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Effects of Finishing and Polishing Methods on the Surface Roughness and Surface Free Energy of Bulk-fill Resin Composites

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Clinical Relevance

The finishing and polishing methods, along with the type of resin composite, significantly affected the surface roughness and surface free energy.

SUMMARY

The purpose of this study was to determine the influence of finishing and polishing methods on surface properties of bulk-fill resin composites through surface roughness (*Ra*) and surface free energy (SFE) measurements, and scanning electron microscopy (SEM) observations. Three bulk-fill resin composites, Tetric EvoCeram Bulk Fill (TB), Filtek Bulk Fill (FB), and Filtek Bulk Fill Flowable Restorative (FF), and two conventional resin composites, Clearfil AP-X (AP) and Estelite ∑ Quick (EQ) were used. Seventy cured specimens of each resin composite were prepared and divided into seven groups of 10 specimens. *Ra*, SFE measurements, and SEM observations were conducted after finishing and polishing procedures. Three groups of specimens were finished with a fine grit diamond bur (FDB), and three with a tungsten carbide bur (CBB). After finishing, one group from each type of finishing was polished with aluminum oxide flexible disks (SSD) and one group from each type of finishing was polished with diamond particles embedded

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DOI: 10.2341/18-246-L

in a silicone point (CMP). A baseline group of samples that were neither finished nor polished after removing the translucent strips from the surface was examined. Although the baseline group showed significantly lower *Ra* values than the other groups, most resin composites showed lower *Ra* values with CBB+SSD than with the other finishing and polishing groups. Among the tested resin composites, EQ showed significantly lower *Ra* values than the other resin composites, regardless of the finishing and polishing methods. On the other hand, AP showed significantly higher *Ra* values than the other resin composites in all finishing and polishing groups, apart from FB with FDB. For the finished specimens, most resin composites showed higher SFE values with CBB than with FDB. For the polished specimens, all the tested resin composites with CMP showed lower γ_S values than those with SSD, regardless of the finishing method. The baseline groups of TB and FB showed significantly lower SFE values than the other finished and polished groups. In the SEM observations, all the examined resin composites showed rougher surfaces after finishing with FDB than with CBB. However, when comparing the different polishing methods (CMP and SSD), surface smoothness appeared to be material dependent.

INTRODUCTION

Recent improvements in direct resin composite technology have led to their increased use in the treatment of posterior lesions.[1] Various types of resin composites with distinctive features, such as esthetics, low shrinkage, favorable mechanical properties, and good handling features, have been introduced in clinical settings.[2,3] In particular, bulk-fill resin composites have been extensively adopted because of their ability to reduce contraction stress along with the number of necessary clinical steps.[4,5] Single-layer bulk-fill resin composites can be used to create thicknesses of up to 4 mm with adequate light irradiation.[6-8] These composites show rapid activation of polymerization thanks to modified initiation systems, and they also have increased translucency due to decreased filler load and increased filler size.[9,10] In addition, high-viscosity bulk-fill resin composites that can be used efficiently as conventional resin composites are also available.[3,11] Although the surface and mechanical properties of these materials are sufficient for use in high-stress-bearing areas, the information available on their surface characteristics is limited compared with low-viscosity bulk-fill resin composites.

Irregularities in restoration surfaces resulting from inappropriate finishing and polishing may create problems in clinical use, including staining, plaque accumulation, restoration degradation, and gingival inflammation.[12-16] Furthermore, rough surfaces on occlusal contact areas also induce friction, leading to wear on the surface of the opposing tooth.[17] Thus, appropriate finishing and polishing procedures are important in order to obtain the desired esthetics and to ensure the properties of the resin composite restorations.

The surface properties of polished resin composites are typically evaluated on the basis of surface roughness, gloss, and morphologic observation. Although these characteristics provide useful information about the surface properties after finishing and polishing, they are less helpful for understanding the chemical interactions between the polished surfaces and adhering substances in the oral environment (eg, salivary glycoproteins, plaque, and stains).[18] In solids, the surface free energy (SFE) is an important parameter that determines the chemical interactions that occur at the surface. SFE is related to the work of adhesion and interfacial tension with liquids[19,20] and can be calculated by measuring contact angles with different liquids of known SFE (eg, 1-bromonaphthalene, diiodomethane, and distilled water). The measurement of contact angles is an established method to understand changes in surface characteristics resulting from chemical interactions between mineralized tissue and functional monomers or the influence of the oxygen-inhibited layer of adhesives.[19-21] However, few studies have been carried out on polishing methods for resin composites from the perspective of interface science. Therefore, it would be valuable to determine the SFEs of the polished surfaces of resin composites.

The objectives of this study were to determine the effects of different finishing and polishing methods on the surface roughness and SFE of bulk-fill resin composites and to compare their surface properties with those of conventional resin composites. The null hypothesis was that the surface roughness and SFE of resin composites are not affected by the finishing and polishing methods or the type of resin composite.

METHODS AND MATERIALS

Study Materials

The components of resin composites used in this study are shown in Table 1. Three bulk-fill resin

Table 1: *Materials Used in This Study*

Code	Resin Composite (Shade: Lot No.)	Main Components	Type of Resin Composite	Manufacturer
TB	Tetric EvoCream Bulk Fill (A2: T21387)	bis-GMA, UDMA, ytterbium trifluoride, Ba glass filler, mixed oxide, prepolymer filler, EBPADMA, additives, catalysts, stabilizers, pigments	High-viscosity bulk-fill	Ivoclar vivadent Schaan, Lichtenstein
FB	Filtek Bulk Fill Posterior restorative (A2: N701975)	Silane-treated ceramic, aromatic UDMA, ytterbium fluoride, UDMA, silane-treated silica, DDDMA, silane-treated zirconia, water, modified methacrylate monomer, EDMAB, benzotriazol	High-viscosity bulk-fill	3M ESPE, St Paul, MN, USA
FF	Filtek Bulk Fill Flowable restorative (A2: N865208)	Silane-treated ceramic, bis-GMA, UDMA, EDMAB, substituted dimethacrylate, bis-EMA, TEGDMA, benzotriazol, ytterbium fluoride,	Low-viscosity bulk-fill	3M ESPE
AP	Clearfil AP-X (A2: CC0043)	bis-GMA, TEGDMA, silane barium glass filler, silane silica filler, silanated colloidal silica, catalysts, accelerators, CQ, pigments, others	Conventional (small particle hybrid)	Kuraray Noritake Dental Tokyo, Japan
EQ	Estelite $\sum$ quick (A2:154095P)	bis-GMA, TEGDMA, silica-zirconia filler, dibutyl hydroxy toluene	Conventional (supra-nano filled)	Tokuyama Dental Tokyo, Japan
	Finishing Bur	**Model**		
FDB	Super fine grit diamond bur	SF102R		Shofu, Kyoto, Japan
CBB	Tungsten carbide bur	FG7714 (12 blades)		Kerr, Orange, CA, USA
	Polishing System			
CMP	Compomaster (one-step system)	One step diamond polisher (6-μm) silicone base (25%), diamond particles (75%)		Shofu
SSD	Super-Snap (multi-step system)	Fine: green: ϕ12-mm disk; 20-μm aluminium oxide		Shofu
		Superfine: red: ϕ12-mm disk; 7-μm aluminium oxide		

Abbreviations: AP, Clearfil AP-X; bis-EMA, bisphenol A polyethylene glycol diether dimethacrylate; bis-GMA, 2,2-bis[4-(2-hydroxy-3-methacryloyloxypropoxy) phenyl) propane; CBB, tungsten carbide bur; CMB, Compomaster; CQ, dl-camphorquinone; DDDMA, 1,12-dodecane dimethacrylate; EBPADMA, ethyoxylated bisphenol A dimethacrylate; EDMAB, ethyl 4-dimethyl aminobenzoate; EQ, Estelite $\sum$ quick; FB, Filtek Bulk Fill Posterior restorative; FDB, super fine grit diamond bur; FF, Filtek Bulk Fill Flowable restorative; SSD, Super-Snap; TB, Tetric EvoCream Bulk; TEGDMA. triethyleneglycol dimethacrylate; UDMA, urethane dimethacrylate.

composites (Tetric EvoCeram Bulk Fill [TB; Ivoclar Vivadent, Schaan, Liechtenstein], Filtek Bulk Fill [FB; 3M ESPE, St Paul, MN, USA], and Filtek Bulk Fill Flowable Restorative [FF; 3M ESPE]) along with two conventional resin composites (Clearfil AP-X [AP; Kuraray Noritake Dental, Tokyo, Japan] as a hybrid resin composite and Estelite $\sum$ Quick [EQ; Tokuyama Dental, Tokyo, Japan] as a supra-nano-filled resin composite) were tested.[1] A halogen quartz tungsten curing unit (Optilux 501, SDS Kerr, Danbury, CT, USA) was used to avoid any influence of the reported nonuniformity of light-emitting diode (LED) curing units.[22,23] The light irradiance (average=600 mW/cm^2) of the curing unit was confirmed using a dental radiometer (Model 100, Kerr).

Inorganic Filler Content

The inorganic filler content of the resin composites was evaluated using thermogravimetry and differential thermal analysis (TG/DTA6300, Seiko Instruments, Tokyo, Japan). A paste of each resin composite (50 mg) was placed in a pure platinum cylindroid crucible (diameter=7 mm, depth=10 mm) and heated in the thermogravimeter from 25°C to 800°C at a heating rate of 10°C/min in atmospheric air until the organic components were completely incinerated. The weight of the residual resin paste was automatically measured using the built-in differential balance, which has a high sensitivity and horizontal accuracy. The inorganic filler content (wt%) was then calculated on the basis of the compensated blank curve. Six measurements per test material were evaluated to obtain an average inorganic filler content.

Specimen Preparation for Finishing and Polishing

The specimens for finishing and polishing were prepared in cylindrical Teflon molds (height=2.0 mm, diameter=10.0 mm; Sanplatec Corp, Osaka, Japan). One end was sealed with a translucent polyester matrix tape (Matrix Tape and Dispenser, 3M ESPE), and the resin paste was inserted from the open end. The other end was then sealed in the same way, and pressure was applied manually through a glass plate. Subsequently, both the top and bottom of

the mold were irradiated with light for 30 seconds. The mold was then cut open with a scalpel and removed from the cured resin composite. The specimens were stored in the dark at 25°C for 24 hours before finishing and polishing to allow postirradiation polymerization to reach a stable state.[24] Seventy specimens were prepared for each resin composite.

Finishing and Polishing Procedures

The 70 specimens of each resin composite were treated in the following way. The specimens were divided into seven groups of 10, and one group was set aside without further treatment to serve as a baseline measurement. The specimens in the remaining six groups were ground flat with 320-grit silicon carbide paper (Fuji Star Type DDC, Sankyo Rikagaku Co, Saitama, Japan) under water as a coolant. Three of the groups were finished using a superfine-grit diamond bur (FDB; SF102R, Shofu, Kyoto, Japan), and the other three were finished using a tungsten carbide bur (CBB; FG7714, long tapered trimming, Kerr). The finishing procedures were performed using a high-speed handpiece under spraying water as a coolant. The finishing procedures were carried out with a light hand pressure in multiple directions, and the burs were changed after five uses. In addition, in order to guarantee the flatness of the finished and polished samples, the sample thickness was measured using a dial gauge micrometer (CPM15-25DM; Mitutoyo, Tokyo, Japan) at five locations. From the three groups finished by each method, one was set aside for measurement. One of the two remaining groups was polished using the one-step point-type polishing system CompoMaster (CMP; Shofu), and the other was polished using the multistep polishing system Super-Snap Rainbow Technique Kit (SSD; Shofu). All polishing procedures were carried out using a slow-speed handpiece (5000 rpm) with a contact pressure of 1.0 N monitored by a digital balance (AT200, Mettler, Greifensee, Switzerland) underneath the specimen. The specimens were finished and polished by a single operator to reduce variability between samples. The final groups of specimens for each composite were as follows: a) no treatment; b) ground, finished with FDB; c) ground, finished with CBB, d) ground, finished with FDB, polished with CMP; e) ground, finished with CBB, polished with CMP; f) ground, finished with FDB, polished with SSD; g) ground, finished with CBB, polished with SSD.

Measurement of Surface Roughness (Ra)

Before the measurement of surface roughness (*Ra*), the specimens were cleaned with distilled water in an ultrasonic cleaner for 1 min and dried with oil-free air. The surfaces of all specimens were observed using a three-dimensional laser scanning microscope (VK-8700, Keyence, Osaka, Japan). The spectral maximum of the excitation light was 658 nm, and the intensity of the excitation light, along with the amplification of the photomultiplier, was kept constant during the observation period. Using software (VK Analyzer, Keyence), the *Ra* values of 10 specimens in each group in 1.0 mm $\times$ 1.0 mm regions were measured. Profilometric measurements were conducted in five regions near the centers of the specimens. The means were then determined for each group.

SFE Measurements

Specimens for SFE measurements were prepared as for the *Ra* measurements, as described earlier. Each resin composite surface was treated in accordance with the experimental protocol for the finishing and polishing procedures. The contact angles of the specimens, including those in the baseline group, were measured in order to evaluate the surface characteristics of each specimen surface. SFE was determined by measuring the contact angles on the specimen surfaces using three test liquids with known SFE parameters: 1-bromonaphthalene, diiodomethane, and distilled water.[19-21] A contact angle meter (Drop Master DM500, Kyowa Interface Science, Saitama, Japan) connected to a charge-coupled device camera was used for automatic measurements of the contact angles.

The equilibrium contact angle (θ) was measured for each test liquid on 10 specimens for each condition using the sessile-drop method at 23 $\pm$ 1°C. Sessile drops (volume=1.0 μL) of each liquid were dispensed using a micropipette. The SFE parameters of the solids were then determined on the basis of the following fundamental concepts of wetting. The Young–Dupré equation relates the work of adhesion for a solid (S) and liquid (L) that are in contact (W_{SL}), the interfacial free energy between the solid and the liquid (γ_{SL}), and the free energies of the liquid and solid (γ_L and γ_S, respectively) as follows:

$$W_{SL} = \gamma_L + \gamma_S - \gamma_{SL} = \gamma_L(1 + \cos\theta).$$

Extending the Fowkes equation following the Kitazaki–Hata approach[25] gives

$$\gamma_{SL} = \gamma_L + \gamma_S - 2(\gamma_L^d\gamma_S^d)^{1/2} - 2(\gamma_L^p\gamma_S^p)^{1/2} - 2(\gamma_L^h\gamma_S^h)^{1/2},$$

$$\gamma_L = \gamma_L^d + \gamma_L^p + \gamma_L^h\gamma_S = \gamma_S^d + \gamma_S^p + \gamma_S^h,$$

where γ^d, γ^p, and γ^h are the components of the SFE (γ) arising from the dispersion force, the polar (permanent and induced) force, and the hydrogen-bonding force, respectively. The θ values were determined for the three test liquids, and the surface-energy parameters of the treated enamel surfaces were calculated using the earlier equations using add-on software along with an interface measurement and analysis system (FAMAS, Kyowa Interface Science).

Scanning Electron Microscopy (SEM) Observations—After polishing the cured resin composite specimens to a high gloss using abrasive discs (Fuji Star Type DDC), they were further polished using a series of diamond pastes down to a particle size of 0.25 μm (DP-Paste; Struers, Ballerup, Denmark). The polished surfaces were then subjected to argon-ion beam etching (IIS-200ER; Elionix Inc, Tokyo, Japan) for 40 seconds with the ion beam directed perpendicular to the polished specimen surface (accelerating voltage=1 kV, ion current density=0.4 mA/cm^2). The surfaces were then coated with a thin film of gold in a vacuum evaporator (Quick Coater Type SC-701; Sanyu Denchi, Tokyo, Japan). Scanning electron microscopy (SEM; FE-8000, Elionix Inc) observations were conducted at an operating voltage of 10 kV and magnifications of 5000× and 30,000×.

Representative samples of the five resin composites polished using different methods were also examined by SEM. The surfaces of the samples were rinsed with tap water after the finishing or polishing procedures followed by evaporation coating. The coated surfaces were visualized by SEM at an operating voltage of 10 kV and a magnification of 2,500×.

Statistical Analysis

A power analysis indicated that at least four samples were necessary for effective measurement of inorganic filler content and eight samples were necessary for *Ra* and SFE measurements. Thus, this study was initially performed with sample sizes of five for inorganic filler content measurement and 10 for *Ra* and SFE measurements. After gathering the data, post hoc power tests were performed using two statistical software systems (G Power calculator version 3.1; http://www.gpower.hhu.de/, and Sigma Plot version 13.0; Systat Software, Inc, Chicago, IL, USA). These tests indicated that the sample size was adequate.

Based on the normal distribution (Kolmogorov–Smirnov test), the data for each test were subjected to analysis of variance (ANOVA) followed by the Tukey honestly significant difference test at a significance level of 0.05. One-way ANOVA was used for inorganic filler content, whereas two-way ANOVA, with the polishing method and type of resin composite as the factors, was used for the *Ra* and SFE data. Statistical analyses were carried out using commercially available statistical software (SigmaPlot version 11.0; SPSS Inc, Chicago, IL, USA).

Table 2: *Inorganic filler contents (wt%)*

	Inorganic Filler Content, mean (SD)	Tukey Group[a]
TB	77.4 (0.4)	b
FB	75.2 (0.3)	c
FF	63.8 (0.4)	e
AP	83.8 (0.5)	a
EQ	67.3 (0.4)	d

Abbreviations: AP, Clearfil AP-X; EQ, Estelite ∑ quick; FB, Filtek Bulk Fill Posterior restorative; FDB, super fine grit diamond bur; FF, Filtek Bulk Fill Flowable restorative; TB, Tetric EvoCream Bulk.
[a] Same lowercase letter in vertical columns indicates no difference at 5% significance level.
Values in parenthesis indicates standard deviation.

RESULTS

Inorganic Filler Content

The inorganic filler content of the resin composites are shown in Table 2. The average inorganic filler content ranged from 63.8 to 83.8 wt% and depended on the material. The inorganic filler content decreased in the following order: AP > TB > FB > EQ > FF. The hybrid conventional resin composite AP showed a significantly higher inorganic filler content than the other resin composites. In contrast, the low-viscosity bulk-fill resin composite FF showed a significantly lower inorganic filler content than the other resin composites.

Ra *Values*

The *Ra* values of the resin composites are shown in Table 3. The low *Ra* values observed in the baseline groups are artifacts of the experimental protocol and are not representative of unfinished composites in clinical settings. The two-way ANOVA results indicate that the finishing and polishing methods, along with the type of resin composite, significantly affected *Ra* ($p<0.001$). The two-way interaction between these two factors was also significant ($p<0.001$). All the finished and polished groups showed significantly higher *Ra* values than the baseline groups, regardless of the type of resin composite. In particular, the resin composites fin-

Table 3: *Influence of Finishing and Polishing Procedures on Surface Roughness, Ra, mean μm (SD)*

	Baseline	FDB	CBB	FDB+CMP	CBB+CMP	FDB+SSD	CBB+SSD
TB	0.08 (0.01) aE	0.68 (0.05) cA	0.39 (0.02) dC	0.43 (0.01) dB	0.32 (0.05) cD	0.29 (0.01) bD	0.31 (0.01) bD
FB	0.09 (0.01) aF	0.99 (0.02) aA	0.68 (0.01) bB	0.49 (0.01) cC	0.48 (0.01) bC	0.31 (0.01) bD	0.25 (0.01) cE
FF	0.08 (0.01) aG	0.88 (0.02) bA	0.59 (0.01) cB	0.54 (0.01) bC	0.45 (0.02) bD	0.31 (0.01) bE	0.26 (0.01) cF
AP	0.09 (0.01) aE	0.87 (0.02) bA	0.80 (0.01) aB	0.86 (0.04) aA	0.76 (0.02) aC	0.75 (0.02) aC	0.64 (0.01) aD
EQ	0.08 (0.02) aD	0.62 (0.02) dA	0.30 (0.02) eB	0.28 (0.01) eB	0.28 (0.01) dB	0.22 (0.01) cC	0.21 (0.01) dC

Abbreviations: AP, Clearfil AP-X; CBB, tungsten carbide bur; CMB, Compomaster; EQ, Estelite ∑ quick; FB, Filtek Bulk Fill Posterior restorative; FDB, super fine grit diamond bur; FF, Filtek Bulk Fill Flowable restorative; SSD, Super-Snap; TB, Tetric EvoCream Bulk.
[a] Same lowercase letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.

ished with FDB showed higher *Ra* values than the other finishing and polishing groups. In contrast, the CBB+SSD groups showed lower *Ra* values than the other groups, with the exception of the baseline groups. Upon comparing the different finishing procedures (FDB and CBB), CBB resulted in significantly lower *Ra* values than FDB, regardless of the type of resin composite. Among the polishing methods, SSD resulted in significantly lower *Ra* values than CMP, regardless of the finishing method. Among the tested resin composites, EQ showed significantly lower *Ra* values than the other resin composites, regardless of the finishing and polishing methods. In contrast, AP showed significantly higher *Ra* values than the other resin composites in all finishing and polishing groups, with the exception of FB with FDB. For the bulk-fill resin composites, FB groups without polishing showed significantly higher *Ra* values than the other bulk-fill resin composites.

SFE Parameters—The total SFE (γ_S) values and the three corresponding parameters are shown in Table 4 and Figure 1. Two-way ANOVA revealed that the finishing and polishing methods, along with the type of resin composite, significantly affected the γ_S value ($p<0.001$). The two-way interaction between the factors was also significant ($p<0.001$).

For the finished specimens, most resin composites showed higher γ_S values with CBB than with FDB. For the polished specimens, all the tested resin composites with CMP showed lower γ_S values than those with SSD, regardless of the finishing method. Considering each resin composite across different finishing and polishing groups, the baseline groups of TB and FB showed significantly lower γ_S values than the other finished and polished groups. Comparing the resin composites in the groups finished with FDB and CBB, AP with SF resulted in a significantly higher γ_S value than the other resin composites; however, the γ_S value of AP was not significantly higher than those of FB and EQ with CBB. On the other hand, TB and FF showed lower γ_S values than the other resin composites with CBB. For groups polished with CMP, EQ showed significantly lower γ_S than the other resin composites. In contrast, for SSD, AP had significantly lower γ_S values than the other resin composites. In both cases, these trends did not depend on the finishing method.

Next, we examined the different components of γ_S. In all groups, the dispersion force (γ_S^d) showed a similar value of approximately 41 $mN \cdot m^{-1}$, whereas the polar force (γ_S^p) and hydrogen-bonding force (γ_S^h) varied by group. In terms of γ_S^p (Table 5), the resin composites could be classified into three groups: 1) for TB and FB, although the baseline groups showed somewhat lower γ_S^p values, finishing and polishing tended to increase γ_S^p; 2) for AP, although the groups

Table 4: *Influence of Finishing and Polishing Procedures on Total Surface Free Energy, mean (SD).* [a]

	Baseline	FDB	CBB	FDB+CMP	CBB+CMP	FDB+SSD	CBB+SSD
TB	44.1 (0.5) cD	48.2 (1.2) bAB	46.8 (1.1) bBC	47.9 (1.4) bABC	46.5 (1.2) aC	48.4 (1.3) cA	47.3 (0.9) cABC
FB	42.6 (0.8) dE	49.1 (0.8) bC	54.2 (1.3) aA	49.2 (1.4) aC	47.3 (0.8) aD	51.7 (1.1) aB	52.4 (1.1) aB
FF	48.3 (1.1) aA	45.2 (1.1) cBC	47.7 (0.9) bAB	43.9 (1.0) cC	46.4 (2.0) aB	49.0 (1.3) bcA	49.3 (1.3) bA
AP	47.3 (0.9) abC	50.9 (1.2) aB	55.3 (1.1) aA	43.8 (1.1) cE	44.7 (0.6) bDE	45.3 (0.9) dD	45.8 (0.8) dD
EQ	47.1(1.1) bC	48.6 (1.2) bC	54.9 (1.2) aA	42.2 (1.0) dD	42.4 (1.3) cD	50.2 (1.1) bB	49.6 (1.1) bBC

Abbreviations: AP, Clearfil AP-X; CBB, tungsten carbide bur; CMB, Compomaster; EQ, Estelite ∑ quick; FB, Filtek Bulk Fill Posterior restorative; FDB, super fine grit diamond bur; FF, Filtek Bulk Fill Flowable restorative; SSD, Super-Snap; TB, Tetric EvoCream Bulk.
[a] Same lowercase letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.

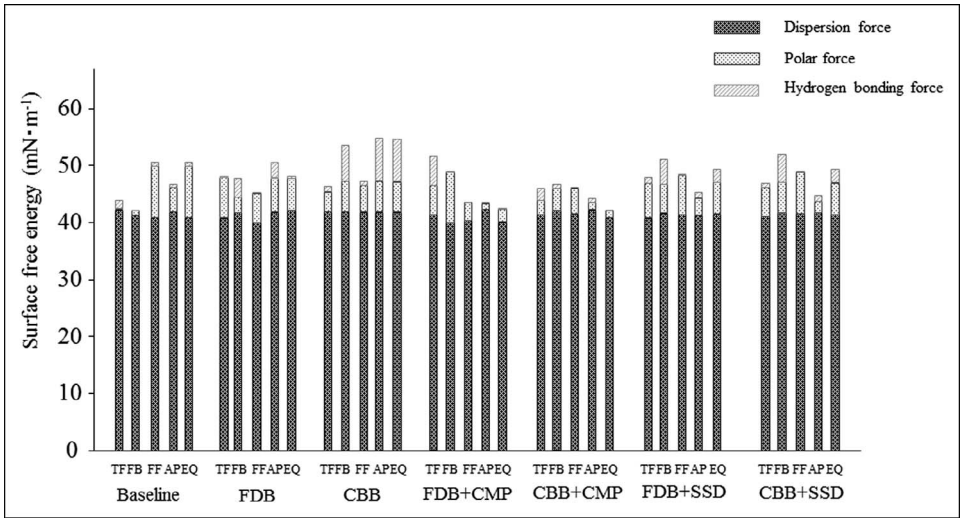

Figure 1. *The total SFE (γ_S) values and the three corresponding parameters.*

finished with FDB and CBB showed significantly higher $\gamma_S{}^p$ values than the baseline group, all polished groups showed significantly lower $\gamma_S{}^p$ values than the baseline and finishing groups; 3) for FF and EQ, the SSD groups showed somewhat higher $\gamma_S{}^p$ values than the other groups, whereas the CMP groups showed lower $\gamma_S{}^p$ values.

The observed changes in $\gamma_S{}^h$ (Table 6) depended strongly on the composite material, along with the finishing and polishing methods. Overall, FF showed low $\gamma_S{}^h$ and significantly lower $\gamma_S{}^h$ values in the finished and polished groups than the baseline group. In contrast, the other resin composites generally showed higher $\gamma_S{}^h$ values after finishing or polishing. AP and EQ showed significantly higher $\gamma_S{}^h$ values with CBB than the other groups. FB and EQ showed significantly higher $\gamma_S{}^h$ values with SSD than with CMP, regardless of the finishing method. Compared with the other resin composites, the TB groups showed significantly higher $\gamma_S{}^h$ values with CMP than with SSD, and the $\gamma_S{}^h$ values were significantly higher than those for the other resin composites, regardless of the finishing method.

SEM Observations—The SEM images of polished surfaces after argon-ion etching are shown in Figure 2. The shapes, sizes, and distributions of inorganic fillers depended on the composite material. In the high-viscosity bulk-fill resin composite TB, 0.5–2.0 μm irregular fillers and nanosized spherical fillers were packed at a high density (Figure 2A). In addition to the nanosized spherical fillers used in TB, FB included 0.5–5.0 μm aggregates of filler particles (Figure 2B). FF was similar to FB but had larger interspaces between filler particles (Figure 2C). The hybrid composite AP had 0.5–10.0 μm irregular fillers (Figure 2D). EQ had nanosize spherical fillers and pre-polymerized fillers that use the same nanosize spherical fillers (Figure 2E).

Representative SEM images of the resin composite surfaces after different finishing and polishing methods are shown in Figures 3 through 7. All the examined resin composites showed rougher surfaces after finishing with FDB than with CBB (Figures 3AB, 4AB, 5AB, 6AB, and 7AB). Evidence of scratches and plucked-out filler was obvious after FDB finishing. More specifically, the plucking out of aggregated fillers in FF and FB, pre-polymerized

Table 5: *Influence of Finishing and Polishing Procedures on Polar Force, mean (SD)* [a]

	Baseline	FDB	CBB	FDB+CMP	CBB+CMP	FDB+SSD	CBB+SSD
TB	0.2 (0.1) cD	7.2 (1.8) aA	3.5 (0.9) bC	3.2 (0.7) bC	2.7 (1.0) bcC	6.2 (1.2) abAB	5.2 (1.3) bB
FB	1.0 (0.6) cD	2.8 (0.7) cC	5.4 (1.1) aB	9.0 (1.4) aA	3.9 (0.8) abC	5.2 (0.9) bB	5.4 (0.9) bB
FF	4.3 (1.0) bBC	5.4 (0.9) bB	4.8 (0.9) abBC	3.3 (1.1) cBC	4.7 (1.9) aC	7.1 (0.8) aA	7.5 (1.3) aA
AP	4.3 (0.8) bB	6.0 (1.0) abA	5.5 (0.9) aA	1.3 (0.8) dD	1.4 (0.5) cD	3.1 (0.7) cC	2.0 (0.7) cD
EQ	5.5 (1.0) aA	5.8 (1.0) abA	5.4 (1.3) aA	2.4 (1.3) cdB	1.3 (1.0) cB	5.7 (1.0) bA	5.7 (1.0) bA

Abbreviations: AP, Clearfil AP-X; CBB, tungsten carbide bur; CMB, Compomaster; EQ, Estelite ∑ quick; FB, Filtek Bulk Fill Posterior restorative; FDB, super fine grit diamond bur; FF, Filtek Bulk Fill Flowable restorative; SSD, Super-Snap; TB, Tetric EvoCream Bulk.
[a] *Same lowercase letter in vertical columns indicates no difference at 5% significance level.*
Same capital letter in horizontal rows indicates no difference at 5% significance level.

Table 6: *Influence of Finishing and Polishing Procedures on Hydrogen Bonding Force, mean (SD)* [a]

	Baseline	FDB	CBB	FDB+CMP	CBB+CMP	FDB+SSD	CBB+SSD
TB	1.7 (0.3) aA	0.1 (0.1) cE	1.1 (0.3) cB	2.3 (0.2) aA	2.2 (0.5) aA	1.1 (0.5) cC	0.8 (0.3) cCD
FB	0.2 (0.1) cE	3.4 (0.3) aC	6.5 (0.6) bA	0.2 (0.1) bE	1.0 (0.2) bC	4.6 (0.6) aB	5.0 (0.6) aB
FF	2.0 (0.3) aA	0.1 (0.1) cC	0.8 (0.2) cB	0.2 (0.1) bC	0.1 (0.1) cC	0.3 (0.2) dC	0.2 (0.1) dC
AP	0.8 (0.1) bC	2.8 (0.3) bB	7.6 (0.6) aA	0.2 (0.1) bD	0.9 (0.5) bC	1.2 (0.6) cC	1.2 (0.5) cC
EQ	1.0 (0.3) bC	0.5 (0.2) cCD	7.6 (0.6) aA	0.1 (0.1) bD	0.2 (0.2) cD	2.4 (0.4) bB	2.6 (0.4) bB

Abbreviations: AP, Clearfil AP-X; CBB, tungsten carbide bur; CMB, Compomaster; EQ, Estelite ∑ quick; FB, Filtek Bulk Fill Posterior restorative; FDB, super fine grit diamond bur; FF, Filtek Bulk Fill Flowable restorative; SSD, Super-Snap; TB, Tetric EvoCream Bulk.
[a] *Same lowercase letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.*

fillers in EQ, and large glass fillers in AP was observed. In contrast, with the exception of AP specimens, which exhibited some superficial scratches, the surfaces finished with CBB were relatively smooth.

FB specimens finished with FDB exhibited rougher surfaces than those finished with CBB, regardless of the polishing method. For the other resin composites, no clear differences in morphology were observed between the samples finished with FDB and CBB, regardless of the polishing method. When comparing the different polishing methods (CMP and SSD), smoother surfaces were obtained with SSD for TB, FF, and EQ, regardless of the finishing method. For FB, polishing with CMP after finishing with CBB produced the smoothest surface among the different polishing methods. For AP, no clear differences in morphology were observed between the samples polished with CMP and SSD.

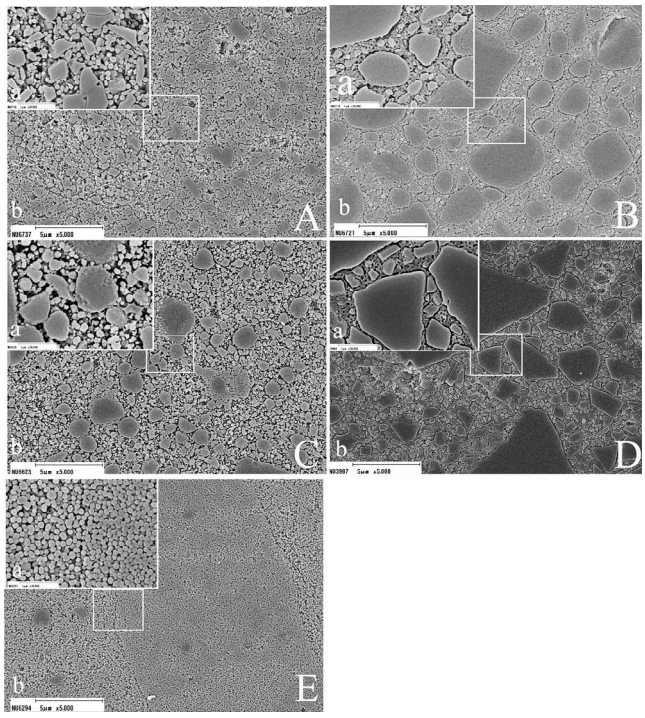

Figure 2. *SEM images of resin composite surfaces after argon-ion etching. (A): Tetric EvoCeram Bulk Fill (TB)— (a) 5000× and (b) 30,000×. (B): Filtek Bulk Fill posterior restorative (FB)—(a) 5000× and (b) 30,000×. (C): Filtek Bulk Fill Flowable Restorative (FF)—(a) 5000× and (b) 30,000×. (D): Clearfil AP-X (AP)—(a) 5000× and (b) 30,000×. (E); Estelite ∑ Quick (EQ)—(a) 5000× and (b) 30,000×.*

DISCUSSION

In recent years, LED-based curing sources have been used extensively in clinics instead of halogen quartz tungsten curing units due to their compactness and easy handling. However, the range of wavelengths of an LED curing unit is narrower than that of a conventional halogen quartz-tungsten based curing unit. In addition, it has been reported that some LED curing units have uneven light intensity and wavelength, depending on the location of the curing light guide.[22,23] In this study, to evaluate the basic surface characteristics of bulk-fill and conventional resin composite using a stable curing light source, a conventional halogen quartz-tungsten based curing unit was used.

In practice, the surfaces of resin composite restorations are directly exposed to degradation by biofilm attack, acid erosion, water sorption, occlusal and thermal stresses, enzymatic degradation, and other sources.[1,26-28] Thus, it is necessary to determine the surface properties of resin composite restorations in order to understand the relationship between degradation sources and the restoration surface. In this study, we evaluated the chemical and morphologic changes of bulk-fill resin composites and compared them with those of conventional resin composites after different finishing and polishing methods.

The results indicated that the finishing and polishing methods, along with the type of resin composite, significantly affected Ra, in agreement with previous reports.[12-17,29-31] Thus, the null hy-

pothesis that the surface roughness is not affected by the finishing or polishing method or the type of resin composite was rejected. Finishing with FDB resulted in significantly higher *Ra* values than finishing with CBB, regardless of the type of resin composite. Although FB, FF, and EQ use nano-sized spherical fillers, FB and FF exhibited rougher surfaces than the conventional hybrid resin composite AP with FDB, and the roughness of EQ with FDB was nearly twice that of EQ with CBB. Based on SEM observations, scratches and filler plucking were more obvious with FDB than with CBB for all resin composites. This may be attributed to the different finishing mechanisms of CBB and FDB[32,33]; tungsten carbide burs have several fine blades that cut away the surface, whereas diamond burs grind the surface with many abrasive diamond particles. When considering SEM images (FDB and CBB), the abrasive particles might have promoted the plucking of filler particles, generating voids in the resin surface and making it rougher (Figures 3A, 4A, 5A, 6A, and 7A). In contrast, the tungsten carbide burs cut the filler particles so that part of the filler particle was embedded in the surface, which resulted in a smoother surface (Figures 3B, 4B, 5B, 6B, and 7B). It has been reported that although tungsten carbide burs do not cut as efficiently as diamond burs, tungsten carbide burs are best suited for smoothing and finishing.[32] Therefore, the CBB-finished specimens exhibited less scratching and filler plucking than the FDB-finished specimens. The FB and FF composite materials use 0.5–5.0 μm cluster fillers that aggregate nano-sized fillers, and EQ also uses pre-polymerized fillers. Because the adhesion strength between pre-polymerized or cluster fillers and the resin matrix might be low, the plucking of pre-polymerized or cluster fillers after finishing with FDB might result in a rougher surface.[34]

To date, various polishing systems using different materials and shapes have been introduced.[33] In this study, a one-step polishing system with diamond particles impregnated in a silicone point (CMP) and a multiple-step polishing system using aluminum oxide abrasive disks (SSD) were examined. In the results for *Ra* after polishing, SSD showed significantly lower *Ra* values than CMP for most resin composites used, regardless of the finishing method. In particular, polishing with SSD after finishing with CBB produced the smoothest surfaces, irrespective of the type of resin composite. Earlier studies also showed that aluminum oxide flexible disks created the smoothest surfaces on resin composite restorations due to their tendency to abrade filler particles and resin matrix equally without plucking filler particles or gouging into the material.[32,33] In addition, it has also been reported that *Ra* and gloss strongly depend on polishing time and application force.[35,36] The polishing system SSD takes multiple steps, and total polishing time was twice as long as CMP in this experimental protocol. These differences in polishing mechanism and polishing time might explain the differences in results between SSD and CMP.

In this study, most tested composites polished with SSD showed *Ra* values of approximately 0.3 μm or lower. The exception is AP, which showed a value over 0.6 μm with every polishing combination. AP uses irregular fillers with a wide range of sizes, and the interspaces between filler particles are larger than in EQ. EQ showed significantly lower *Ra* values than the other resin composites, and its *Ra* values after polishing with SSD were close to 0.2 μm. After argon-ion etching, the surface of EQ appeared homogeneous, despite the fact that EQ uses pre-polymerized fillers and has a relatively low inorganic filler content. The high polishability of EQ can be attributed to its fine and even spherical fillers and the small interspaces between filler particles (Figure 2E [see a and b]).[37]

Another aim of this study was to investigate the surface chemical properties through SFE measurements after different finishing and polishing methods. As for *Ra*, the finishing and polishing methods, along with the type of resin composite, significantly affected SFE. Thus, the null hypothesis that the SFEs of resin composites are not influenced by the finishing or polishing method or type of resin composite was rejected. For most resin composites, the baseline specimens showed lower γ_S values than the finishing samples. The baseline high-viscosity TB and FB composites showed significantly lower γ_S compared with the finished and polished TB and FB, along with the other resin composites. Baseline surfaces produced by translucent matrix tape in contact with resin composites make up a resin-rich layer. In general, the hydrophilic nature of inorganic fillers gives them high wettability, whereas the resin matrix is hydrophobic. FF, AP, and EQ contain the hydrophilic resin monomer triethylene glycol dimethacrylate (TEGDMA)[23]; however, TB and FB each use different resin monomers with a hydrophobic backbone and increased molecular mobility, ethyoxylated bisphenol A dimethacrylate (EBDADMA) and 1,12-dodecane dimethacrylate (DDDMA), respectively.[3,35] This may explain the lower γ_S values observed

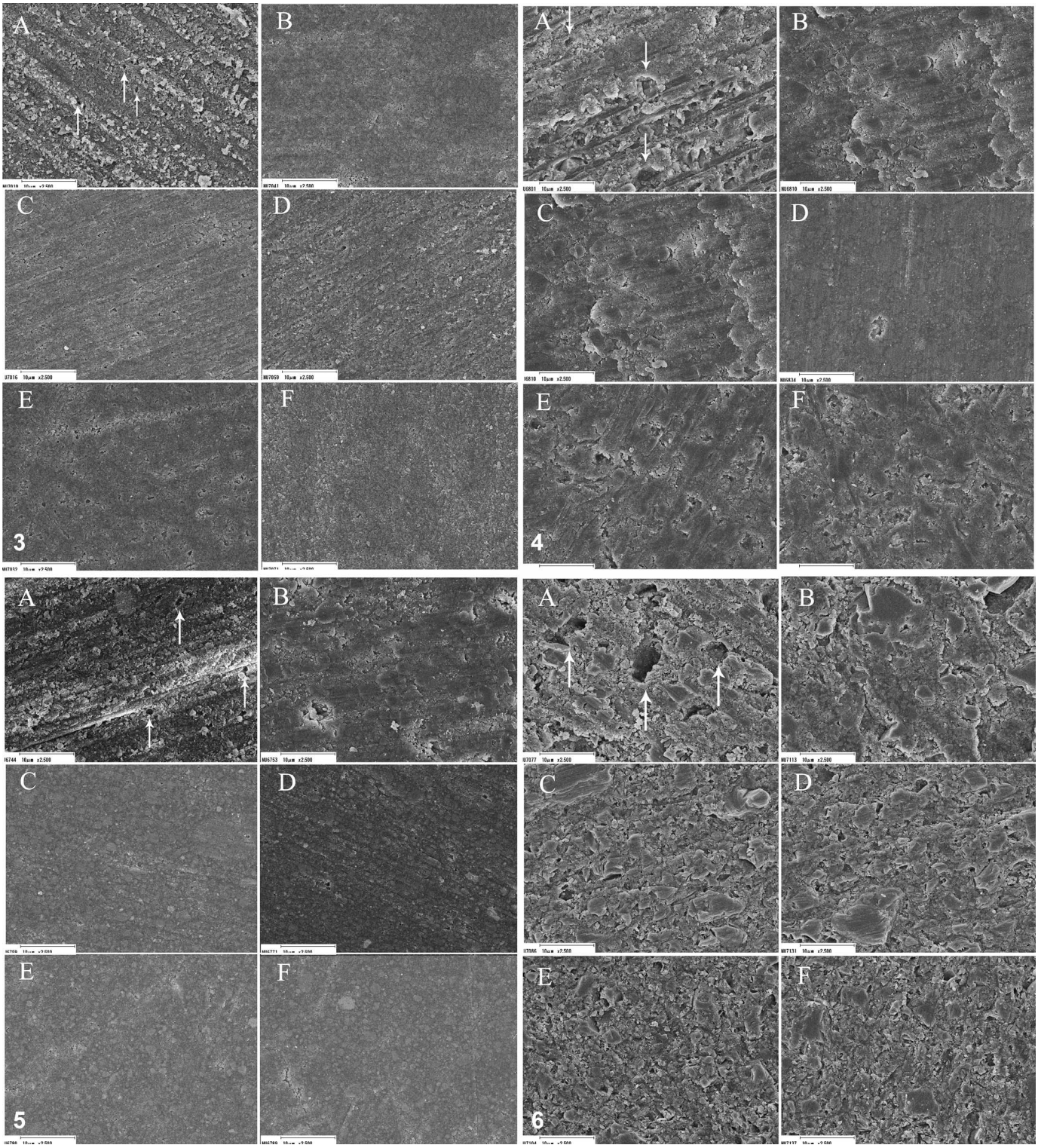

Figure 3. *Representative SEM images of resin composite surfaces after different finishing and polishing procedures. (A): TB finished with FDB (2500×). (B): TB finished with CBB (2500×). (C): TB polished with CMP after finishing with FDB (2500×). (D): TB polished with CMP after finishing with CBB (2500×). (E): TB polished with SSD after finishing with FDB (2500×). (F); TB polished with SSD after finishing with CBB (2500×). The arrows indicate evidence of plucked-out filler.*

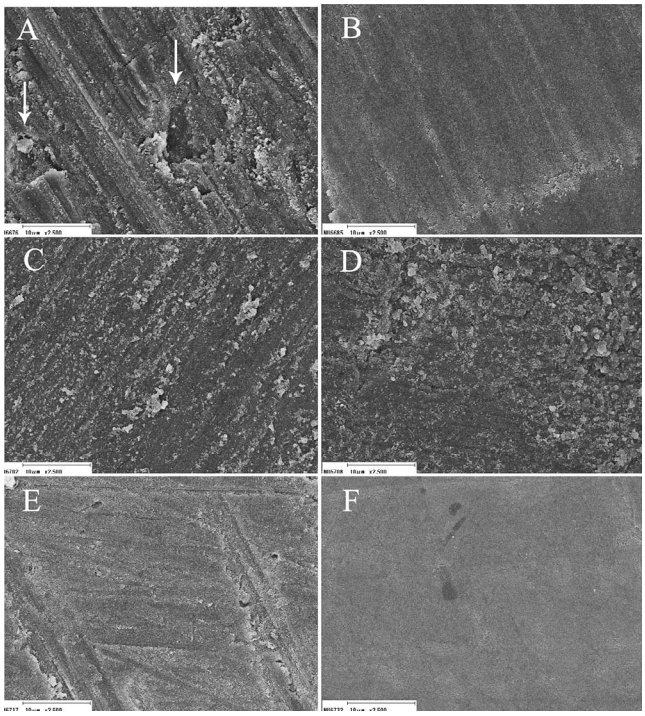

Figure 7. *Representative SEM images of resin composite surfaces after different finishing and polishing procedures. (A): EQ finished with FDB (2500×). (B): EQ finished with SF CBB (2500×). (C): EQ polished with CMP after finishing with FDB (2500×). (D): EQ polished with CMP after finishing with CBB (2500×). (E): EQ polished with SSD after finishing with FDB (2500×). (F): EQ polished with CMP after finishing with CBB (2500×) The arrows indicate evidence of plucked-out filler.*

for TB and FB. In particular, their baseline $\gamma_S{}^p$ was significantly lower than that of the other resin composites. The polar force ($\gamma_S{}^p$) is thought to be related to electric and metallic interactions, in addition to dipolar interactions.[19]

In the finished groups, AP, EQ, and FB showed significantly higher γ_S and $\gamma_S{}^h$ values with CBB than with FDB. This phenomenon might be explained by the different finishing mechanisms of the burs used. Although AP, FB, and EQ exhibited many large voids after finishing with SF, finishing with CBB resulted in relatively flat and even surfaces, as discussed earlier. Hence, the cutting of the filler particles, leaving parts of the filler particles exposed at the surface, might have contributed to the higher γ_S and $\gamma_S{}^h$ values. The hydrogen-bonding force ($\gamma_S{}^h$) represents water and hydroxyl components of the resin composite surface.[19] In the polished groups, most resin composites showed higher γ_S values with SSD compared with CMP, regardless of the finishing method. This suggests that different polishing methods result in different surface chemistries. Specifically, most resin composites polished with CMP had lower $\gamma_S{}^p$ and $\gamma_S{}^h$ values than those of composites polished with SSD. In addition to the different polishing mechanisms of CMP and SSD, the γ_S values may have been influenced by remnants of silicone from CMP, making the surface more hydrophobic.

The use of inappropriate finishing and polishing procedures on resin composite restorations compromises the long-term clinical performance of the restorations.[17,32,36] Finishing is necessary to produce a precise anatomical form, good contours, appropriate occlusion, and healthy embrasure form.[12-14] Finishing also eliminates the upper resin-rich and oxygen-inhibited layer of the resin composite.[38] Polishing after finishing is critical in order to obtain a smooth surface with gloss and to modify the surface to resist degradation.[36,37,39] The results of this study indicate that the size and shape of the filler of a resin composite can influence its surface roughness, and the type of resin matrix may be the dominant factor in determining SFE. Therefore, the combination of finishing method, polishing method, and type of resin composite should be carefully considered for clinical applications. In addition, the results of this study are consistent with findings of previous reports on conventional resin composites,

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Figure 4. *Representative SEM images of resin composite surfaces after different finishing and polishing procedures. (A): FB finished with FDB (2500×). (B): FB finished with CBB (2500×). (C(: FB polished with CMP after finishing with FDB (2500×). (D): FB polished with CMP after finishing with CBB (2500×). (E): FB polished with SSD after finishing with FDB (2500×). (F): FB polished with SSD after finishing with CBB (2500×). The arrows indicate evidence of plucked-out filler.*

Figure 5. *Representative SEM images of resin composite surfaces after different finishing and polishing procedures. (A): FF finished with FDB (2500×). (B): FF finished with CBB (2500×). (C): FF polished with CMP after finishing with FDB (2500×). (D): FF polished with CMP after finishing with CBB (2500×). (E): FF polished with SSD after finishing with FDB (2500×). (F): FF polished with SSD after finishing with CBB (2500×). The arrows indicate evidence of plucked-out filler.*

Figure 6. *Representative SEM images of resin composite surfaces after different finishing and polishing procedures. (A): AP finished with FDB (2500×). (B): AP finished with CBB (2500×). (C): AP polished with CMP after finishing with FDB (2500×). (D): AP polished with CMP after finishing with CBB (2500×). (E): AP polished with SSD after finishing with FDB (2500×). (F): AP polished with SSD after finishing with CBB (2500×). The arrows indicate evidence of plucked-out filler.*

suggesting that bulk-fill and conventional composites respond similarly to finishing and polishing.

On the other hand, recent studies have indicated that biofilm formation is more influenced by material characteristics and composition than surface roughness.[40,41] In particular, filler size, filler shape, distribution, and matrix composition are critical factors for biofilm formation.[42] Although matrix components are not influenced by finishing and polishing procedures, it is probable that different finishing and polishing procedures may have an effect on not only on surface topography but also on the surface chemistry of resin composite restorations.

While SFE reflects some of the surface characteristics of materials, further research is needed to investigate the influence of different finishing and polishing methods and types of resin composites on the surface characteristics of resin composite using different methodologies.

CONCLUSION

This study demonstrated that the finishing and polishing methods, along with the type of resin composite, significantly affect the surface properties of the composite in terms of both *Ra* and SFE. Finishing and polishing significantly increased the SFEs of the high-viscosity bulk-fill resin composites. Finishing with FDB resulted in significantly higher *Ra* values than finishing with CBB, regardless of the type of resin composite. However, most resin composites finished with FDB showed lower SFEs than those finished with CBB. Polishing with SSD resulted in significantly lower *Ra* values than polishing with CMP, regardless of the finishing method. On the other hand, most resin composites polished with SSD showed higher γ_S than those polished with CMP. SEM observation revealed that the shapes, sizes, and distributions of inorganic fillers depended on the composite material. Regardless of the type of resin composite, polishing with SSD after finishing with CBB resulted in a smoother surface than other combinations of finishing and polishing.

Acknowledgements

This work was supported in part by a Grant-in-Aid for Scientific Research (C) (16K11565 and 17K11716) and a Grant-in-Aid for Young Scientists (B) (17K17141, and 17K17142) from the Japan Society for the Promotion of Science. This project was also supported in part by the Sato Fund and by a grant from the Dental Research Center of the Nihon University School of Dentistry, Japan.

Conflict of Interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

(Accepted 30 November 2018)

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