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ORIGINAL ARTICLE

The combined effect of light-illuminating direction and enamel rod orientation on color adjustment at the enamel borders of composite restorations

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Abstract

Objectives To investigate the effect of light-illuminating direction (from composite or enamel side) on color adjustment at the coronal and cervical enamel borders in composite restorations.

Materials and methods Forty cylindrical holes (3.0-mm diameters) were prepared in bovine enamel disks (1.0-mm thickness). After application of a one-step self-etch adhesive, one of four resin composites (Estelite Asteria, EA; Estelite Pro, EP; Kalore, KA; Clearfil Majesty ES-2 Premium, MJ) was restored in the holes. After 24-h storage, the colors (L^*, C^*, or h^* values) at the restored enamel disks over a black background were measured in a black box using a CIE XYZ camera, spotted with D65 standard illuminant either from coronal or cervical side at 45°/0° geometry. The color shifting rate was calculated at the coronal and cervical enamel borders of the composite restorations, and analyzed by three-way ANOVA with Dunnett's T3 and t test for post hoc analysis ($p < 0.05$).

Results The light-illuminating directions significantly affected the L^* shifting rate at the cervical enamel border in EP and MJ ($p < 0.05$), and the C^* shifting rate at the coronal enamel border in EA, EP, and MJ ($p < 0.05$).

Conclusions The color appearance at the border of the composite restoration was influenced by the light-illuminating direction in conjunction with the enamel rod orientation in the coronal or cervical enamel border.

Clinical relevance The line-of-vision angle would affect the perception of color adaptation at the enamel borders in the composite restorations.

Keywords Color shifting · Enamel borders · Enamel rod orientations · Color adaptation · Color of resin composite

Introduction

Recently, optical and mechanical properties of resin composite materials have been improved with development of adhesive materials, which can produce superior aesthetic/functional restorations for posterior tooth as well as anterior tooth. However, shade-matching of filling resin composite to the surrounding tooth structure still remains a problem to be dissolved, because the color and optical properties in human tooth are varied in the type, site, and/or age of tooth. The color appearance of resin composite is influenced and perceived by various factors: color elements of hue; value and chroma; and optical properties—light transmission properties (straight-line and diffusion), translucency, fluorescence and opalescence, and also surface characteristics. Translucent materials, such as resin composite and enamel, can reflect a color from the adjoining substrates, leading to the color shifting between each other. It is widely known that the color difference between filled composite and the surrounding tooth structure is perceived smaller than that would be predicted from the individual colors. This color shifting effect in composite restoration is often called the "chameleon effect." Investigating and

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understanding the color shifting mechanism in composite restorations would improve the aestheticity in composite restorations and simplify shade-taking for the restored tooth through saving the number of the necessary shades of resin composite materials [1, 2].

Recently, it has been demonstrated that color shifting at the border in composite restorations occurs on the tooth side as well as on the composite side, in which the color shifting phenomenon on the tooth side was greater than that of the composite side [2]. Furthermore, older teeth exhibit potentially less color adjustment in the composite restoration than younger teeth because of the larger amount of transmitted light in aged dentin compared to younger dentin, which affects light reflection from the dentin cavity walls [3]. These results would indicate that the color adjustment in composite restoration is influenced by the light-transmission properties of the surrounding tooth structure as well as shade-matching between the tooth and resin composite materials.

Enamel has minor, yet noticeable effects on the color appearance and transparency of a natural tooth [4, 5]. Recently, it has been demonstrated that tooth color was influenced by variability in the mineral composition of enamel [6] and the refractive index (n) of enamel was a statistically significant predictor for tooth color change [7]. Furthermore, enamel rods can affect the optical properties of enamel, and enamel rod orientation causes optical anisotropy [8]. The optical properties of enamel play an important role in visual perception at the border in a composite restoration because cavity margins are mainly composed of enamel. Recently, it has been reported that the color shifting effect in a composite restoration was different between the coronal and cervical borders [9] and the configuration at enamel margins also affected the color adjustment in a composite restoration [10].

When incident light enters the interface between enamel and resin composite material, it scatters at the interface in multiple directions. This phenomenon would be altered by incident light coming from the composite side or enamel side in conjunction with the enamel rod orientation at the interface. Therefore, the color appearance at the border of a composite restoration might be influenced by the directions of the illuminating light and also by the vision line-angle. However, there have been few studies on the combined effect of light-illuminating directions with enamel rod orientation on color shifting at enamel borders in composite restoration. Therefore, this study was carried out to investigate the effect of light-illuminating directions (from composite or enamel side) on color appearance (L^*, C^*, and h^*) at the enamel borders in composite restorations and to compare the color appearances at coronal- and cervical-enamel borders with different enamel rod orientations. The null hypotheses tested were that light-illuminating directions and regions of enamel border do not affect the color appearance of the border in composite restorations.

Materials and methods

Four commercial contemporary light-cure resin composites, Estelite Asteria (shade: A2B) (EA), Estelite Pro (shade: A2E) (EP), Kalore (shade: WE) (KA), and Clearfil Majesty ES-2 Premium (shade: A2E) (MJ), were investigated in this study (Table 1).

Forty frozen-stored extracted bovine mandibular central incisors were used. Enamel disks of 1.0 mm thick were cut from the labial part using a slow-speed water-cooled diamond saw (Isomet, Buehler, Lake Bluff, IL). Each side of the enamel disks was polished with silicon carbide papers up to 2000-grit under running water (Fig. 1).

Cylindrical hole with 3.0-mm diameter was punched in each enamel disk using a superfine diamond bar (#K1ff, ISO 288 010, GC, Tokyo, Japan). Enamel surface in the hole was bonded with a one-step self-etch adhesive (Clearfil SE One, Kuraray Noritake Dental, Tokyo, Japan) in accordance with the manufacturer's instructions, and then light-irradiated for 10 s using a light curing unit (Optilux 501, Kerr, Orange, CA) with an intensity of 850 mW/cm^2. The hole was filled with one of the four resin composites (EA, KA, MJ, and EP). The filled resin composite, covered with celluloid strips on glass plates on the upper

Table 1 Materials

	Shade	Filler composition	Filler load	Matrix composition
Estelite Asteria (TOKUYMA) EA	A2B	Silica-zirconia spherical (200 nm) filler, composite filler	82 wt%	Bis-GMA, UDMA, Bis-MPEPP, TEGDMA
ESTELITE Pro (TOKUYMA) EP	A2E	Silica-zirconia spherical (200 nm) filler, composite filler	82 wt%	Bis-GMA, TEGDMA
KALORE (GC America) KA	WE	Fluoroaluminosilicate glass filler, silicon dioxide nanofiller, strontium-barium glass, pre-polymerized filler	82 wt%	UDMA DX-511
CLEARFIL MAJESTY ES-2 Premium (KURARAY NORITAKE) MJ	A2E	Silanated barium glass filler, micro glass filler (1.5 mm), nano glass filler (20 nm), pre-polymerized organic filler	78 wt%	Bis-GMA, hydrophobic aromatic dimethacrylate

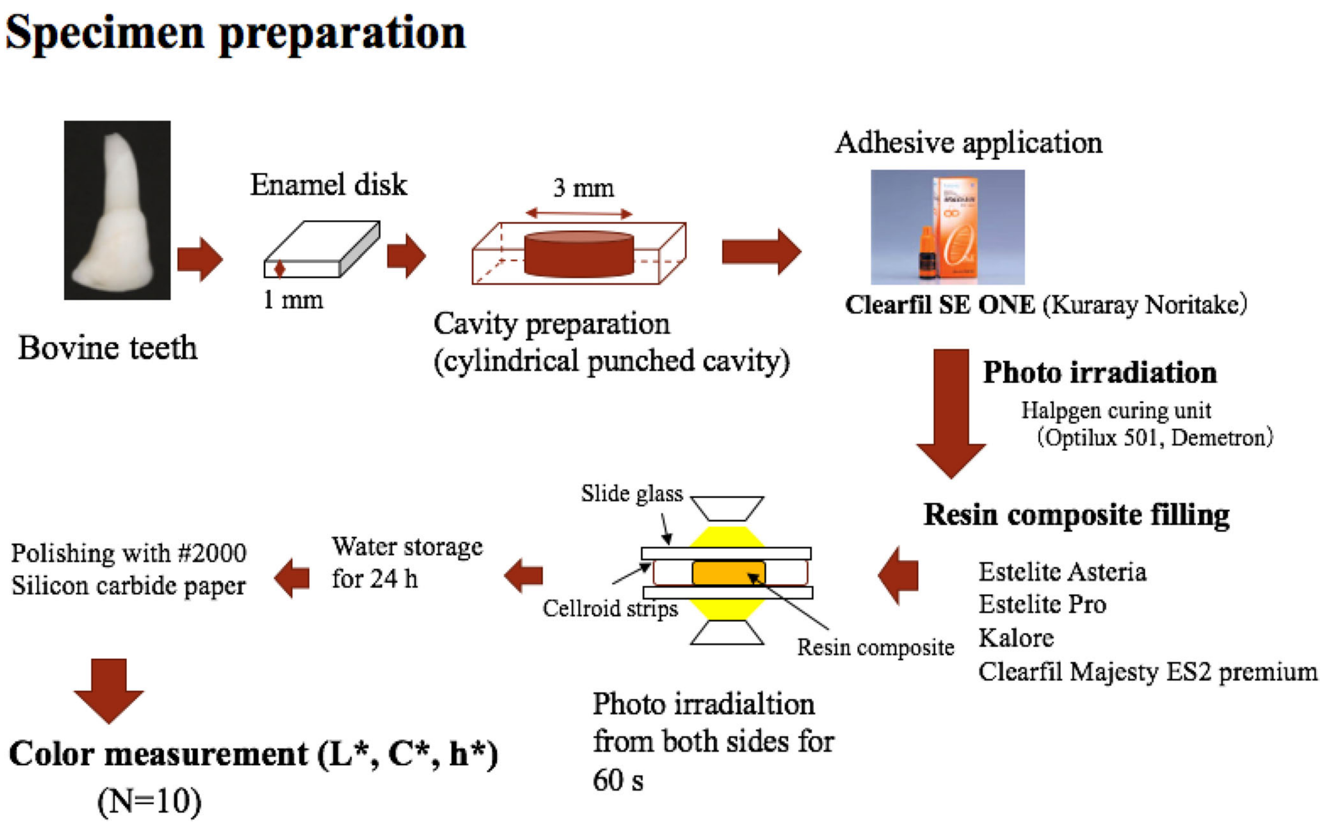

Fig. 1 Schematic illustration of sample preparation for color (L^*, C^*, or h^* values) measurement

and bottom sides, was light-cured for 60 s from both sides to sufficiently polymerize. After removig the strips and glass plates, the restored enamel disks were stored in 100% relative humidity at 37 °C for 24 h. Both surfaces of the restored enamel disks were polished using 2000-grit silicon carbide paper under running water before color measurement (Fig. 1).

The color images of the restored enamel disks over a black background (EVER-BLACK, No.0005, Evers, Osaka, Japan) were captured in a black box with 100% relative humidity, using a CIE XYZ camera (RC500, PaPaLaB, Shizuoka, Japan), from a distance of 20 cm, a duration time of 0.2 s; with a shutter speed of 1/1000 to 1/15 s, spotted with D65 standard illuminant either from coronal or cervical side at 45°/0° geometry (Fig. 2). The XYZ color information was converted to $L^*C^*h^*$ values through $L^*a^*b^*$ values as previously described [10].

The data of the L^*, C^*, and h^* values, with an average value in a square of 3 × 2 pixel (0.099 mm (w) × 0.066 mm

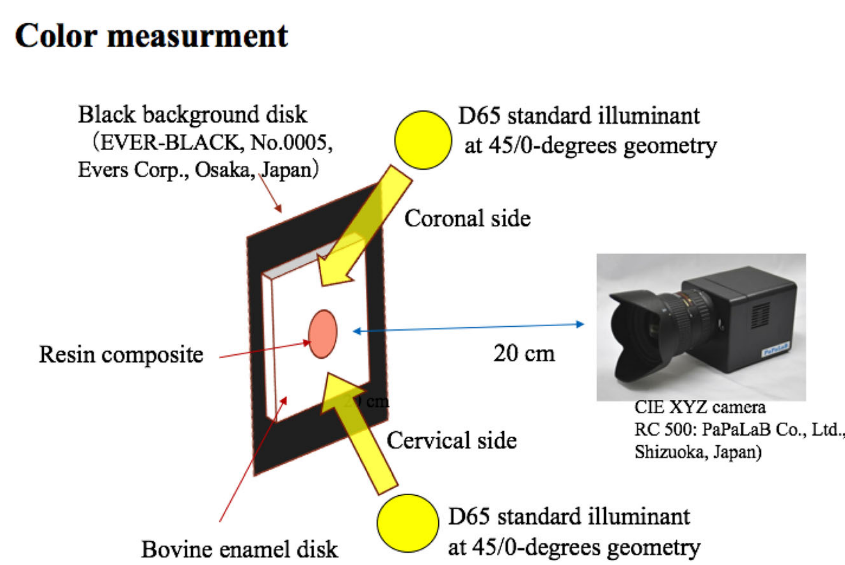

Fig. 2 Schematic illustration of color measurement on restored enamel disk. D65 standard illuminant was spotted either from coronal or cervical side at 45°/0° geometry in a black box

(h)), are graphically represented along a longitudinal direction from coronal to cervical at the centerline of the restorative materials on the enamel disks. The color shifting rate and range of each L^*, C^*, and h^* color element were calculated at the coronal and cervical borders in the composite restoration on the graphs of L^*, C^*, and h^*, as previously described (Fig. 3) [9].

The data of color shifting range and rate were analyzed using three-way ANOVA (materials, borders of composite restoration (coronal vs. cervical), light-illuminating directions) followed by post hoc analysis of Dunnett's T3 and *t* test. Statistical analysis was carried out at the significant level of 0.05 using SPSS Ver.11 (SPSS, Chicago, IL).

Results

Representative curves for changes in the L^*, C^*, and h^* color elements in the composite restorations from coronal to cervical side are presented in Figs. 4, 5, and 6. The light-illuminating direction affected the variation curve in the L^* and C^* color elements, except for Kalore. On the other hand, the h^* values in all the composite restorations were not influenced by the light-illuminating directions; therefore, the h^* shifting rate and range at the borders were not analyzed.

The results of the L^* and C^* shifting rate and range are presented in Tables 2, 3, 4, and 5. Three-way ANOVA revealed that borders ($p < 0.001$), materials ($p < 0.001$), and light-illuminating directions ($p = 0.031$) had a significant effect on the L^* color shifting rates, while the L^* color shifting ranges were significantly affected by borders ($p < 0.001$) and materials ($p = 0.009$), but not affected by light-illuminating directions ($p = 0.839$) (Tables 2 and 3). There were significant interactions in the L^* color shifting rates between borders vs. materials ($p < 0.001$) and light-illuminating directions ($p = 0.032$). For the L^* color appearance, the coronal border had a lower L^* color shifting rate and higher L^* color shifting range than the cervical border regardless of the light-illuminating directions. The light-illuminating directions affected the L^* shifting rate at the cervical-enamel border in EP and MJ ($p < 0.05$), but not in EA and KA ($p > 0.05$). On the other hand, at the coronal-enamel border, the L^* shifting rate in all the composite materials was not affected by the light-illuminating direction ($p > 0.05$). Additionally, the light-illuminating directions did not affect the L^* shifting range at both coronal and cervical borders in all the composite materials ($p > 0.05$).

Three-way ANOVA revealed that the C^* color shifting rates were significantly affected by materials ($p < 0.001$) and light-illuminating directions ($p = 0.008$), but not affected by borders ($p = 0.567$), and there were significant interactions in the C^* color shifting rates between borders vs. light-illuminating directions ($p < 0.001$) (Tables 4 and 5). On the other hand, for the C^* color shifting ranges, there were no significant differences among borders ($p = 0.785$), light-illuminating directions ($p = 0.199$), and materials ($p = 0.389$). For the C^* color appearance at the coronal-enamel border, the light-illuminating directions significantly affected the C^* shifting rate in EA, EP, and MJ ($p < 0.05$), except for KA ($p > 0.05$). On the other hand, at the cervical-enamel border, the C^* shifting rate in all the composite materials was not affected by light-illuminating direction ($p > 0.05$). The light-illuminating directions did not affect the C^* shifting range at both coronal and cervical borders in all the composite materials ($p > 0.05$).

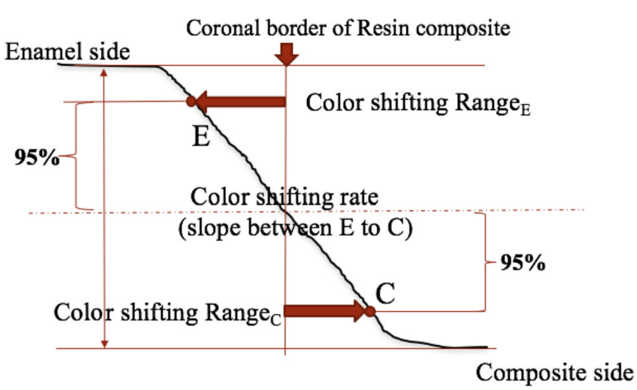

Fig. 3 The color shifting range at each border was measured as the distance from point E to C where the change in the value of each color element (L^*, C^*, or h^*) was less than 95% of the maximum value change on the enamel sides or 95% of the minimum value change on the composite sides [9]. The color shifting rate was calculated as the slope between the points of E and C [9]

Discussion

Bovine mandibular incisors can provide larger amount of enamel than human teeth. Additionally, bovine enamel has similar microstructure to human enamel with same size and shape of enamel rod, and same amounts of constituents (hydroxyapatite and organic matrix) [11, 12]. The hydroxyapatite crystals are responsible for the back-scattering of enamel [13], and the organic components (aromatic amino acids: tryptophan, tyrosin, and phenylalanine) are responsible for most or all of the observed optical absorption [14, 15]. Antiseptic such as Chloramine-T, used in storage solutions, can affect the organic components, which might affect the optical properties of enamel. Therefore, frozen-stored bovine teeth were used in this study.

The perception of tooth color is a complex phenomenon and can be influenced by a number of factors, including the visual state of the observer, the context in which the tooth is viewed and the light illumination, as well as the optical properties and color of enamel and dentin [16]. The visual perception of a composite restoration in the tooth cavity would be

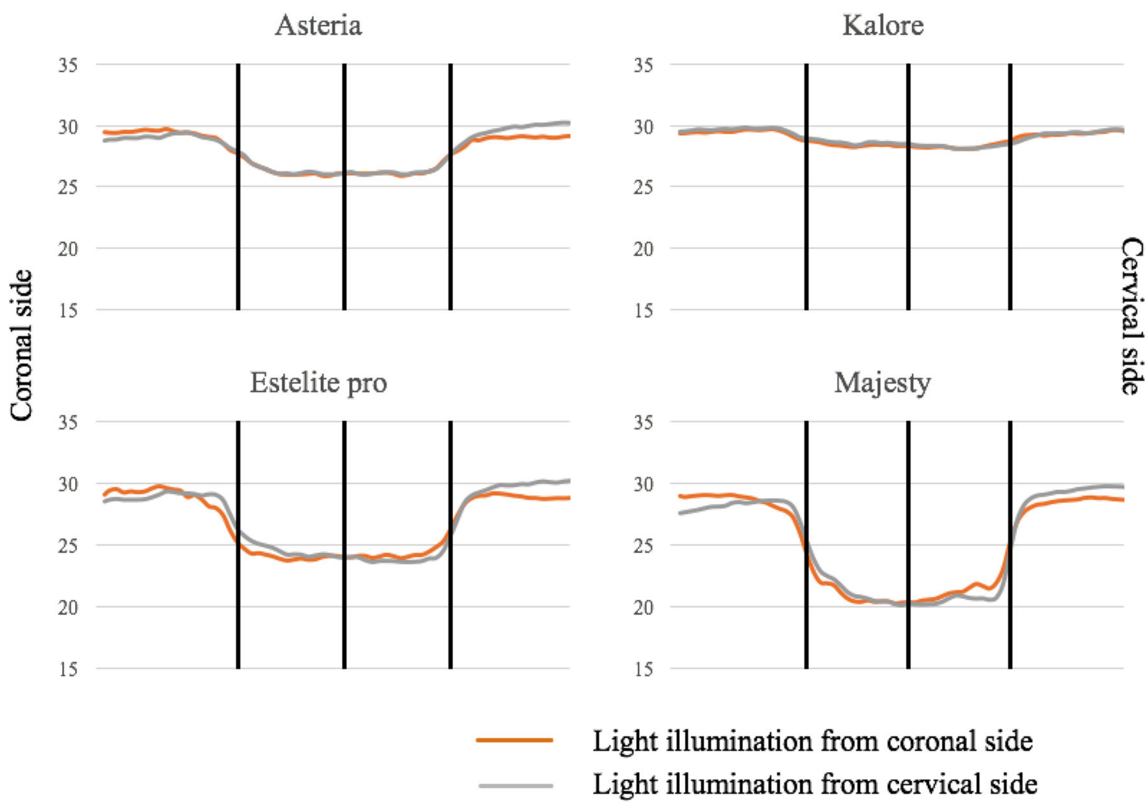

Fig. 4 The L^* values investigated along a longitudinal direction from coronal to cervical at the centerline of the composite restoration on the restored enamel disks

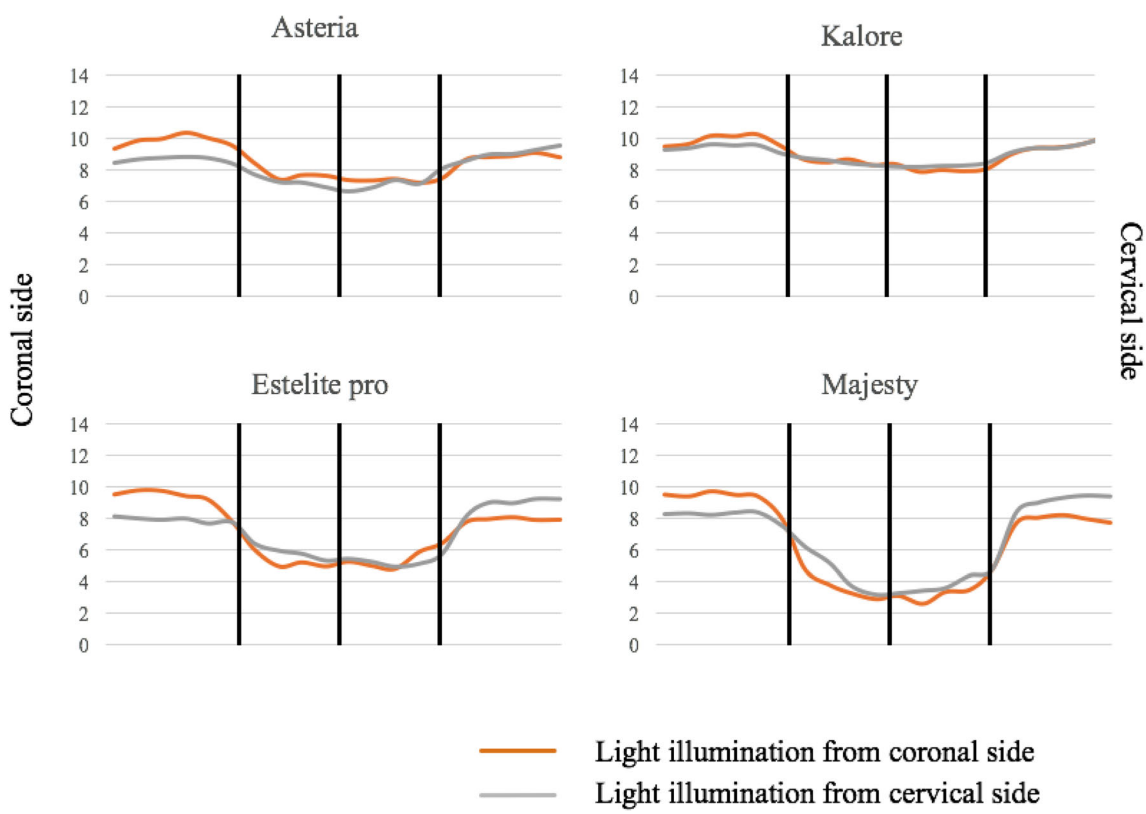

Fig. 5 The C^* values investigated along a longitudinal direction from coronal to cervical at the centerline of the composite restoration on the restored enamel disks

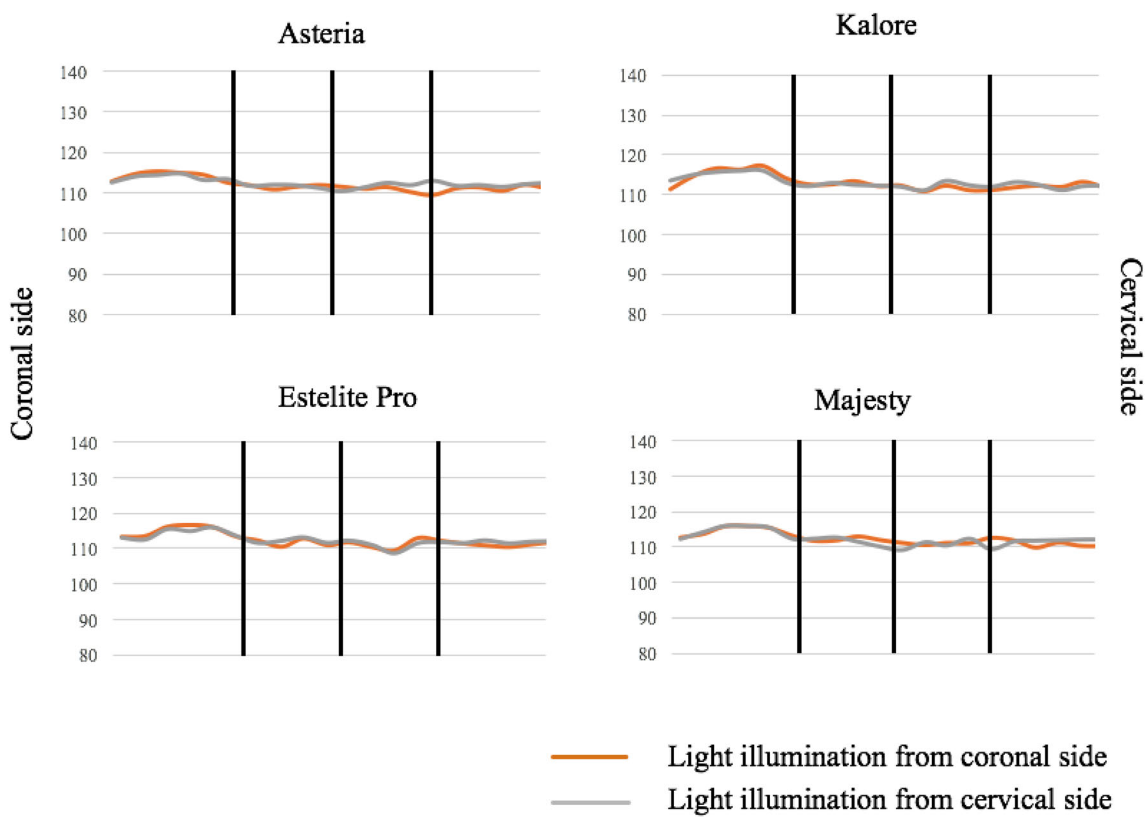

Fig. 6 The h^* values investigated along a longitudinal direction from coronal to cervical at the centerline of the composite restoration on the restored enamel disks

similarly influenced. In this study, the light-illuminating directions affected the L^* color appearance in composite restorations at the cervical border and the C^* color appearance at the coronal border, but not the h^* color appearance of both borders. Thus, the null hypotheses were partially rejected.

The color shifting phenomenon at the border in composite restoration is influenced by a mutual relationship of optical properties between the adjoining materials. Enamel rods are the most important structure regarding light scattering within enamel [13]. Additionally, enamel rods can act as optical fibers to collect and distribute light [17], and the light is transmitted following the path of the enamel rods [16]. The majority of enamel rods are arranged with their long axes at approximately 90° to the enamel-dentin junction (EDJ) [18], whereas their orientations are perpendicular towards the enamel surface in the cervical area but gradually lean in the coronal area [18]. Therefore, the enamel rod orientations are different at the margin of a Class V cavity between the coronal and cervical sides. Most of enamel rods are diagonally cut at the coronal side in the cavity margin, whereas at the cervical side, they were cut longitudinally. In this study, the coronal border had a lower L^* color shifting rate and higher L^* color shifting range than the cervical border regardless of the light-illuminating directions, which is in an agreement with the previous study with both-side light illumination from composite and enamel [9]. The gentle and widespread color shifting phenomenon at the coronal border could promote an obscure perception of the border [9]. Therefore, the coronal enamel border would have the advantage for color adjustment in composite restorations compared to the cervical border regardless

Table 2 L^* color-shifting rate

	Coronal border				Cervical border		
	Light from enamel		Light from composite		Light from enamel		Light from composite
EA	0.115 ± 0.030^{A}	NS	0.113 ± 0.013^{a}	EA	0.185 ± 0.065^{A}	NS	0.153 ± 0.102^{a}
KA	0.066 ± 0.023^{A}	NS	0.051 ± 0.012^{b}	KA	0.066 ± 0.065^{A}	NS	0.069 ± 0.034^{a}
EP	0.292 ± 0.039^{BC}	NS	0.311 ± 0.047^{cd}	EP	0.437 ± 0.047^{BC}	$p < 0.05$	0.342 ± 0.016^{ac}
MJ	0.366 ± 0.123^{AC}	NS	0.364 ± 0.100^{d}	MJ	0.700 ± 0.176^{C}	$p < 0.05$	0.500 ± 0.045^{b}

Table 3 L^* color-shifting total range with enamel and composite sides

	Coronal border				Cervical border		
	Light from enamel		Light from composite		Light from enamel		Light from composite
EA	0.772 ± 0.060[A]	NS	0.785 ± 0.146[a]	EA	0.667 ± 0.218[A]	NS	0.568 ± 0.097[a]
KA	0.660 ± 0.173[A]	NS	0.680 ± 0.087[a]	KA	0.482 ± 0.092[A]	NS	0.462 ± 0.093[a]
EP	0.607 ± 0.100[A]	NS	0.634 ± 0.1711[a]	EP	0.528 ± 0.084[A]	NS	0.598 ± 0.088[a]
MJ	0.739 ± 0.166[A]	NS	0.698 ± 0.100[a]	MJ	0.488 ± 0.166[A]	NS	0.581 ± 0.103[a]

of light-illuminating directions. The enamel rod orientations (diagonal-cut vs. longitudinal-cut enamel rod) at the cavity wall could affect light penetration from enamel to composite and from composite to enamel at the border. When light illumination is from the enamel side, the coronal border with diagonal-cut enamel rods would allow a larger amount of light penetration into the composite than the cervical border with longitudinally enamel rods. The larger amount of light reaching the coronal enamel border could enhance the L^* color shifting effect and promote gentle L^* color changes at the border, while the smaller amount of light reaching the cervical enamel border would reduce the L^* color shifting effect and caused rapid L^* color change at the border. On the other hand, when light illumination is from the composite side, the coronal enamel border would promote deeper light penetration into the surrounding enamel than the cervical enamel border. In this study, there were significant interactions in the L^* color shifting rates between borders vs. light-illuminating directions ($p = 0.032$). The light penetration behavior through the surrounding enamel would play an important role in the L^* color shifting at the enamel border.

For EP and MJ, light illumination from enamel particularly increased the L^* color shifting rate at the cervical border, leading to significant differences at the cervical border between the light-illuminating directions. KA (WE), EP (A2E), and MJ (A2E) used in this study were enamel shade composites. On the other hand, EA (A2B) used in this study was a body (dentin) shade composite, in which the manufacturer recommends direct placement on the enamel margin without use of an enamel shade composite. Generally, enamel shades of resin composite have higher transparency than dentin shade resin composite because enamel exhibits higher light transmission than dentin [19–21]. Additionally, among the enamel shade composites used in this study, EP and MJ have a higher light diffusion property than KA [9]. The lightness of transparent composites with the higher light diffusion properties would be strongly influenced by amount of the incident light. This might be a reason why EP and MJ produced larger differences in the L^* color shifting rate between the coronal border with diagonal-cut enamel rods and the cervical border with longitudinal-cut enamel rods with light illumination from the enamel side. On the other hand, the L^* color shifting rate of KA was influenced by light-illuminating directions at the coronal and cervical borders. The enamel shade of KA composite has a high straight-line light transmission property [9]. This similar characteristic to enamel might reduce effect of incident-light directions on the L^* color shifting at the border in composite restoration.

In the previous study with the both-side light illumination, the coronal border had a lower C^* color shifting rate than the cervical border [9]. However, in this study, the C^* color shifting rate was dependent upon the light-illuminating directions. That is, light illumination from enamel side increased the C^* shifting rate at the coronal border compared with at cervical border, whereas light illumination from composite side reduced the C^* shifting rate at the coronal border compared with the cervical border, except for EA. As a result, at the coronal border, light illumination from composite produced lower C^* shifting rate than light illumination from enamel. Additionally, there were significant interactions in

Table 4 C^* color-shifting rate

	Coronal border				Cervical border		
	Light from enamel		Light from composite		Light from enamel		Light from composite
EA	0.151 ± 0.065[A]	$p < 0.05$	0.081 ± 0.031[a]	EA	0.109 ± 0.058A	NS	0.079 ± 0.041[a]
KA	0.083 ± 0.043[B]	NS	0.057 ± 0.016[a]	KA	0.044 ± 0.015[A]	NS	0.072 ± 0.058[a]
EP	0.213 ± 0.074[AC]	$p < 0.05$	0.118 ± 0.055[a]	EP	0.209 ± 0.052[B]	NS	0.170 ± 0.009[bc]
MJ	0.290 ± 0.050[C]	$p < 0.05$	0.145 ± 0.061[a]	MJ	0.264 ± 0.034[B]	NS	0.233 ± 0.042[c]

Table 5 C^* color-shifting total-range with enamel and composite sides

	Coronal border				Cervical border		
	Light from enamel		Light from composite		Light from enamel		Light from composite
EA	0.574 ± 0.186^A	NS	0.495 ± 0.023^a	EA	0.508 ± 0.141^A	NS	0.495 ± 0.140^a
KA	0.465 ± 0.099^A	NS	0.521 ± 0.167^a	KA	0.601 ± 0.148^A	NS	0.5346 ± 0.205^a
EP	0.396 ± 0.153^A	NS	0.515 ± 0.163^a	EP	0.475 ± 0.044^A	NS	0.462 ± 0.132^a
MJ	0.495 ± 0.096^A	NS	0.581 ± 0.151^a	MJ	0.469 ± 0.075^A	NS	0.433 ± 0.034^a

the C^* color shifting rates between borders vs. light-illuminating directions ($p < 0.001$). It is speculated that when light illumination was from the composite side, coronal enamel with a large number of diagonal-cut enamel rods could cause C^* color shifting due to a larger amount of light penetration into the coronal surrounding enamel through the composite. On the other hand, light illumination from enamel side could not promote C^* color shifting of the resin composite through the enamel, because enamel is intrinsically colorless. These results would indicate that the line-of-vision angle affected the C^* color appearance at the coronal border in the composite restorations.

When light illumination was from the composite side, only EA body shade composite, exhibited no difference in the C^* color shifting rate between the coronal and cervical borders, although light illumination from enamel side gave similar results to the enamel shade composites (KA, EP, and MJ) with an increase of the C^* color shifting rate at the coronal border compared with the cervical border. EA had a higher opacity, and the smaller amount of light penetration into the surrounding enamel through the composite might have caused no alteration in C^* color shifting at the coronal and cervical borders when light illumination was from the composite side.

Changes of C^* color at the coronal border in composite restorations with line-of-vision angle would be aesthetically undesirable even if the coronal enamel border with diagonal-cut enamel rods had an advantage for the color adjustment in composite restoration. It has been reported that bevel preparation could improve the color adjustment in composite restorations, while reverse-bevel preparation (presence of free enamel) was not effective in improving the color adjustment in composite restoration [10]. These results might indicate that the incident-light direction from composite side could generate higher color adjustment potential at the enamel bevel in composite restoration than that from enamel side. At the coronal border, beveling would create parallel-cut enamel rods, resulting in loss of the advantage for color adjustment of composite restoration. However, a bevel preparation might be recommended at the coronal border of the cavity because at the enamel bevel, most of the light reaches enamel through resin composite regardless of light-illuminating directions.

Conclusionf

Within the limitations of this study, it was concluded that color appearance at the border in composite restorations is influenced by light-illuminating directions in conjunction with the enamel rod orientation. The orientation of the enamel rods would affect light transmission behavior within the surrounding enamel of composite restorations, depending upon incident-light directions (from enamel or composite side) to the border. At the coronal enamel border with diagonal-cut enamel rods, the C^* color shifting effect with the composite restorations was influenced by incident-light directions from enamel or composite side, and at the cervical-enamel border with longitudinal-cut enamel rods, the L^* color shifting effect in the composite restoration was slightly influenced by incident-light direction, depending upon the materials. The line-of-vision angle would affect the perception of color adaptation at the border in composite restorations, especially at the coronal-enamel border.

Author contribution statement Takashi Hatayama: Main research executor

Yukinori Kano: Sub research executor and advisor of color measurement

Asami Aida: Sub research executor and advisor of color measurement

Ayaka Chiba: Sub research executor and advisor of research model

Kento Sato: Sub research executor and advisor of research model

Naoko Seki: Sub research executor and English proofreading

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Richard M Foxton: Sub research executor and English proofreading

Junji Tagami: Sub research executor and Integration

Masatoshi Nakajima: Corresponding Author and main organizer of research model

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Compliance with ethical standards

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

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

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