since dental all-ceramic restorations are fabricated by building up several layers to reproduce the tooth shade, the optical properties of each layer should be optimized for successful shade reproduction. This study aimed to determine the separate contributions of the color shifts in each of the core and veneer layers of all-ceramics by switching the illuminating lights on the color shifts of layered ceramics. Specimens of seven kinds of core ceramics and the corresponding veneer ceramics for each core were fabricated with a layered thickness of 1.5 mm. A sintering ceramic was used as a reference core material. The Commission Internationale de l'Eclairage (CIE) color coordinates of core, veneer, and layered specimens were measured with a spectroradiometer under the CIE illuminant D65 (daylight), A (incandescent lamp), and F9 (fluorescent lamp) simulating lights. Color shifts of the layered specimens were primarily determined by the CIE $a*$ shifts (D65 to A switch) or by the CIE $b*$ shifts (D65 to F9 switch) of the veneer layer. The color coordinates shifts in the constituent layers differentially influenced those of the layered specimens by the kind of switched lights. Therefore, the optical properties of the constituent layers of all-ceramics should be controlled to reflect these findings. [DOI: 10.1117/1.JBO.19.9.095002]

Keywords: all-ceramic; layering; illumination; color shift; core and veneer.

Paper 140372RRR received Jun. 11, 2014; revised manuscript received Aug. 31, 2014; accepted for publication Sep. 2, 2014; published online Sep. 23, 2014.

1 Introduction

Dental esthetic restorations should mimic a natural and pleasing appearance of the teeth, and dental all-ceramics can be made to optically simulate teeth.[1] To optimize the shade reproduction in dental ceramics, a number of optical properties have been studied and applied.[2] When light falls on the tooth surface, a multitude of interactions such as transmission, reflection, scattering, and refraction of light between enamel and dentine may occur simultaneously.[3] The color of the teeth and corresponding ceramic restorations is decided by the double layer effect, which indicates that apparent color is the result of diffuse reflectance from the inner dentin or opaque layer through the outer enamel or translucent layer.[2] For an optical simulation of the tooth shade, ceramic restorations are made of several layers of different opacity, shade, and thickness.[4] Therefore, the optical properties of each of the constituent layers of ceramics should be optimized for the successful shade reproduction of natural teeth.

As for the influence of thickness of each layer in ceramic restorations on shade, a significant correlation between the thickness ratio of the opaque and veneer layers and the final shade of all-ceramic restorations was confirmed.[4] It was also reported that the reduction of the enamel ceramic thickness produced changes in the lightness, hue, and chroma.[5] Meanwhile, the influence of the optical properties of the constituent layers on the color of layered direct restorative materials was determined, which concluded that the Commission Internationale de l'Eclairage (CIE) $L*$, $a*$, and $b*$ values of layered specimens were mainly decided by the optical properties of the enamel layer.[6]

Since patients are seen under various lights, the ability to assess appearance matching characteristics under diverse lights would help to assure an optimum shade match of restorations for the patient.[7] Although chromatic adaptation has been identified as a major source of error in observing shades under artificial lights,[2] color under a specific light is not the same when compared to the same color under another type of light.[8,9] An illumination is a source of natural or artificial light, and illuminating lights, which vary in type, intensity and incident angle, influence the color behavior of an object.[9] Lighting conditions also affect the shade matching performance of dental professionals.[10]

Because lighting conditions vary by diverse factors, the CIE defined the standard illuminants by their relative spectral power distributions and classified them according to their effects on color perception. These illuminants are used in a spectrophotometer (SP). The CIE illuminants are classified in A, B, C, D, a hypothetical E series and, unofficially, an F series.[11] A natural, bluish–white daylight is simulated in the illuminant D65,[12] which shows the spectral power distribution corresponding to a typical mixture of direct sunlight and scattered skylight.[13] Based on SP-based studies, it was confirmed that switching illuminants resulted in significant changes in the CIE color coordinates of dental esthetic materials.[14–16] Even the shade guide tabs showed the perceptible color shifts with the real light switches based on

---

*Address all correspondence to: Yong-Keun Lee, E-mail: ykleedm@gmail.com

0091-3286/2014/$25.00 © 2014 SPIE

spectroradiometer (SR) readings.[17] It was reported that the color shifts of all-ceramics with a switch from the D65 to A simulating lights were in the range of 5.9 to 10.2 $\Delta E*_{\mathrm{ab}}$ units based on SR readings.[18]

Translucent and fluorescent properties might influence the amount of color shifts with different types of lights. It was confirmed that the translucency of dental ceramics was a linear function of thickness,[19,20] and the changes of translucency in tooth enamel due to the different lights altered the tooth color.[2] Changes in the translucency of porcelain and repairing resin composites under different types of lights were also confirmed.[21]

Correlations between visual perception and instrument-based color values have been studied to establish the clinical meanings of the numeric values from instrumental readings. Although varied visual threshold values were proposed, 2.6 $\Delta E*_{\mathrm{ab}}$ units were considered as the clinically perceptible threshold, while 5.5 $\Delta E*_{\mathrm{ab}}$ units were considered as the clinically acceptable threshold based on SR measurements.[22]

Although there have been studies on the influence of background conditions and layering techniques on the optical properties of dental ceramics,[15,23] and also on the influence of illumination on the color matching performance of these materials,[10,16] the separate contributions of the color coordinate shifts in the veneer and core layers to the color shifts of layered ceramics are not fully elucidated. The purpose of this study was to determine the influence of the shifts in the color coordinates of the core and veneer layers under three different real types of ambient lights on the color shifts of seven kinds of layered all-ceramics. The null hypothesis assumed was that the color shifts of the layered ceramics under different lights were equally correlated with the color shifts of the constituent layers regardless of the kind of light. If the differential influences of the color shifts in the constituent layers under different lights on the color shifts of layered ceramics by the layer or by the kind of light could be confirmed, these results should be applied in the development of constituent layer materials for optimal shade reproduction.

2 Material and Methods

Specimens of seven kinds of all-ceramic core ceramics were fabricated, 11 mm in diameter, following the manufacturers' instructions. A sintering ceramic (VITA VM 7; VITA Zahnfabrik, Bad Säckingen, Germany) was used as a reference core material. The shade for these specimens was the VITA Lumin A2 shade (VITA Zahnfabrik). Thickness of the core specimens was decided considering the manufacturers' recommended thickness required to mask a discolored abutment (Table 1). Specimens of the corresponding veneer ceramic for each of the core ceramics were prepared (Tables 1 and 2), and the thicknesses of the veneer specimens were decided so that the final thickness of the layered specimens was 1.5 mm.[1] Two shades corresponding to the A2 and A3 shades (VITA Zahnfabrik) were selected. Seven specimens were made for each kind of the core and veneer ceramics. The number of specimens was determined based on previous color studies,[4,6,14,16] in which five specimens were generally investigated and the standard errors based on these numbers of specimens have been regarded to be relatively stable. Detailed specimen preparation procedures were previously reported.[24] Briefly, each core and veneer ceramic specimen was fabricated according to the manufacturers' instructions with a size similar to the final

Table 1 Dental ceramic materials investigated.

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

Table 2 Combinations of core and veneer ceramics.

Core	Veneer (A2/A3)
ICS	V7-2, V7-3 (2M2/2M3)
ICA	V7-2, V7-3
AZC	V92-2, V92-3 (2M2/2M3)
DIZ	V92-2, V92-3
VIZ	V92-2, V92-3
MK2	V91-2, V91-3 (2M2/2M3)
EM2	ER-2, ER-3 (120/210)
VM7	V7-2, V7-3 (2M2/2M3)

specimen's dimensions. Then the final thickness was adjusted by grinding with a grinder.

The CIE $L*$, $a*$, and $b*$ values of the core, veneer, and layered specimens were measured over a white tile (CIE $L* = 94.4$, $a* = -0.1$, and $b* = 0.6$) under three lights, which simulate the CIE illuminants D65 (daylight), A (incandescent lamp), and F9 (fluorescent lamp), respectively. An SR (PR-670 SpectraScan; Photo Research, Chatsworth, California) was used. When the color of layered specimens was measured (Table 2), the corresponding veneer specimen was laid over a core specimen. In this procedure, a drop of optical fluid (refraction fluid, 1.5 index; Cargille Lab, Cedar Grove, New Jersey) was applied between the veneer and core specimens for an optical connection.[17] Lighting conditions and detailed color measurement protocols were presented in a previous study.[17]

Vectorial shifts of lightness (CIE $L*$) and chroma, and those of the CIE $a*$ and $b*$ with a light switch were determined. Shifts in color and color coordinates with different types of lights from D65 to A and from D65 to F9 were calculated. Chroma was calculated as $C*_{ab} = (a*^2 + b*^2)^{1/2}$, and the amount of color shift was calculated as $\Delta E*_{ab} = [(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2]^{1/2}$.[12]

Pearson correlations between the color shifts of the layered specimens and the shifts in color coordinates in each of the core and veneer specimens with different lights were determined using a regression analysis ($\alpha = 0.05$). Within each of the core, veneer, and layered ceramics, influencing variables among the shifts in the color coordinates on the color shift were determined with a multiple regression analysis ($\alpha = 0.01$). Influence of the shifts of the color coordinates in the core and veneer layers on the shifts in the color and color coordinates of the layered ceramics was analyzed with a multiple regression analysis ($\alpha = 0.01$). To eliminate the impact of interrelated independent variables, the variable which showed the lower correlation coefficient (β) was not included in the regression equation when the tolerance between two variables was lower than 0.30.[25]

3 Results

Shifts in color and color coordinates with different types of lights are presented in Table 3. By switching from the D65 simulating light to A simulating light, the mean (±standard deviation) value for the color shifts ($\Delta E*_{ab}$) was 6.2 ± 0.4, that for the CIE $a*$ shifts ($\Delta a*$: values under A minus those under D65) was 6.0 ± 0.4, and that for the CIE $b*$ shifts ($\Delta b*$) was 0.7 ± 0.5 for the A2-veneered specimens. For the A3-veneered specimens, a similar range of values was observed.

Pearson correlations between the color shifts in the layered specimens and the shifts of the color coordinates in the core and veneer layers under different types of lights are listed in Table 4. Several pairs showed significant correlations ($r = 0.164$ to

Table 3 Shifts in color and color coordinates under different lights for core, veneer, and layered ceramics.

	$\Delta E*_{ab}$		$\Delta L*$		$\Delta a*$		$\Delta b*$		$\Delta C*_{ab}$	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean
D65 to A switch (A-D65)										
Core	1.9–5.8	4.6 (1.4)[a]	–5.6–1.4	–1.1 (2.8)	1.5–5.6	3.3 (1.9)	–0.6–0.6	0.0 (0.5)	–0.3–1.2	0.3 (0.5)
Veneer	8.1–10.2	9.3 (0.7)	5.8–7.3	6.6 (0.5)	5.5–7.1	6.4 (0.6)	–0.4–0.6	0.0 (0.4)	0.4–1.8	1.0 (0.5)
A2-veneered	5.9–6.9	6.2 (0.4)	0.2–1.6	0.7 (0.5)	5.6–6.6	6.0 (0.4)	–0.1–1.3	0.7 (0.5)	1.1–2.6	1.9 (0.5)
A3-veneered	6.8–7.7	7.2 (0.3)	–1.3–0.3	–0.4 (0.6)	6.8–7.6	7.0 (0.2)	0.1–1.0	0.7 (0.3)	1.2–2.3	2.0 (0.4)
D65 to F9 switch (F9-D65)										
Core	1.4–4.7	3.3 (1.0)	–3.9–1.6	–0.2 (2.2)	–0.4–1.4	0.3 (0.6)	1.2–3.3	2.3 (0.6)	1.2–3.3	2.3 (0.6)
Veneer	5.7–7.0	6.4 (0.4)	5.3–6.0	5.6 (0.3)	1.4–2.1	1.9 (0.3)	1.6–3.1	2.3 (0.5)	1.7–3.2	2.4 (0.5)
A2-veneered	7.7–9.9	8.7 (0.7)	5.9–6.9	6.3 (0.4)	–0.9–0.1	–0.5 (0.3)	4.9–7.1	5.9 (0.7)	4.9–7.0	5.9 (0.7)
A3-veneered	8.6–10.2	9.7 (0.5)	5.9–7.0	6.5 (0.4)	–0.6–0.1	–0.4 (0.2)	6.4–7.8	7.2 (0.4)	6.4–7.7	7.2 (0.4)

[a] Standard deviations are in parentheses.

Table 4 Pearson correlations between color shifts of layered specimens and shifts in color coordinates of core and veneer layers under different lights.

Light[a]	$\Delta L*$-C	$\Delta a*$-C	$\Delta b*$-C	$\Delta C*_{ab}$-C	$\Delta L*$-V	$\Delta a*$-V	$\Delta b*$-V	$\Delta C*_{ab}$-V
A-D65		.222[c]		.182[b]	.356[c]	.836[c]	.185[b]	.164[b]
F9-D65			.173[b]	.183[b]	.256[c]	.235[c]	.487[c]	.479[c]

[a] A-D65 indicates light switch from D65 to A and F9-D65 indicates D65 to F9 switch.
C: Core; V: Veneer; L: Layered.
[b] Significant at 0.05
[c] Significant at 0.01

0.836, $P < 0.05$) for the light switch from the D65 to A, and several pairs also showed correlations ($r = 0.173$ to 0.487, $P < 0.05$) for the D65 to F9 switch.

Within each of the core, veneer, and layered specimens, the influencing color coordinates on the color shift are listed in Table 5. When switched from the D65 to A, color shifts in the core and layered specimens were mainly influenced by the shifts in the CIE $a*$ and $L*$, but the influence of the CIE $L*$ shifts was the highest in the veneer specimens. When switched from the D65 to F9, color shifts in the core and veneer specimens were mainly influenced by the shifts in the CIE $L*$ and $b*$, but the influence of the CIE $b*$ shifts was the highest in the layered specimens.

Influencing variables among the shifts in color coordinates of the core or veneer specimens on the color shift of the layered specimens are presented in Table 6. Color shifts were mainly influenced by the shifts in the CIE $a*$ (to A shift) and those in the CIE $b*$ (to F9 shift) in the veneer layer. As to the shifts in the CIE $a*$ of the layered specimens, the influence of the shifts in CIE $a*$ in the veneer layer was significant in both switches. As to the shifts in the CIE $b*$, the influence of the shifts in the CIE $b*$ in the veneer layer was the highest for the D65 to F9 switch.

4 Discussion

The null hypothesis was rejected because the color shifts of the layered ceramics were differently influenced by the shifts in the CIE $a*$ (from D65 to A switch), or by the shifts in the CIE $b*$ (from D65 to F9 switch) in the veneer layer as presented in Table 6. Meanwhile, the influence of the color coordinates shifts on the color shifts in the core, veneer, and layered specimens were different as indicated in Table 5. Therefore, optical properties of the constituent layer ceramics should be controlled reflecting these results.

The range of color shifts by the switch from the D65 to A was 4.6 to 9.3 $\Delta E*_{ab}$ units in three kinds of specimens, and that by the switch from the D65 to F9 was 3.3 to 9.7 $\Delta E*_{ab}$ units (Table 3). Although the measurement protocols of the present study were not the same as those for the clinical threshold determination of the previous study,[22] when the threshold color difference values were applied, all of the color shifts were higher than the perceptible limit ($\Delta E*_{ab} > 2.6$, Table 3), and several of them showed unacceptable shifts ($\Delta E*_{ab} > 5.5$) when switching between different types of ambient lights such as daylight, incandescent lamp and fluorescent lamp. In a recent review paper,[26] the commonly used acceptability threshold was reported as 3.7 $\Delta E*_{ab}$ units, whereas the perceptibility thresholds were 1 $\Delta E*_{ab}$ units. Color difference values generally propose the visual thresholds; however, these thresholds are influenced by the lighting conditions.[10] Therefore, further determination for the illumination-dependent variations in visual thresholds should be performed. As to the shifts of chromatic coordinates, when switched from the D65 to A, the CIE $a*$ increased; when switched from the D65 to F9, the CIE $b*$ value increased. These results confirm the light-dependent color shifts of ceramics, which w coincident with the results based on SP.[15]

The color coordinates of core and veneer ceramic combinations were measured relative to the illuminant D65 by SP.[24] The results indicate that the CIE $L*$ was primarily influenced by the

Table 5 Influencing variables among shifts in color coordinates on color shift within core, veneer, and layered specimens.

Specimen	Light[a]	Multiple r^{2b}	Influencing variables (β, t-value)[c]
Core	A-D65	0.871	$\Delta a*$ (1.29, 25.21), $\Delta L*$ (−1.28, −24.31), $\Delta C*_{ab}$ (−0.19, −5.06)
	F9-D65	0.722	$\Delta L*$ (−0.88, −12.68), $\Delta b*$ (0.40, 7.40), $\Delta a*$ (0.36, 4.91)
Veneer	A-D65	0.997	$\Delta L*$ (0.70, 120.26), $\Delta a*$ (0.54, 91.28), $\Delta b*$ (−0.31, −5.27)
	F9-D65	0.989	$\Delta L*$ (0.75, 67.89), $\Delta b*$ (0.38, 34.48), $\Delta a*$ (0.14, 13.61)
Layered	A-D65	0.965	$\Delta a*$ (1.01, 44.21), $\Delta L*$ (0.10, 4.59), $\Delta C*_{ab}$ (0.08, 4.40)
	F9-D65	0.999	$\Delta b*$ (0.65, 198.24), $\Delta L*$ (0.52, 156.42)

[a] A-D65 indicates light switch from D65 to A and F9-D65 indicates D65 to F9 switch.
[b] Square of multiple correlation coefficient. All of the significant F-values were lower than 0.01.
[c] In the order from the most influencing determined by t-value.

Table 6 Influencing variables of shifts in color coordinates of core and veneer layers on color shift of layered specimens.

Parameter	Light$^{\text{a}}$	Multiple $r^{2\text{b}}$	Influencing variables (β, t-value)$^{\text{d}}$
$\Delta E*_{\text{ab}}$	A-D65	0.767	$\Delta a*$-V (0.83, 17.71), $\Delta a*$-C (0.24, 5.03), $\Delta b*$-C (0.17, 3.65)
	F9-D65	0.219	$\Delta b*$-V (0.43, 5.04), $\Delta C*_{\text{ab}}$-C (0.24, 2.83)
$\Delta L*$	A-D65	0.192	$\Delta a*$-V (−0.44, −5.11)
	F9-D65	0.082	$\Delta a*$-C (−0.29, −3.13)
$\Delta a*$	A-D65	0.796	$\Delta a*$-V (0.85, 19.51), $\Delta a*$-C (0.24, 5.27), $\Delta b*$-C (0.14, 3.08)
	F9-D65	0.560	$\Delta a*$-V (0.75, 11.82)
$\Delta b*$	A-D65	0.163	$\Delta C*_{\text{ab}}$-C (0.32, 3.59), $\Delta a*$-C (−0.24, −2.79)
	F9-D65	0.413	$\Delta b*$-V (0.46, 5.94), $\Delta a*$-V (0.29, 3.59), $\Delta C*_{\text{ab}}$-C (0.23, 2.91)
$\Delta \text{C}*_{\text{ab}}$	A-D65	0.234	$\Delta C*_{\text{ab}}$-core (0.39, 4.59), $\Delta a*$-core (−0.28, −3.38)
	F9-D65	0.418	$\Delta b*$-V (0.45, 5.88), $\Delta a*$-V (0.30, 3.76), $\Delta C*_{\text{ab}}$-C (0.23, 2.89)

C: Core; V: Veneer; L: Layered.

[a] A-D65 indicates light switch from D65 to A and F9-D65 indicates D65 to F9 switch.

[b] Square of multiple correlation coefficient. All of the significant F-values were lower than 0.01.

[c] In the order from the most influencing determined by t-value.

CIE $L*$ of the core ceramics, and the CIE $a*$ and $b*$ were primarily influenced by each corresponding coordinate of the veneer ceramics. Based on the results of the present study, the color shifts of the layered ceramics were mainly influenced by the shifts in the CIE $a*$ (A switch) or those in the CIE $b*$ (F9 switch) in the veneer layer (Table 6). Therefore, in addition to the influence of the color coordinates in constituent layers on the layered color, differential shifts of the optical properties in the constituent layers under different types of lights on the layered color shifts as determined in the present study should be considered.

As for the correlation among the color coordinates, the chroma of dental ceramics was mainly decided by the CIE $b*$.[27] Based on the results of the present study, it was also observed that the chroma was mainly determined by the CIE $b*$, in which the range of CIE $b*$ for the core specimens under the D65 light was 3.8 to 17.7, and that of the chroma was 3.8 to 17.9. As to the shifts in the color coordinates under different types of lights, they showed characteristic patterns (Table 3).

Color shifts of layered all-ceramics when switching the types of illumination were determined by SP.[15] As a result, when switching from the D65 to A, the mean color shift was 2.7 $\Delta E*_{\text{ab}}$ units and that of the lightness ($\Delta L*$) was 0.9, while that of the chroma was 1.0. By switching from the D65 to F2, the mean color shift was 2.0 $\Delta E*_{\text{ab}}$ units, that of the lightness was 0.6, and that of the chroma was 1.7. Although the color determining method of the present study was different from that of the previous study, color shifts measured by SR in the present study (Table 3) were higher than those of the SP-based results. These discrepancies might be explained by (1) the difference in measurement geometry between SP and SR and (2) difference in illuminating conditions.

Influence of the kind of illuminants on the color of all-ceramics was determined by SP.[16] The results presented significant differences in the CIE $a*$ and $b*$ under different illuminants, and it was also argued that the CIE $L*$ should not be individually evaluated in order to obtain a reliable color match[16] because lightness is the parameter that is most perceptible due to the greater number of rod cells than cone cells in the human retina.[28] For this reason, a variation in the CIE $L*$ has the greatest impact on color perception.[28] As to the CIE $L*$ shifts, in the present study the amount of shifts varied by the kinds of specimens and kinds of light (Table 3), and the shifts in the veneer ceramics were high, such as 6.6 and 5.6 $\Delta L*$ units. The cause for this phenomenon should be further studied.

Optical properties, such as translucency and fluorescence, can influence the color shifts caused by light switches. Translucency of all-ceramics showed a linear relationship as the ceramic thickness increased from 0.7 to 1.5 mm.[19] The color of the core composites changed the color of the ceramic-composite combinations with color differences ranging from 6.3 to 8.3 $\Delta E*_{\text{ab}}$ units,[29] which were associated with translucency. Since the thickness range of the core specimens in the present study was 0.4 to 0.8 mm and that of the veneer specimens was 0.7 to 1.1 mm, these thickness deviations should have influenced the amount of the color shifts. The influence of the thicknesses of the core and veneer ceramics on the illumination-dependent color shifts should be further studied.

Translucency parameter (TP) values of all-ceramics relative to the illuminant D65 were lower than those relative to the illuminants A or F2, although the correlation coefficients among them were higher than 0.99.[30] It was also reported that translucent materials showed higher shifts in the TP values when switching illuminants.[30] As to the translucency of the ceramics investigated in the present study,[31] the range of the TP values for the core specimens was 8.8 to 26.2, while that for the veneer specimens was 12.0 to 25.4. The range for the A2-veneered ceramics was 4.4 to 12.0, and that for the A3-veneered ceramics was 4.4 to 12.5. As for the TP values of porcelain and porcelain repairing resin composites relative to the illuminants,[21] the TP values were influenced by the illuminants, and the color shifts due to switching illuminants were correlated with the translucency shift in the resin composites ($r = 0.47$ to 0.65). Correlations between the shifts in translucency and color should be further studied. Those studies should provide further elucidation of the illumination-dependent color shifts phenomenon. Further studies simulating the clinical scenarios should be performed, and experimentally controlled materials, not commercial products, should be tested for the optical layering performance of these materials.

5 Conclusions

Within the limitations of this study, the shifts in color coordinates of the core, veneer, and layered ceramic specimens due to different types of lights varied with the type of light and the kinds of specimens. When ambient lights were switched, the shifts in the color coordinates in the core and veneer layers influenced the overall color shifts of the layered ceramics differentially based on the kind light. Therefore, these differential influences of different lights by the layer and the kind of light should be reflected in the design of the optical properties of constituent layer ceramics, simultaneously considering the changes in translucency and fluorescence of these materials. Clinicians should consider the differential effects of different types of light on the color shift of the constituent and layered all-ceramic materials in their color matching procedure.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51102237).

References

1. S. F. Rosenstiel, M. F. Land, and J. Fujimoto, *Contemporary Fixed Prothodontics*, 4th ed., p. 774, Mosby, St. Louis, Missouri (2006).
2. W. J. O'Brien, "Double layer effect and other optical phenomena related to esthetics," *Dent. Clin. North Am.* **29**(4), 667–672 (1985).
3. X. Ma et al., "Separate contribution of enamel and dentine to overall tooth colour change in tooth bleaching," *J. Dent.* **39**(11), 739–745 (2011).
4. A. Dozic et al., "The influence of porcelain layer thickness on the final shade of ceramic restorations," *J. Prosthet. Dent.* **90**(6), 563–570 (2003).
5. F. D. Jarad et al., "The effect of enamel porcelain thickness on color and the ability of a shade guide to prescribe chroma," *Dent. Mater.* **23**(4), 454–460 (2007).
6. Y. K. Lee and J. M. Powers, "Calculation of color resulting from composite/compomer layering techniques," *J. Oral Rehabil.* **31**(11), 1102–1108 (2004).
7. S. S. Mikhail et al., "Optical characteristics of contemporary dental composite resin materials," *J. Dent.* **41**(9), 771–778 (2013).
8. S. J. Dain, "Daylight simulators and color vision tests," *Ophthalmic Physiol. Opt.* **18**(6), 540–544 (1998).
9. H. Dagg et al., "The influence of some different factors on the accuracy of shade selection," *J. Oral Rehabil.* **31**(9), 900–904 (2004).
10. H. S. Gokce et al., "Shade matching performance of normal and color vision-deficient dental professionals with standard daylight and tungsten illuminants," *J. Prosthet. Dent.* **103**(3), 139–147 (2010).
11. S. J. Chu, A. Devigus, and A. J. Mieleszko, *Fundamentals of Color: Shade Matching and Communication in Esthetic Dentistry*, 1st ed., pp. 20–30, Quintessence, Chicago (2004).
12. CIE (Commission Internationale de l'Eclairage), "Colorimetry," Technical Report, CIE Pub. No. 15, Bureau Central de la CIE, Vienna (2004).
13. K. Amano and D. H. Foster, "Color constancy under simultaneous changes in surface position and illuminant," *Proc. Biol. Soc.* **271**(1555), 2319–2326 (2004).
14. Y. K. Lee and J. M. Powers, "Color difference of four esthetic restorative materials by the illuminant," *Am. J. Dent.* **18**(5), 359–363 (2005).
15. B. Yu and Y. K. Lee, "Color difference of all-ceramic materials by the change of illuminant," *Am. J. Dent.* **22**(2), 73–78 (2009).
16. C. A. Volpato et al., "Optical influence of the type of illuminant, substrates and thickness of ceramic materials," *Dent. Mater.* **25**(1), 87–93 (2009).
17. Y. K. Lee et al., "Perceived color shift of a shade guide according to the change of illuminant," *J. Prosthet. Dent.* **105**(2), 91–99 (2011).
18. H. S. Cha, B. Yu, and Y. K. Lee, "Perceived color shift of ceramics according to the change of illuminating light with spectroradiometer," *J. Adv. Prosthodont.* **5**(3), 262–269 (2013).
19. S. A. Antonson and K. J. Anusavice, "Contrast ratio of veneering and core ceramics as a function of thickness," *Int. J. Prosthodont.* **14**(4), 316–320 (2001).
20. F. Wang, H. Takahashi, and N. Iwasaki, "Translucency of dental ceramics with different thicknesses," *J. Prosthet. Dent.* **110**(1), 14–20 (2013).
21. Y. K. Lee, "Changes in the translucency of porcelain and repairing resin composite by the illumination," *Dent. Mater.* **23**(4), 492–497 (2007).
22. R. D. Douglas, T. J. Steinhauer, and A. G. Wee, "Intraoral determination of the tolerance of dentists for perceptibility and acceptability of shade mismatch," *J. Prosthet. Dent.* **97**(4), 200–208 (2007).
23. S. S. Azer et al., "Effect of esthetic core shades on the final color of IPS Empress all-ceramic crowns," *J. Prosthet. Dent.* **96**(6), 397–401 (2006).
24. Y. K. Lee, H. S. Cha, and J. S. Ahn, "Layered color of all-ceramic core and veneer ceramics," *J. Prosthet. Dent.* **97**(5), 279–286 (2007).
25. G. R. Norman and D. L. Streiner, *Biostatistics*, pp. 100–116, Mosby, St. Louis (1984).
26. G. Khashayar et al., "Perceptibility and acceptability thresholds for color differences in dentistry," *J. Dent.* **42**(6), 637–644 (2014).
27. D. J. Wood et al., "Spectral reflectance and color of dentin ceramics for all-ceramic restorations," *Dent. Mater.* **24**(12), 1661–1669 (2008).
28. G. Corciolani et al., "Influence of layering thickness on the color parameters of a ceramic system," *Dent. Mater.* **26**(8), 737–742 (2010).
29. Q. Li, H. Yu, and Y. N. Wang, "Spectrophotometric evaluation of the optical influence of core build-up composites on all-ceramic materials," *Dent. Mater.* **25**(2), 158–165 (2009).
30. J. S. Ahn and Y. K. Lee, "Difference in the translucency of all-ceramics by the illuminant," *Dent. Mater.* **24**(11), 1539–1544 (2008).
31. H. N. Lim, B. Yu, and Y. K. Lee, "Spectroradiometric and spectrophotometric translucency of ceramic materials," *J. Prosthet. Dent.* **104**(4), 239–246 (2010).

Yong-Keun Lee is the director for the Institute for Clinical Performance of Biomaterials (ICPB) and ETN Dental Clinic, Seoul, Republic of Korea.

Hyun-Suk Cha is an associate professor, Department of Dentistry, College of Medicine, University of Ulsan, Seoul, Republic of Korea.

Bin Yu is an associate professor, State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing, China.