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Changes in surface characteristics of dental resin composites after polishing

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The objectives of this study were (1) to determine *in vitro* changes in surface roughness and color of dental resin composites after application of three finishing and polishing systems; (2) to evaluate the difference in color stability after immersion in a dye solution after polishing; and (3) to evaluate the effects of surface condition, especially roughness, on measured color depending on the color measuring geometries of specular component excluded (SCE) and specular component included (SCI). Color and surface roughness (R_a) of resin composites of four brands of A2 shade and one brand of Yellow Enamel shade were measured after polymerization, after polishing with Enhance (Dentsply), Sof-Lex (3M ESPE), or Super-Snap (Shofu) composite finishing and polishing systems. Color was also measured after immersion in 2% methylene blue solution. Color was measured according to the CIELAB color scale. Color changes (ΔE^*_{ab}) after polishing/staining and by the measuring geometry were calculated by the equation; $\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$. Ra value was measured with a surface roughness tester. ΔE^*_{ab} and ΔL^* values after polishing and after staining varied among polishing systems when measured with SCE geometry. Composites polished with Super-Snap and Sof-Lex systems showed higher ΔE^*_{ab} and ΔL^* values than those polished with Enhance polishing system with SCE geometry. ΔE^*_{ab} and ΔL^* values between specimens with different surface conditions measured with SCE geometry were significantly higher than those with SCI ($p < 0.01$). Changes in R_a value after polishing was insignificant in most cases.

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1. Introduction

Proper finishing and polishing of dental restoratives are critical clinical procedures that enhance esthetics and longevity of restorations. The rough surface of a restoration increases plaque accumulation, which may result in gingival inflammation, superficial staining, secondary caries and color change [1]. Therefore, maintaining the smooth surface of a restoration is of utmost importance for its success [2].

Finishing refers to the gross contouring of a restoration to obtain desired anatomy, and polishing refers to the reduction of the roughness and the removal of scratches created by the finishing instruments. Although restoratives that are cured against Mylar matrix are not devoid of surface imperfections, it provides the smoothest surface possible. However, despite careful placement of matrices, removal of excess materials or recontouring of restorations is often necessary.

Finishing and polishing devices can be broadly classified into four groups [3]; (1) coated abrasives, e.g. abrasive finishing discs, (2) cutting devices, e.g. carbide burs and white stones, (3) micron-sized diamond finishing burs and other bonded or rubberized abrasives, and (4) loose, particulate abrasives, e.g. polishing pastes or powders.

In esthetic dentistry, restorative materials should duplicate the appearance of natural tooth, and failure or success of esthetic restoration depends first on the color match and then on the color stability of the material. The structure of the resin matrix and characteristics of the filler particles have a direct impact on the surface smoothness [4], and the susceptibility to extrinsic staining [5]. The roughening of the surface caused by wear and chemical degradation can affect gloss [6], and consequently can increase extrinsic staining [7]. The resin's affinity for extrinsic stains is modulated by its conversion rate [8], and its chemical characteristics and water sorption rate are also of particular importance [9–11]. An insufficient resin conversion rate will indeed favor the absorption of some colorants [8]. As for water sorption, it has been shown that materials exhibiting high water sorption rates are more easily stained by

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hydrophobic colorings in aqueous solutions, the water presumably acting as a penetration vehicle [10].

Optical properties of dental resin composites are influenced by surface changes during restorative procedures of finishing and polishing [12]. Color of teeth and of esthetic dental materials is commonly measured in reflected light by visual or instrumental technique. Two types of color measuring instrument such as colorimeter and spectrophotometer with an integrating sphere are used. A spectrophotometer can operate two different measuring geometries of specular component excluded (SCE) and specular component included (SCI) [13]. SCI geometry includes the specular component of reflected light, and SCE geometry excludes the specular component of reflected light [14, 15]. The specular component is the reflected light from the surface such that the angle of reflection equals the angle of incidence. Color measuring geometry and standard illumination influence the color measurement of dental resin composites [16].

The objectives of this study were (1) to determine *in vitro* changes in surface roughness and color of resin composites after application of three finishing and polishing systems; (2) to evaluate the difference in color stability after immersion in a dye solution; and (3) to evaluate the effects of surface condition, especially roughness, on measured color depending on the color measuring geometries of SCE and SCI.

2. Materials and methods

Four brands (five shades) of commercial resin composites were used. All except one were light cured composites intended for direct restoration, and one (Tescera; TCA2) was for indirect restoration (Table I). Filtek Supreme (FS) contained 5–15% of bisphenol A polyethylene glycol diether dimethacrylate (BisEMA), 1–10% of bisphenol A diglycidyl ether dimethacrylate (BisGMA), 5–15% of diurethane methacrylate and less than 5% of triethylene glycol dimethacrylate (TEGDMA). However, since the compositions of fillers varied by the shade, two shades were investigated. Synergy Compact (SCA2) was composed of HCM (highly cohesive molecule) resin matrix containing BisGMA, BisEMA and TEGDMA. Z100 (Z1A2) was composed of 5–15% of BisGMA and 5–15% of TEGDMA resin matrix. TCA2 was indirect dental resin composite composed of 2–15% of ethoxylated bisphenol A dimethacrylate and 2–15% of BisGMA. In this indirect composite, curing procedure consisted of two steps. Proprietary curing unit (TESCERA$^{\text{TM}}$ ATL, Schaumburg, IL, Bisco, USA) was used with the light cup and heat cup. In the first step, using the light cup and curing unit, the specimen was subjected to a pressure cycle to reduce the defects and porosity, and then the light-curing procedure was applied under the same pressure to polymerize the material. In the second step, using the heat cup and curing unit, the specimen was immersed in water, and heat was transferred quickly to the material via water.

All the resin composites were packed into a PTFE mold (10 mm in diameter and 2 mm in thickness) on a cover glass. After packing the composites, another cover glass was pressed on the top of the specimen. Specimens except for TCA2 composite were then light cured for 40 s with a light-curing unit (Spectrum 800, Dentsply/Caulk, Milford, DE, USA) with the intensity setting of 400 mW/cm^2, and the output of the light was checked with a radiometer (SDS/Kerr, Orange, CA, USA). TCA2 specimens were cured as mentioned above. Twenty specimens were prepared for each composite. Of these, five specimens were measured without any polishing procedures after removing the cover glass (CTL, control group) and five for each group were polished with Enhance (EHN, Dentsply/Caulk, Milford, DE, USA), Sof-Lex (SFX, 3M ESPE, St. Paul, MN, USA), or Super-Snap (SPS, Shofu, Kyoto, Japan).

The polishing sequence of EHN included the rubber-like polishing disks followed by the fine and super-fine polishing pastes. A slow-speed handpiece was used rotating at approximately 60,000 rpm. With light pressure, a circular pattern was used for 15 s for each polishing sequence as recommended by the manufacturer. Polishing disks and cups were discarded after each use. In the cases of the aluminum oxide polishing systems such as SFX and SPS, the polishing sequence of

TABLE I Composite resins used in this study

Code	Brand name (shade)	Filler composition	Batch number	Manufacturer
FSA2	Filtek Supreme (A2)	59.5 vol.% of aggregated zirconia/silica cluster filler of 0.6–1.4 μm with primary particle size of 5–20 nm and non-aggregated 20 nm silica filler	20030416	3M ESPE, St. Paul, MN, USA
FSYT	Filtek Supreme (Yellow Translucent)	57.7 vol.% of aggregated zirconia/silica cluster filler of 0.6–1.4 μm with primary particle size of 75 nm and a non-agglomerated/non-aggregated 75 nm silica filler	20030505	3M ESPE, St. Paul, MN, USA
SCA2	Synergy Compact (A2)	59 vol.% strontium-barium-borosilicate filler particles of 0.04–2.5 μm (average 0.6 μm)	MF475	Coltene/Whaledent, Cuyahoga Falls, OH, USA
TCA2	Tescera (A2)	72 wt.% microfilled composite (10–30 wt.% glass frit and 20–50 wt.% amorphous silica) for indirect use	0300009994	Bisco, Schaumburg, IL, USA
Z1A2	Z100 (A2)	66 vol.% of zirconia/silica filler of 0.01–3.5 μm (average 0.65 μm)	20030711	3M ESPE, St. Paul, MN, USA

medium, fine and superfine disks were used. The disks were mounted on a slow speed handpiece rotating at approximately 60,000 rpm. With light pressure, a circular pattern was used for 10 s for each abrasive step [12]. The disks were discarded following each use. The specimens were stored in 37 °C distilled water during the experiment.

After then, staining procedure was performed. Each specimen was immersed separately into 3 ml of 2% methylene blue solution at 37 °C. After 24 h, specimens were rinsed with distilled water for 30 s.

Average surface roughness (R_a) of each specimen was measured 10 times with a cutoff value of 0.8 mm, transverse length of 4.5 mm, and a measuring speed of 0.25 mm/s with a surface roughness tester (Surtronic 3P, Taylor-Hobson, Leicester, England).

Color of specimens before- and after-polishing, and after staining was measured after immersion in distilled water for one day and blotting, according to the CIELAB color scale relative to the CIE standard illuminant D65 against a white background on a reflection spectrometer (CM-3500d, Minolta, Tokyo, Japan) with SCE and SCI geometries [17]. The aperture diameter of the measuring port of the instrument was 8 mm, and the illuminating and viewing condition was CIE diffuse/8 ° geometry. Blotting was done by holding a paper tissue against the surface of the specimen for one second to produce surface similar to that of clinical condition.

Differences in color (ΔE^*_{ab}) and lightness (ΔL^*) were calculated between the specimen conditions of before- and after-polishing, and before- and after-staining. ΔE^*_{ab} was also calculated between the color measured with SCE and SCI geometries. Color difference was calculated by the equation; $\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$. A value of ΔE^*_{ab} of 3.3 was considered clinically acceptable in the present study [18].

Differences in the R_a value and the color were analyzed by analysis variance (ANOVA) and Scheffe's multiple range tests (SPSS 11, SPSS, Chicago, IL, USA, $p = 0.01$). T-test was used to compare the color coordinates with SCE and SCI geometries ($p = 0.01$). Multiple regression analysis was used to determine the correlation between the R_a value and color coordinates.

3. Result

R_a values are presented in Table II. Two-way ANOVA for R_a values after polishing by composites and polishing systems demonstrated significant effects for composites and polishing systems and a significant interaction between composites and polishing systems ($p < 0.01$). R_a values before and after polishing were not different ($p > 0.01$) except FSA2 polished with SPS.

Changes in CIE L^* value (ΔL^*) after polishing and after staining with two measuring geometries are presented in the Table III. In FSA2, ΔL^* value after polishing with SPS was higher than those of EHN and CTL with SCE geometry. In SCA2 and TCA2, ΔL^* values after polishing with SPS and SFX were higher than those of EHN and CTL with SCE geometry. However, there was no significant difference in ΔL^* values with SCI geometry. In all the composites investigated, absolute ΔL^* values after polishing measured with SCE were significantly higher than those with SCI of the polishing systems ($p < 0.01$). ΔL^* values after polishing were from −0.45 to 2.84 with SCE and from −0.08 to 0.53 with SCI. After staining, absolute ΔL^* values of FSA2 composites were generally higher than those of other composites with SCE (−8.72 to −11.57 vs. −4.26 to −8.76) and SCI (−7.90 to −10.32 vs. −2.61 to −8.03).

TABLE II R_a values before and after polishing (standard deviations are in parentheses)

Material	Polishing	Before-polishing (I)	After-polishing (II)	DG1[a]
FSA2	CTL	0.17 (0.05)	0.16 (0.04)	NS
	EHN	0.17 (0.06)	0.15 (0.04)	NS
	SFX	0.17 (0.08)	0.18 (0.05)	NS
	SPS	0.16 (0.05)	0.24 (0.04)	I<II
	DG2[b]	NS	2.1.3 < 4	NS
FSYE	CTL	0.18 (0.06)	0.18 (0.05)	NS
	EHN	0.18 (0.07)	0.18 (0.08)	NS
	SFX	0.18 (0.07)	0.21 (0.08)	NS
	SPS	0.18 (0.08)	0.17 (0.07)	NS
	DG2	NS	NS	NS
SCA2	CTL	0.21 (0.09)	0.21 (0.09)	NS
	EHN	0.21 (0.07)	0.22 (0.09)	NS
	SFX	0.21 (0.08)	0.20 (0.08)	NS
	SPS	0.20 (0.08)	0.21 (0.07)	NS
	DG2	NS	NS	NS
TCA2	CTL	0.19 (0.07)	0.19 (0.07)	NS
	EHN	0.19 (0.08)	0.16 (0.06)	NS
	SFX	0.18 (0.06)	0.21 (0.06)	NS
	SPS	0.18 (0.06)	0.19 (0.08)	NS
	DG2	NS	NS	NS
Z1A2	CTL	0.20 (0.05)	0.19 (0.07)	NS
	EHN	0.19 (0.08)	0.18 (0.06)	NS
	SFX	0.19 (0.08)	0.20 (0.07)	NS
	SPS	0.19 (0.05)	0.22 (0.06)	NS
	DG2	NS	NS	NS

[a] DG1 means different groups from t-test after polishing ($p < 0.01$). NS means not significantly different.

[b] DG2 means different groups from Scheffe's multiple range test by the polishing system ($p < 0.01$). NS means not significantly different. Numeric code 1 means CTL, 2 means EHN, 3 means SFX and 4 means SPS.

Changes in color (ΔE^*_{ab}) after polishing and after staining with two measuring geometries are shown in Table IV. Similar to the changes in L^* values, ΔE^*_{ab} value of FSA2 polished with SPS was higher than those of others with SCE geometry ($p < 0.01$).InFSYE and TCA2, there was no significant difference in ΔE^*_{ab} values by the polishing with SCE geometry. ΔE^*_{ab} values of SCA2 polished with SPS and SFX were higher than those of EHN and CTL with SCE geometry ($p < 0.01$). In all the composites investigated, ΔE^*_{ab} values after polishing measured with SCE (1.63–3.34) were higher than those with SCI (0.37–2.59) regardless of the polishing systems. After staining, ΔE^*_{ab} values of FSA2 were higher than those of other composites with SCE (20.85–26.72 vs. 8.36–16.52) and SCI (19.79–24.98 vs. 6.31–15.43).

Color difference (ΔE^*_{ab}) by the measuring geometries of SCE and SCI are shown in Table V. ΔE^*_{ab} values of before-polishing (2.12–3.72) were generally higher than those of after-polishing (0.51–3.54)

TABLE III Changes in CIE L^* value (ΔL^*) after polishing and staining with SCE and SCI geometry (standard deviations are in parentheses)

		After polishing		After staining	
Material	Polishing	SCE	SCI	SCE	SCI
FSA2	CTL	0.30 (0.42)	0.21 (0.12)	−8.72 (0.71)	−7.90 (0.58)
	EHN	1.39 (0.88)	0.11 (0.86)	−10.01 (0.64)	−9.06 (0.47)
	SFX	2.14 (0.15)	0.30 (0.11)	−11.57 (0.64)	−10.32 (0.47)
	SPS	2.82 (0.78)	0.35 (0.66)	−10.72 (1.61)	−9.94 (1.19)
	AVG[a]	1.66 (1.12)	0.24 (0.54)	−10.25 (1.43)	−9.30 (1.18)
	DG[b]	1 < 2 < 4	NS	3 < 2 < 1	3 < 2 < 1
FSYT	CTL	0.25 (0.88)	−0.09 (0.21)	−4.62 (0.51)	−3.90 (0.59)
	EHN	0.66 (0.72)	−0.07 (1.11)	−5.40 (1.14)	−3.95 (1.00)
	SFX	0.65 (0.09)	−0.01 (0.31)	−6.12 (0.34)	−4.94 (0.19)
	SPS	1.05 (1.08)	0.08 (1.01)	−6.54 (0.80)	−5.62 (0.41)
	AVG	0.66 (0.82)	−0.02 (0.76)	−5.67 (1.05)	−4.60 (0.94)
	DG	NS	NS	4 < 1	4.3 < 2.1
SCA2	CTL	−0.02 (0.25)	0.18 (0.16)	−4.26 (0.50)	−2.61 (0.34)
	EHN	1.46 (0.61)	−0.08 (0.55)	−4.67 (0.51)	−3.59 (1.56)
	SFX	2.84 (0.29)	0.21 (0.19)	−7.08 (0.55)	−5.64 (0.48)
	SPS	2.81 (0.62)	0.31 (0.61)	−5.92 (0.63)	−6.20 (1.57)
	AVG	1.77 (1.27)	0.15 (0.44)	−5.48 (1.24)	−4.51 (1.85)
	DG	1 < 2 < 4.3	NS	3 < 4 < 2.1	4.3 < 2.1
TCA2	CTL	0.08 (0.16)	0.33 (0.09)	−5.96 (2.80)	−4.55 (2.58)
	EHN	0.45 (0.49)	0.35 (0.37)	−4.83 (0.65)	−3.07 (0.61)
	SFX	1.07 (0.24)	0.31 (0.20)	−6.93 (0.75)	−5.33 (0.75)
	SPS	1.37 (0.40)	0.36 (0.36)	−6.97 (0.75)	−5.16 (0.57)
	AVG	0.74 (0.62)	0.34 (0.27)	−6.17 (1.73)	−4.53 (1.64)
	DG	1.2 < 3.4	NS	4.3 < 2	3.4 < 2
Z1A2	CTL	−0.08 (0.21)	0.12 (0.23)	−5.95 (0.32)	−5.09 (0.41)
	EHN	2.19 (0.72)	−0.05 (0.70)	−6.00 (0.41)	−4.95 (0.65)
	SFX	2.81 (0.22)	0.38 (0.17)	−8.75 (1.35)	−7.92 (1.26)
	SPS	2.70 (0.64)	0.53 (0.56)	−7.41 (0.35)	−8.03 (1.35)
	AVG	1.90 (1.28)	0.25 (0.51)	−7.03 (1.37)	−6.50 (1.78)
	DG	1 < 2.4.3	NS	3 < 4 < 2.1	4.3 < 1.2

[a] AVG means the average value of four conditions.

[b] DG means different groups from Scheffe's multiple range test by the polishing system ($p < 0.01$). NS means not significantly different among four conditions. Numeric code 1 means CTL, 2 means EHN, 3 means SFX and 4 means SPS.

in most composites. After staining, ΔE^*_{ab} values increased compared to those of before-polishing and after-polishing.

4. Discussion

Finishing and polishing procedures directly influence the esthetics and longevity of the esthetic restorations. However, resin composite materials cannot be finished to an absolutely smooth surface. Surface micromorphology of resin composites after finishing and polishing has been shown to be influenced by the size, hardness and amount of filler particles in composite [12, 19]. Microfilled and microhybrid composites can be finished to a very smooth surface with a surface roughness average (R_a) varying from 0.12 to 0.25 μm, due to their small filler particle size and arrangement [20, 21]. Average size of filler particle in microfilled composite is 0.04 μm, and a microhybrid contains particles that range between 0.01 and 2.0 μm, therefore they can be polished to a smoother surface than the conventional composites containing large filler particle. The size of the aggregated filler particle of nano-filled composite (FS of the present study) was 0.6–1.4 μm that was clustered with 5–20 nm and 75 nm primary particles, which is similar to the filler size of microhybrid resin composites. Though the size and distribution of fillers were different in the composites investigated, the range of R_a values after polishing was 0.15–0.24 μm. There were no significant changes in R_a values after polishing ($p > 0.01$) compared to those cured against cover glasses except for one case. In FSA2-SPS case, small primary particle size of 5–20 nm and relatively small non-aggregated 20 nm silica filler might have influenced the R_a value after polishing. However, the R_a value was within the clinically acceptable range [20].

Factors related to the efficiency of abrasive systems include flexibility of the backing material in which the abrasive is embedded, hardness of the abrasive, geometry of the instrument, and how the instruments are used. These factors contribute to the surface roughness of composites [22, 23]. In the present study, although three different polishing systems were employed, R_a value after polishing did not vary with the polishing systems except for FSA2 composite. Therefore, all the polishing systems of the present study performed equally well in polishing the different resin composites except for FSA2-SPS case.

For a composites finishing system to be effective, the abrasive particles must be relatively harder than the filler materials. If this is not the case, the polishing agent will only remove the soft resin matrix and leave the filler particles protruding from the surface [20]. The hardness of aluminum oxide is significantly higher than that of silicon dioxide, and generally, higher than most filler materials used in composite formulations [12]. In

TABLE IV Changes in color (ΔE^*_{ab}) after polishing and staining with SCE and SCI geometry (standard deviations are in parentheses)

		After polishing		After staining	
Material	Polishing	SCE	SCI	SCE	SCI
FSA2	CTL	0.97 (0.18)	0.59 (0.17)	20.85 (1.63)	19.79 (1.59)
	EHN	2.40 (0.45)	0.96 (0.36)	25.90 (1.51)	24.13 (1.37)
	SFX	2.57 (0.18)	0.37 (0.10)	26.72 (1.40)	24.98 (1.27)
	SPS	3.34 (0.66)	0.78 (0.55)	23.93 (1.58)	23.14 (1.66)
	AVG[a]	2.32 (0.96)	0.68 (0.40)	24.35 (2.73)	23.01 (2.45)
	DG[b]	1 < 2.3 < 4	3 < 2	1 < 4 < 3	1 < 4.2.3
FSYE	CTL	1.50 (0.60)	0.98 (0.30)	8.36 (0.77)	6.83 (0.62)
	EHN	1.65 (0.72)	1.04 (0.82)	8.49 (0.63)	6.91 (1.19)
	SFX	1.63 (0.21)	0.40 (0.28)	10.80 (0.59)	8.72 (0.47)
	SPS	2.09 (0.45)	1.31 (0.68)	11.69 (1.13)	9.60 (0.65)
	AVG	1.72 (0.56)	0.93 (0.65)	9.90 (1.66)	8.01 (1.42)
	DG	NS	3 < 4	1.2 < 3.4	1.2 < 3.4
SCA2	CTL	0.45 (0.21)	0.38 (0.12)	9.10 (0.64)	5.36 (0.53)
	EHN	2.18 (0.34)	0.59 (0.31)	9.39 (0.35)	6.78 (0.63)
	SFX	3.08 (0.20)	0.53 (0.31)	13.94 (0.75)	11.34 (0.80)
	SPS	3.08 (0.33)	0.89 (0.25)	12.59 (0.81)	10.92 (1.59)
	AVG	2.20 (1.12)	0.60 (0.31)	11.25 (2.18)	8.51 (2.78)
	DG	1 < 2 < 3.4	1.3 < 4	1.2 < 4 < 3	1 < 2 < 4.3
TCA2	CTL	2.07 (0.42)	1.89 (0.21)	11.11 (4.35)	6.31 (0.15)
	EHN	2.19 (0.94)	2.59 (0.93)	8.67 (1.01)	5.43 (0.54)
	SFX	2.19 (0.28)	1.50 (0.15)	12.83 (1.23)	9.36 (1.11)
	SPS	2.31 (0.52)	1.54 (0.60)	13.15 (1.06)	9.54 (0.83)
	AVG	2.18 (0.56)	1.81 (0.63)	11.58 (2.92)	7.86 (1.97)
	DG	NS	3.4 < 2	2 < 3.4	2.1 < 3.4
Z1A2	CTL	0.47 (0.16)	0.45 (0.19)	13.53 (0.35)	11.89 (0.85)
	EHN	3.11 (0.63)	0.97 (0.36)	11.53 (0.61)	10.15 (0.48)
	SFX	3.27 (0.27)	0.52 (0.25)	16.52 (2.01)	15.43 (1.83)
	SPS	3.24 (0.79)	0.99 (0.29)	15.62 (1.46)	15.26 (0.94)
	AVG	2.52 (1.30)	0.73 (0.37)	14.33 (2.24)	13.11 (2.48)
	DG	1 < 2.4.3	1.3 < 2.4	2 < 1 < 4.3	2 < 1 < 4.3

[a] AVG means the average value of four conditions.

[b] DG means different groups from Scheffe's multiple range test by the polishing system ($p < 0.01$). NS means not significantly different among four conditions. Numeric code 1 means CTL, 2 means EHN, 3 means SFX and 4 means SPS.

the case of microfilled resin composites, since the filler particles are small, the effect of the hardness of abrasive particle might be minimal. In the hybrid and packable resin composites, the effect of the hardness of abrasive particles might influence the R_a value. In the present study, however, the R_a values of hybrid and packable resin composites after polishing were not different from those of others. In the case of nano-filled composites, the aggregated filler might be broken into its primary filler during polishing (R_a value after polishing; 0.15–0.24 μm vs. aggregated filler size; 0.6–1.4 μm). Increased R_a value in FSA2-SPS case might reflect the incomplete breakdown of aggregated fillers. However, if the surface roughness were measured with a more precise tool such as confocal laser scanning microscope, the surface morphology could be more clearly evaluated.

Surface texture controls the degree of scattering or reflection of the light striking on the natural tooth and restorative material. With a highly polished surface, the restoration becomes more translucent and the color hue changes toward yellow-orange [24]. Spectrophotometric color measurements can differ depending on the instrumental conditions, that is, how the sample is illuminated, how the intensity of reflected light is measured, and what kind of illuminant is used. A spectrophotometer with an integrating sphere can operate two different measuring geometries such as SCE and SCI. An increasingly roughened surface will reflect the individual segment of specular beam at slightly different angles [25]. Often a dentist is satisfied with the choice of shade selected from a shade guide, but finds that the completed restoration does not match as well as expected, especially after finishing and polishing. Apparently, the finishing and polishing procedures can influence the color and gloss of a restoration. In general, polished composites tend to appear lighter, whiter, and less glossy than the corresponding Mylar-covered surface [26]. In the present study, CIE L^* values increased after polishing with SCE, which meant the lightness increased. Polishing with the aluminum oxide systems (SFX and SPS) resulted in higher changes in CIE L^* values for four of five resin composites investigated. These results were also reflected in color changes. SFX and SPC polishing systems caused higher color changes in FSA2, SCA2 and Z1A2 composites. However, R_a values after polishing were not different by the polishing systems except for FSA2. This result might suggest that other parameter for surface roughness such as the mean peak spacing (Sm) may influence color of resin composites [27]. However, all the color changes were within the clinically acceptable range ($\Delta E^*_{ab} < 3.3$) [18].

CIE L^* value reflects the lightness and CIE a^* and CIE b^* values reflect chroma of a substance. In the present study, ΔL^* values after polishing with SPS were generally higher than those after polishing with

TABLE V Difference in measured color (ΔE^*_{ab}) by the measuring geometries of SCE and SCI (standard deviations are in parentheses)

Material	Polishing	Before-polishing	After-polishing	After-staining
FSA2	CTL (1)	3.42 (0.31)	3.18 (0.41)	3.73 (0.18)
	EHN (2)	3.72 (0.11)	1.97 (0.20)	3.00 (0.32)
	SFX (3)	3.68 (0.09)	1.39 (0.18)	2.73 (0.28)
	SPS (4)	3.72 (0.23)	0.78 (0.25)	2.90 (1.86)
	AVG[a]	3.64 (0.24)	1.83 (0.93)	3.09 (1.01)
	DG[b]	1 < 4.2	4 < 3 < 2 < 1	NS
FSYE	CTL (1)	3.60 (0.79)	3.14 (0.25)	3.78 (0.43)
	EHN (2)	3.49 (0.74)	2.36 (0.31)	4.07 (0.55)
	SFX (3)	3.20 (0.04)	2.07 (0.20)	3.48 (0.37)
	SPS (4)	3.60 (0.71)	2.18 (0.39)	3.27 (0.27)
	AVG	3.47 (0.65)	2.43 (0.51)	3.65 (0.51)
	DG[a]	NS	3.4.2 < 1	4.3 < 2
SCA2	CTL (1)	3.39 (0.14)	3.57 (0.24)	5.06 (0.23)
	EHN (2)	3.35 (0.14)	1.34 (0.12)	3.35 (0.41)
	SFX (3)	3.46 (0.17)	0.51 (0.17)	2.69 (0.27)
	SPS (4)	3.34 (0.13)	0.52 (0.28)	2.55 (0.94)
	AVG	3.38 (0.15)	1.48 (1.28)	3.41 (1.13)
	DG[a]	NS	3.4 < 2 < 1	4 < 2 < 1
TCA2	CTL (1)	2.38 (0.19)	2.51 (0.26)	4.21 (0.25)
	EHN (2)	2.32 (0.35)	1.99 (0.13)	4.18 (0.45)
	SFX (3)	2.12 (0.17)	1.21 (0.16)	3.79 (0.57)
	SPS (4)	2.28 (0.12)	1.14 (0.18)	3.93 (0.48)
	AVG	2.28 (0.24)	1.72 (0.60)	4.03 (0.48)
	DG[a]	NS	4.3 < 2 < 1	NS
Z1A2	CTL (1)	3.39 (0.16)	3.54 (0.18)	4.06 (0.38)
	EHN (2)	3.47 (0.16)	0.74 (0.13)	1.98 (0.46)
	SFX (3)	3.40 (0.18)	0.57 (0.27)	1.61 (0.61)
	SPS (4)	3.22 (0.21)	0.67 (0.22)	2.05 (1.08)
	AVG	3.37 (0.20)	1.38 (1.27)	2.44 (1.17)
	DG[a]	4 < 2	3.4.2 < 1	3.2.4 < 1

[a] AVG means the average value of four conditions.

[b] DG means different groups from Scheffe's multiple range test by the polishing system ($p < 0.01$). NS means not significantly different among four conditions. Numeric code 1 means CTL, 2 means EHN, 3 means SFX and 4 means SPS.

EHN and SFX when measured with SCE geometry, and CIE L^* values with SCI did not change appreciably after polishing with all the composites (lower than 0.53 unit). Since the changes in CIE a^* and b^* values after polishing were relatively low, the changes in CIE L^* had the greatest influence on the overall color change between pairs of composites with different R_{a} values [26]. In the present study, changes in CIE L^* values also mainly influenced the color change. ΔE^*_{ab} values after polishing changed in a similar way to the changes in CIE L^* values. Though ΔE^*_{ab} measured with SCE geometry (0.47–3.34) was higher than those measured with SCI (0.37–2.59), all the color changes after polishing were clinically acceptable ($\Delta E^*_{\mathrm{ab}} < 3.3$). The change in Value (CIE L^*) measured with SCE geometry (-0.08 to 2.84) was significantly higher than those measured with SCI (-0.09 to 0.53) in a similar way to the difference in ΔE^*_{ab}. This is additional evidence that SCE geometry is more appropriate to detect small color differences of dental esthetic restorative materials when the surface conditions are not the same [16].

Color stability is critical for the long-term esthetics of restorations. Discoloration of tooth-colored, resin-based materials may be caused by intrinsic and extrinsic factors. Intrinsic factors involve the discoloration of the resin composite itself, such as the alteration of the resin matrix and of the interface of matrix and fillers. Every component of material may take part in this phenomenon. Extrinsic factors include staining by adsorption or absorption of colorants as a result of contamination from exogenous sources. The staining of polymeric materials by colored solutions [28], coffee and tea [29], nicotine [30], and beverages [31] has been reported. In the present study, FSA2 resulted in the highest staining (20.85–25.90) compared to other composites (8.36–16.52). Since FSA2 contains aggregated fillers, there might be porosity in filler particle itself. These results were in agreement with the results of Iazetti *et al.* [32], where high color change was attributed to the porosity of the glass filler particles. Color stability is directly related to the resin phase of composites and urethane dimethacrylate (UDMA) has been found to be more stain resistant than BisGMA [28]. The resin matrix of FS composite consists of four components such as BisGMA, BisEMA, UDMA and TEGDMA. Of these, TEGDMA and BisGMA are somewhat hydrophilic monomers [33]. Therefore, the combination of the porosity of the filler and the hydrophilicity of the resin matrix may have contributed to the higher stain accumulation. The exact cause should be studied further.

Indirect resin composite, TCA2 showed no difference in the change of CIE L^* value and color compared with the four direct resin composites. It showed same level of roughness and changes in Value and color after polishing. Therefore, the optical characteristics and surface conditions after polymerization and polishing of direct and indirect resin composites were similar.

In summary, the composites polished with the aluminum oxide polishing systems showed higher changes in color (ΔE^*_{ab}) and lightness (ΔL^*) than those polished with Enhance system with SCE geometry. Polishing increased the CIE L^* value (0.45–2.84 with SCE), and caused color change of 1.63–3.34 with SCE geometry. Staining susceptibility of composites was not related to surface roughness alone, and one composite showed a higher stain uptake than others. Color change after staining (8.36–26.72 with SCE) was very high. ΔE^*_{ab} and ΔL^* values measured with the SCE between the specimens of the different surface conditions were significantly higher than those with the SCI ($p < 0.01$). Therefore, SCE geometry seemed more suitable to use in the measurement of the color of dental resin composites with different surface roughness. Polishing systems investigated caused clinically acceptable color changes ($\Delta E^*_{\mathrm{ab}} < 3.3$) and clinically insignificant surface roughness increases compared to the surface cured against cover glasses except one case. Therefore three polishing systems would result in similar clinical performance.

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