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Performance of a novel polishing rubber wheel in improving surface roughness of feldspathic porcelain

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Replacing glazing with polishing is still controversial in terms of the surface roughness of dental porcelains. This study investigated the polishing performance of a ceramic-polishing rubber wheel (CP-RW), which contains large uniform and rounded silicon carbide particles and small diamond particles, in improving the surface roughness of two feldspathic porcelains for sintering and CAD/CAM milling. Using a confocal laser scanning microscopy, the changes in the surface roughness parameters were evaluated before and after polishing or glazing for three surface treatment groups: SofLex polishing, CP-RW polishing, and Glazing. Regardless of the parameters, all treatments reduced roughness values (repeated measures ANOVA, $p<0.05$). The roughness values obtained after CP-RW polishing were lower than those obtained after SofLex polishing and glazing (2-way ANOVA, $p<0.05$). Polishing both ceramics with CP-RW made the surfaces smooth with the lowest roughness values in all parameters. The effect was dependent on the materials used.

Keywords: Ceramic, Feldspathic porcelain, Polishing rubber wheel, Roughness parameter, Surface roughness

INTRODUCTION

Dental porcelain has unique properties, including translucency, color, and strength, as well as excellent biocompatibility and durability. After adjustment of the interproximal and occlusal contacts and refinement of the contour and cervical margins, ceramic surfaces have traditionally been glazed to mask surface defects[1)], increase the mechanical properties such as the strength and fracture resistance of the porcelain[1-3)], prevent excessive wear of the opposing tooth surface[4)], and increase the longevity of the restored tooth. Glazing is also needed to minimize plaque accumulation[5,6)], improve soft tissue compatibility[6,7)], and increase surface luster and aesthetics.

Ceramic restoration is so brittle that it cannot be performed to adjust occlusion before cementation. Intraoral polishing of the ceramic surface should be required[8,9)], as brittle fractures of ceramic restoration are known to be affected by surface flaws[1)] . In contrast to the glazing procedure, chair-side polishing after cementation is easy and time-saving for both the patient and the dentist[2,10)]. However, there are still controversies about the effects of the surface treatments on the strength of the ceramic. Some studies have reported no difference in the flexural strength and the fracture resistance of glazed and polished ceramics[2,11,12)], while others have reported that polished porcelain has higher fracture resistance than glazed porcelain[3,13)]. As an alternative to the glazing procedure, various chair-side polishing instruments have been evaluated, especially in terms of enamel wear of the opposing teeth[8,14,15)]. Some polishing materials, such as diamond pastes and Sof-Lex discs, were reported to fulfill the smoothness requirements for minimal wear of the opposing teeth and provide the strength and fracture resistance for the ceramics in order to be viable replacements for the glazing procedure[2,16,17)].

In general, the effectiveness of polishing and glazing procedures are compared by measuring surface roughness[1,2,8,9,18,19)]. Measurements of surface roughness have been performed using profilometry with a contact stylus[1-3,8,9)], scanning electron microscopy (SEM)[5,8)], laser specular reflectance[20)], and atomic force microscopy[5,9)]. In recent years, confocal laser scanning microscopy (CLSM) has been used as a new imaging technique in dentistry[21)]. Unlike conventional digitization methods, CLSM uses a non-tactile laser and enables the three-dimensional measurement of surface roughness without destroying the specimen[22)]. CLSM also provides high-resolution optical images with depth profiles of the surface topography. The degree of roughness may then be evaluated with surface roughness parameters in micrometers (Ra, Rq, Rp, Rv, Rz, and RSm, Table 1)[22-24)].

Most studies have reported on polishing effects in terms of the particle size. Improvements in the surface roughness have been attributed to the microstructure of the polishing systems[25,26)]. The efficiency of polishing depends on the polishing materials and the procedural variables[27-29)]. The former includes the type of the abrasive used, the size and content of the abrasive

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Table 1 Surface roughness parameters measured in this study and their definitions

Parameters	Definition
*R*a	Arithmetic average roughness, the arithmetic average value of all absolute distances of the roughness profile ordinates within the measured section (average height), that is, the mean height of the profile above and below a central line[22,23,29]
*R*q	Root mean square roughness, the root mean square (rms) value of the roughness profile ordinates within the measured section.[22,23,27]
*R*v	The depth of the deepest valley in the profile based on the average height.[22,27]
*R*p	The maximal height of the profile ordinates based on the average height.[22,27]
*R*z	The average maximum peak-to-valley height [23,35]
RSm	The mean spacing between peaks used to describe the horizontal dimension of roughness[24]

fillers, and the geometry of the polishing materials (*e.g.* discs, cups, and cones). The latter includes the direction of polishing, the amount of pressure applied, and the time spent for the procedure. Few studies have been performed evaluating the effects of the polishing material compositions[30].

The aim of this study was to investigate the performance of a novel ceramic-polishing rubber wheel (CP-RW, ZG 1735, D&Z, Incheon, Korea), which contains large smooth-edged and relatively uniform silicon carbide (SiC) abrasive particles and small round diamond powders, in improving the surface roughness of dental ceramics. The null hypothesis tested in this study was that the surface roughness of the ceramic materials polished with the CP-RW would be the same as that of the glazed surface. The surface roughness changes of two feldspathic porcelains for sintering and CAD/CAM milling were evaluated before and after polishing or glazing using CLSM, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS).

MATERIALS AND METHODS

Specimen preparation

Two kinds of feldspathic porcelain, a machinable porcelain block (M porcelain, VITABLOCS Mark II for CEREC/inLab, 2M2C I10, Vita Zahnfabrik, Bad Sackingen, Germany) and a sintering porcelain in powder form (S porcelain, Ceramco 3, Lot No. 05001819, Dentsply Ceramco, Burlington, NJ, USA) were used for the present study. Their composition, particle size, and properties are presented in Table 2[31-33]. M porcelain blocks (10 mm×8 mm×15 mm) were cut into 2 mm-thick slice specimens with a low-speed diamond saw (Isomet, Buehler, Lake Bluff, IL, USA). Specimens of S porcelain were fabricated by condensing enamel powder slurry in "plastic-like" consistency recommended by the manufacturer. The slurry was packed and vibrated into the mold while the excess liquid was removed with absorbent tissues. The specimens were fired in a programmable vacuum furnace (Ceramco 7.0, Dentsply Ceramco, York, PA, USA) according to the firing cycles recommended by the manufacturer. All ceramic specimens were polished with #220 grit SiC papers using an automatic grinding machine (Rotopol-V, Struers, Glasgow, UK) to obtain a baseline roughness on the basis of the similar particle size of both diamond particles of diamond points and the grits of coated abrasives.

The prepared specimens made of each porcelain material were randomly divided into three subgroups according to the treatments (Table 3). The assigned surface treatment procedures were done by an experienced operator. According to the manufacturer's instructions, polishing with Sof-Lex discs (Group SofLex, Sof-Lex Pop-on-discs, 3M ESPE, St. Paul, MN, USA) was sequentially performed for 10 s each for the coarse, medium, fine, and super-fine discs using an electric handpiece set at a speed of 30,000 rotations per min (rpm). Polishing with a novel ceramic-polishing rubber wheel (Group CPRW) was performed for 20 s using an electric handpiece at the same rotational speed. Polishing instruments were applied with constant and repetitive stroking motions in a single direction under dry conditions. The glazing of the specimens (Group Glazing) was performed with a commercial glazing agent (Finegrain, Dentsply Ceramco) according to the firing cycles recommended by the manufacturer. All specimens were ultrasonically cleaned in deionized water for 5 min and then dried with compressed air.

Measurement of surface roughness

Each specimen was placed on the stage of a CLSM (LSM 5-Pascal, Carl Zeiss, Oberkochen, Germany) with the polished or glazed surface facing the scanning aperture. A reflection image of the surface was generated using a HeNe(G) laser (emission 543 nm green light), with an objective magnification of ×10, a numerical aperture set at 0.3 (×10/0.3), a scan time of 1.97 s/frame, and a scan speed of 3.2 microseconds. The stage was moved 50 μm vertically through the first and last detectable light reflex and a z-series of 50 optical sections was generated. The z-series were converted to topographical images, which were created within the regions of interest of 920

Table 2 Composition, particle size, and properties of Vita Mark II and Ceramco 3†

		Particle size	Composition (Wt%)	Density (g/cm³)	Transformation temperature (°C)	Viekers hardness (kg/mm²)	Flexural strength (MPa)	Manufacturer
Ceramco 3	Amorphous and tetragonal Leucite ($K_2O \cdot Al_2O_3 \cdot 4SiO_2$) containing feldspathic porcelain	Average 31.6 µm	SiO_2 60~65 Al_2O_3 10~15 Na_2O 5~10 K_2O 10~15 CaO 0~3 BaO 0~2	2.40±0.01	970	479±26	63.3±5.0	Ceramco-Dentsply, Burlington, NJ, USA
Vita Mark II	Homogenous fine mica crystalline particle (35–45%) in a glass matrix	Average 4 µm (1–5 µm)	SiO_2 56~64 Al_2O_3 20~23 Na_2O 6~9 K_2O 6~8 CaO 0.3~0.6 TiO_2 0.0~0.1	2.44±0.01	1,170	569±10	94.1±14.2	Vita Zahnfabrik, Bad Sackingen, Germany

† Data were collected from the References 31–33).

Table 3 Surface roughness values for each parameter as a baseline roughness for the sintered and machinable feldspathic porcelain before surface treatments with two polishing systems and glazing

Material	Treatment	Surface roughness parameters (mean±SD, n=15; Unit, µm)									
		Ra		Rq		Rp		Rv		Rz	
Sintered porcelain	SofLex	0.787±0.185		1.043±0.229		3.736±1.536		4.715±1.737		4.066±1.003	
	CPRW	0.803±0.168		1.110±0.323		2.769±1.046		4.403±1.293		3.889±1.056	
	Glazing	0.870±0.102		1.230±0.230		3.253±0.848		5.627±2.734		4.388±0.660	
Machinable porcelain	SofLex	0.760±0.155		0.984±0.193		3.110±1.214		4.573±1.321		3.592±0.598	
	CPRW	0.940±0.198		1.210±0.242		3.708±1.074		4.979±1.732		4.693±0.922	
	Glazing	0.864±0.122		1.137±0.177		3.270±0.934		5.444±2.762		4.263±0.516	
2-way ANOVA results		F	p	F	p	F	p	F	p	F	p
	Materials	1.121	0.293	0.121	0.729	0.212	0.646	0.039	0.845	0.156	0.693
	Treatments	3.646	0.030	4.537	0.013	0.238	0.789	1.846	0.164	3.430	0.037
	Interaction	2.361	0.101	1.423	0.247	3.627	0.031	0.335	0.717	4.881	0.010

µm×920 µm and used for the measurement of surface roughness. Profilometeric measurements were obtained at three regions as close as possible to the center of the five samples. Surface roughness parameters were obtained for each of the polished groups.

Qualitative analyses using SEM and EDS

In order to interpret the effects of the abrasive particles in the polishing materials on the topographic differences between the treated surfaces, the microscopic images were evaluated using a field-emission scanning electron microscope (FE-SEM, S-4700, HITACHI high technologies Co., Tokyo, Japan) operated at 15 kV. The constituent elements of the polishing materials and treated ceramic surfaces were compared using an energy dispersive spectrometer (EDS, EX-220, Horiba, Kyoto, Japan) embedded in the FE-SEM.

Statistical analysis

For each surface roughness parameter, the surface roughness values before treatment should be the same in all of the groups as a baseline roughness. After confirming that the baseline roughness was the same, the effects of the surface treatments and materials as well as their interactions were evaluated for the roughness measurements after treatment using 2-way analysis of variance (ANOVA) and the *post hoc* Scheffe test at a significance level of α=0.05 (SPSS for Windows statistical software, ver. 19.0, SPSS Inc, Chicago, IL, USA). Within each material, the changes in each roughness parameter before and after the surface treatments and their interactions were also evaluated using repeated measures ANOVA and the *post hoc* Scheffe test at the same significance level.

RESULTS

Surface roughness was compared by five parameters: Ra, Rq, Rp, Rv, and Rz. Before surface treatment, the surface roughness of the prepared specimens as a baseline should be the same among the groups. The prepared specimens showed a relatively good random distribution among the treatment groups of each porcelain material, except the SofLex group in Ra, Rq, and Rz (Table 3). The SofLex groups showed significantly lower values than the other groups in these three parameters before surface treatment, especially in the M porcelain. Although the CPRW group showed the highest initial roughness values, the roughness values obtained after CP-RW polishing were lower than those after Sof-Lex polishing and after glazing (Table 4). The effects of the treatments on surface roughness were significantly different. Polishing with CP-RW resulted in the smoothest surface among the tested treatments. The materials used also had significant effects in the Ra, Rq, and Rz values, with S porcelain showing lower values than M porcelain. There were no interaction effects between the materials and surface treatments in all the parameters.

In order to investigate the effects of the surface treatment methods on the changes in each parameter, repeated measures ANOVA within each material was performed on the data before and after treatment. The changes in Ra after treatment are presented in Table 5. Although the difference in the Ra between S and M porcelains was not evaluated, the effects of treatment and measuring time were significant in the Ra within each material (repeated measures ANOVA, $p<0.05$, Table 5). Although the tables showing the results of repeated measures ANOVA on Rq, Rp, Rv, and Rz were not presented due to too many tables, the main effects of the two factors were usually significant in each parameter, except the effects of surface treatment on the Rp, Rv, and Rz of M porcelain. The interaction effects within each material were usually significant, except in the Ra, Rp, and Rv of S porcelain and in the Rv of M porcelain (repeated measures ANOVA, $p<0.05$). Therefore,

Table 4 Surface roughness values for each parameter for the sintered and machinable feldspathic porcelain after surface treatments with two polishing systems and glazing

Material	Treatment	Surface roughness parameters (mean±SD, n=15; Unit, μm)									
		Ra		Rq		Rp		Rv		Rz	
Sintered porcelain	SofLex	0.560±0.081		0.762±0.130		2.539±0.729		3.656±1.292		2.513±0.492	
	CPRW	0.380±0.064		0.487±0.078		1.311±0.505		2.006±0.572		1.408±0.247	
	Glazing	0.598±0.187		0.737±0.210		2.180±1.144		2.530±0.902		1.515±0.327	
Machinable porcelain	SofLex	0.599±0.081		0.804±0.123		2.556±0.583		3.313±1.037		2.965±0.681	
	CPRW	0.411±0.064		0.536±0.070		1.884±0.548		2.053±0.662		1.690±0.279	
	Glazing	0.686±0.134		0.853±0.175		1.992±0.733		3.363±1.421		2.053±0.656	
2-way ANOVA results		F	p	F	p	F	p	F	p	F	p
	Materials	4.993	0.028	5.453	0.022	0.742	0.391	0.679	0.412	17.184	0.000
	Treatments	39.651	0.000	39.120	0.000	12.413	0.000	15.368	0.000	50.559	0.000
	Interaction	0.583	0.560	0.648	0.526	2.135	0.125	2.550	0.084	0.538	0.586

Table 5 Changes in Ra (average roughness value) before and after treatment according to surface treatments in each ceramic material

Material	Treatment	Ra (mean±SD, n=15; Unit, μm)		Repeated measures ANOVA (split plot factorial design)			
		before	after			F	p
Sintered porcelain	SofLex	0.787±0.185	0.560±0.081	Main effect	Treatment	10.448	0.000
	CPRW	0.803±0.168	0.381±0.064		Measuring time	84.998	0.000
	Glazing	0.870±0.102	0.598±0.187	Interaction		3.164	0.052
Machinable porcelain	SofLex	0.760±0.155	0.599±0.081	Main effect	Treatment	4.762	0.014
	CPRW	0.940±0.198	0.411±0.064		Measuring time	120.224	0.000
	Glazing	0.864±0.122	0.686±0.134	Interaction		20.505	0.000

regardless of the parameters, all treatments reduced the roughness values. The group CPRW demonstrated the lowest roughness values for all the parameters except the Rv and Rz of S porcelain and the Rp and Rz of M porcelain. In these parameters, the roughness values of Glazing were not different from those of CPRW. The roughness values of SofLex were higher than or similar to those of Glazing in most parameters.

The aluminum oxide abrasive particles of the Sof-Lex polishing discs were not uniform in size and shape, with sharp irregular edges (Fig. 1a). The particles of the CP-RW looked relatively uniform and smoothly rounded (Fig. 1b). The surface of the Sof-Lex disc looked more irregular and more porous than that of the CP-RW. The porosities of the CP-RW were filled with fine and uniformly-sized small diamond particles and the surface looked smooth. In contrast to the Sof-Lex disc, the CP-RW contained a dominant silicon component as it was made of silicon carbide and fine diamond particles that were composited with silicon rubber matrix (Figs. 1c and 1d). The Sof-lex disc had more dominant aluminum components compared to the CP-RW (Figs. 1e and 1f). Figures 2 and 3 exhibit the surfaces of both S and M porcelain materials before surface treatments (control),

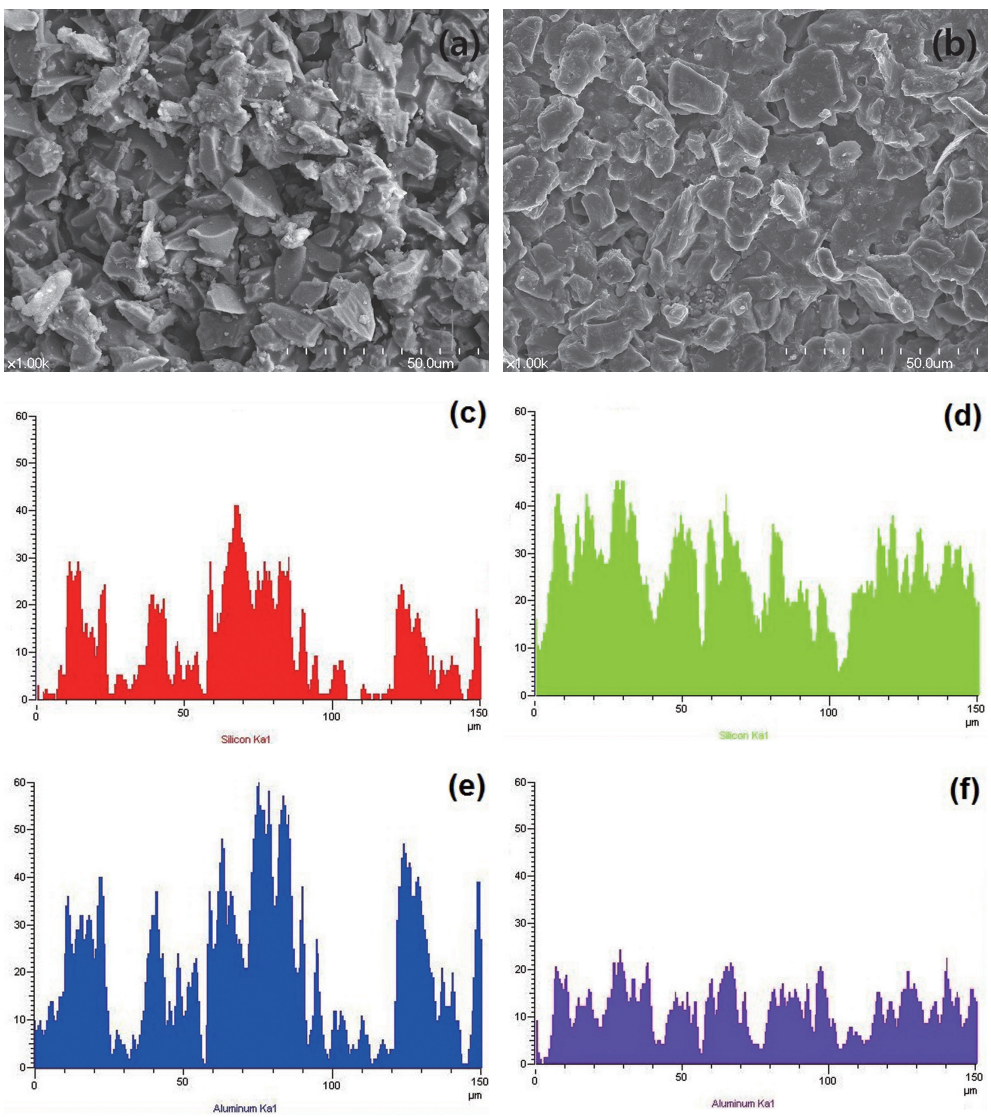

Fig. 1 Scanning electron microscopic images of the surface of the abrasive polishing materials and the amount (%) of dominant elements measured using line scans of energy dispersive spectroscopy.
Left column (a, c and e), super-fine disc of the SofLex polishing system; right column (b, d and f), the ceramic-polishing rubber wheel (CP-RW); (c) and (d), the peaks of Silicon (Si); (e) and (f), the peaks of Aluminum (Al).

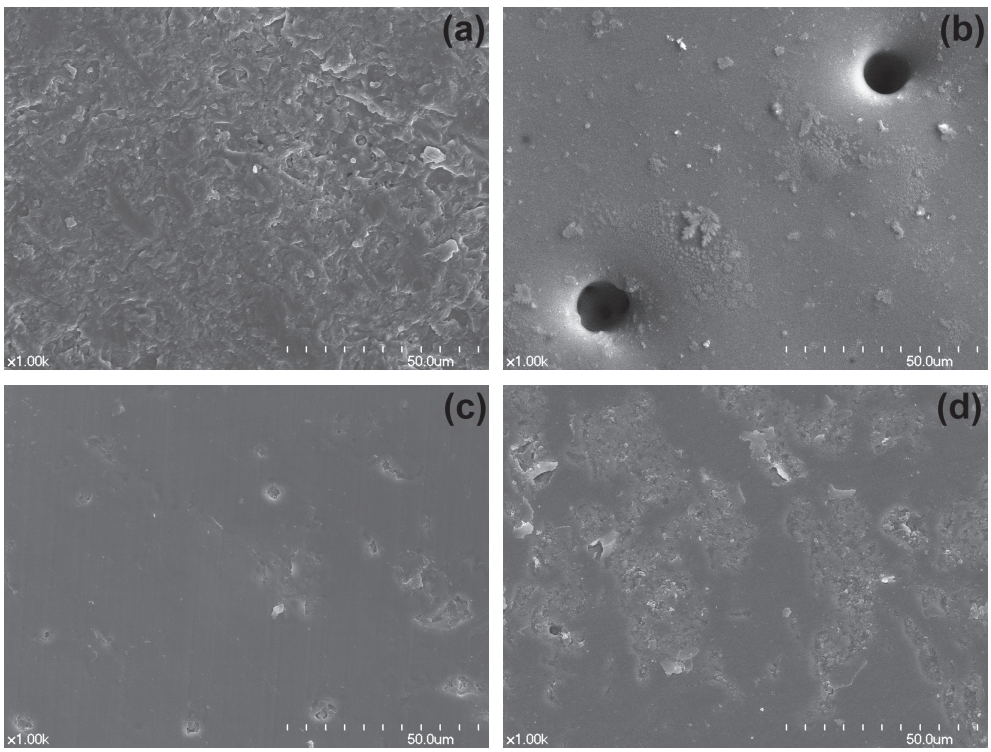

Fig. 2 Scanning electron microscopic image of sintered porcelain.
(a) Control; (b) after glazing; (c) after polishing with the ceramic-polishing rubber wheel (CP-RW); (d) after polishing with the SofLex disc.

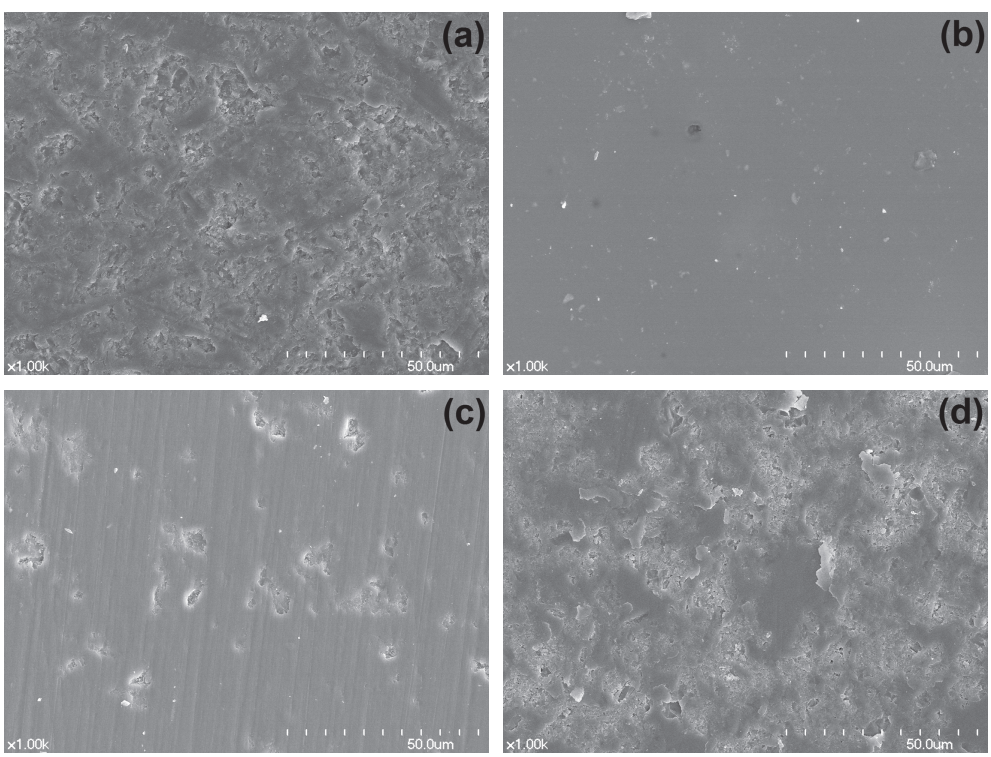

Fig. 3 Scanning electron microscopic image of machinable feldspathic porcelain.
(a) Control; (b) after glazing; (c) after polishing with the ceramic-polishing rubber wheel (CP-RW); (d) after polishing with the SofLex disc.

and after glazing, polishing with the Sof-Lex disc, and polishing with the CP-RW. The surfaces of the control groups of both materials exhibited many striations due to the automatic polishing with #220 SiC abrasive paper for the baseline roughness (Figs. 2a and 3a). The glazed surfaces looked smooth with glazing liquid but relatively wide depressions throughout the entire surface as well as small protrusions and voids were also observed (Figs. 2b and 3b). The polished surfaces with the CP-RW looked very smooth and very small voids were sparsely scattered (Figs. 2c and 3c). Sof-Lex disc also made the polished surface very flat, but there remained a great number of micro-voids on the surfaces (Figs. 2d and 3d). The results of the profileometric measurements were consistent with the SEM findings. The ceramic surfaces polished with the CP-RW looked smoother than those polished with the Sof-Lex disc.

DISCUSSION

In dentistry, the average roughness value, Ra, has been used to describe surface roughness. The Ra value is calculated by averaging the positive heights of the peaks and valleys turned upside down from the base of the centerline[23,34]. However, the Ra value is not sufficient to explain changes in surface roughness. To describe the surface roughness more precisely, it is required to compare other parameters such as the peaks, valleys, profile shapes, and spacing of the surface[22]. It is impossible to distinguish peak undulations with the Ra value because it represents only the average of the total peaks[22]. The value of roughness root mean squared (Rq or RMS) is more sensitive to the peaks and valleys on a surface than the Ra value because extreme peaks and valleys are included in this parameter[22]. The Rp and Rv values provide direct information on the amplitude of the peaks and valleys of a surface, respectively[22]. Rz is defined as the mean of five maximum peak-to-valley heights within the measuring length and is used to describe the degree of roughness of the surfaces of the sample[35]. RSm is defined as the mean spacing between peaks known as roughness spacing parameter that used to describe the horizontal dimension of roughness[24]. Therefore, investigations into the changes in roughness after surface treatment should include the Rq, Rv, Rp, Rz, and RSm values in addition to the Ra value. In this study, Ra, Rq, Rv, Rp, and Rz values were compared before and after surface treatment, except RSm that could not be obtained with our software.

The Ra values obtained in this study agreed well with the results of other reports on the roughness values of ceramic materials[1,6,8,19,22,35]. Compared to the roughness values of composite resins, ceramics show high Ra values because they are composed of ceramic crystals with no matrix substances in between, unlike composite resins[29,36,37]. Surface flaws that develop during restorations must be minimized by polishing or glazing because they affect the strength performance of the brittle ceramic materials[38]. All surface treatments using Sof-Lex discs, CP-RWs, and glazing had significant effects on surface roughness, that is, they made the roughness values lower in all parameters (Table 4). After surface treatments, there were significant differences between S and M porcelains in their Ra, Rq, and Rz. In these cases, the roughness values of S porcelain were lower than those of M porcelain (Table 4). The effects of treatment in each material showed statistically significant differences in the Ra and Rq values, and in both materials CPRW had significantly lower values than the other two treatment groups (Table 5).

The Ra value of CPRW was lower than those of SofLex and Glazing in both S and M porcelains (Tables 4 and 5). This demonstrated that for both ceramics, CP-RW made the ceramic surfaces smoother than Sof-Lex disc and glazing. Although the overall roughness of a surface is evaluated with the Ra value[22,23,34,35], the changes in the flaws, which is more important in fracture resistance, can be evaluated with the Rp and Rv values that represent the maximum values of the peaks and valleys, respectively[22]. Polishing with the CP-RW resulted in a Rv value that was lower than the other two groups, indicating that the flaws on the ceramic surfaces polished with CP-RW would be shallower than those treated with Sof-Lex disc or glazing. Therefore, it could be suggested that CP-RW polishing reduce the probability of developing deep flaws and increase the fracture resistance. In the CPRW group, low roughness values were observed in the Rv and Rz of both the ceramic specimens.

Although there were significant differences in the Rp, Rv, and Rz between treatments in S porcelain, in M porcelain the differences were not statistically different in repeated measurements (These statistical results are not presented in tables because the raw data was already presented in Tables 3 and 4 and an additional four tables with the same format with Table 5 would be redundant). Glazing also showed lower surface roughness values than SofLex in the Rv and Rz parameters in S porcelain and the Rp and Rz parameters in M porcelain (Table 4). Glazing lowered the Rv value of S porcelain because the glazing liquid filled the valleys. However, in M porcelain that had no such valleys due to its composition of uniform and fine mica crystals, glazing did not decrease the Rv value of M porcelain (Table 4)[39]. It could also be suggested that glazing have an effect on fracture resistance in S porcelain, but not in M porcelain. Sof-Lex disc left high peaks after cutting the mica crystals with sharp Al_2O_3 abrasive particles. However, in M porcelain, the main effects of treatment did not significantly impact Rp, Rv, and Rz. The results indicated that the treatments were effective in reducing the average roughness values, but for some parameters, the effect of each treatment was dependent on the materials. The surface treatments of the M porcelain made of uniform and fine mica crystals failed to reduce the surface roughness values with respect to the peaks and valleys. Nevertheless, among the three surface treatments, polishing with the CP-RW composed of SiC and diamond particles resulted in the smoothest surfaces for both materials. Additionally, based on the

lower Rp value in S porcelain, CP-RW could be expected to significantly reduce sharp surface protrusions and reduce the wear of the opposing tooth surface (Table 4). Further studies are needed on the wear of the opposing tooth by the ceramics polished with CP-RW.

In a previous study, excellent results were obtained with glazing and Sof-Lex polishing in Ceramco 3 and Vita Mark II[40]. However, glazing requires an extended waiting time for patients and glazed surfaces are not flat with numerous irregularities because of small protrusions of glaze particles and voids (Figs. 2b and 3b). The Sof-Lex polishing system is comprised of four time-consuming steps. The flexible aluminum oxide discs have limitations in their application because they are effective only on flat or convex surfaces and may have difficulties in efficiently creating, finishing, and anatomically polishing contoured surfaces[28]. The CP-RW was developed to complement these shortcomings. The major components of the CP-RW are silicon carbide (SiC) abrasive particles (70 wt%) and diamond powder (20 wt%) that are uniform in size and have rounded edges. It also contains binders and rubber matrix substances (10 wt%) (Fig. 1). From the SEM images of the wheel, the abrading surface consisted of large and smooth-edged silicon carbide particles of about 5–10 μm in size and small round diamond particles of about 1–2 μm in size. The small diamond particles filled up the micropores evenly between the large silicon carbide particles (Fig. 1b). As shown in this data, the CP-RW containing SiC particles and diamond powders made the surface smoother than Sof-Lex disc and glaze. A combination of uniformly-sized and round-edged SiC abrasive particles and fine small diamond powders that were impregnated in a rubber matrix decreased the irregularities and voids on the surfaces of the polishing wheel, resulting in compositional features that led to smoother polishing (Fig. 1). Compared to the Sof-Lex disc, which has sharp-edged Al_2O_3 abrasive particles as its main component, the excellent result obtained with the CP-RW may be attributed to the hardness of the SiC and diamond particles, rounded-shape of the particles, uniform irregularities, and minimum porosities[41]. In case of Sof-Lex disc, the sharp Al_2O_3 particles might cut the soft phase and push the hard phase to be detached from the surface. However, in case of CP-RW, the extremely hard diamond particles that were small and round and evenly-distributed between the large SiC particles might cut the hard phase and reduce their detachment. As a result, the ceramic surface polished with CP-RW showed less voids than that polished with Sof-Lex disc. Similar to the microprotection theory on the wear mechanism of composite resin, the effect of polishing on surface roughness can also be dependent on the microstructure of the abrasive particles.

Most studies have focused on the effect of particle size on the surface roughness obtained by various polishing systems[25,26]. Super-fine Sof-Lex discs have aluminum oxide particles that are an average of 5 μm in size. Jiffy and Enhance used 0.5 μm diamond paste and 0.3 μm aluminum oxide paste so that the Ra values obtained with these systems would be low. However, although the Pogo system had diamond abrasives that were 10–15 μm in average particle size, the lowest Ra values of the ceramic surfaces treated with the Pogo system was attributed to the resin matrix materials such as silicon and polyurethane[25]. The CP-RW and Sof-Lex disc used in this study had different principal particles composed mainly of SiC and Al_2O_3, respectively. Moreover, their particle sizes were similar to that of the Pogo system. Although multiple scratches were observed on the ceramic surfaces polished by Sof-Lex discs, CP-RW left less scratches even with the same-sized particles (Figs. 2 and 3). First, the difference can be attributed to the shape of the abrasive particles, that is, the sharp Al_2O_3 particles left scratches. The excellent result of the CPRW was attributed to the facts that the shape of the SiC and diamond particles were smooth and rounded-edged. Second, the irregularity of the polishing wheel was reduced to a minimum by filling the pores between large SiC particles with small diamond particles, and the remaining porosity between densely-packed particles were filled with matrix rubber material. Although the particle size of the disc is important, the results of this study suggest that the composition, shape, and distribution of the abrasive particles may also affect the roughness of the polished ceramic surface. Future well-controlled studies are needed on the effects of the variables related to abrasive particles such as composition, shape, distribution, and hardness on surface roughness.

In this study, two types of feldspathic porcelain were used: a sintering porcelain in a powder form and a ceramic block for a CAD/CAM milling procedure. The former was selected because the outer surface of the ceramic crown has been built up with sintering feldspathic porcelain supplied in a powder form. The latter was also selected for comparison because the milled surface of the ceramic block was exposed in CAD/CAM restorations for inlays and single crowns. As shown in Table 3, even with the random allocation, slight differences were observed in the Ra, Rq, and Rz between the treatment groups prepared in an automatic polishing machine before surface treatments. The failure in random allocation of the specimens in terms of the roughness value was ascribed to the great roughness of #220 SiC paper. It was selected as a baseline roughness on the basis of the similar particle size of both diamond particles on fine grit diamond points (60–74 μm) and the grits of coated abrasives on SiC papers (P240, 58.5±2.0 μm, the highest grits in the standard) and it was used to simulate the roughness made by the diamond points during occlusal adjustments[42-44]. However, as shown in Table 4, although the baseline roughness values in the CPRW were not the lowest in most parameters, the roughness values after polishing with CP-RW exhibited the lowest roughness values in all parameters for both materials ($p<0.05$ in all parameters). After surface treatment, S porcelain showed superior surface roughness in the Ra, Rq, and Rz values of both materials ($p<0.05$, Table 4). Moreover, because there were no significant interactions between the materials and

treatments in all parameters, the CPRW showed the best results in both materials. The clinical use of the CP-RW is highly supported by these *in vitro* results. Further studies are needed with ceramic specimens of various and well-controlled initial roughness values to investigate the effect of the initial roughness on the polishing effect. There are several factors that affect the surface roughness of the polished restoration. Operator factors were eliminated by a single operator performing all of the procedures[25]. Considering that polishing strokes can be made in rotary, planar, or reciprocating motions, it has been shown that planar motions achieved the smoothest surfaces[25,28]. In the current study, polishing was performed in a unidirectional planar motion. In addition, the CP-RW is easy to use because it is stiffer than Sof-Lex disc, which is too flexible to exert pressure on the substrate. The stiffness of the CP-RW facilitated to exert pressure on ceramics to create smoother surfaces.

CONCLUSIONS

Within the limitations of this study, polishing with CP-RW provided a fast and easy surface treatment for ceramic restorations, with the polished feldspathic porcelains showing smooth surfaces comparable to the surfaces obtained with Sof-Lex polishing or glazing. The excellent result was attributed to the composition of the particles and matrix substance, the rounded shape of the particles, and the even distribution of large SiC and small diamond particles within the CP-RW. In addition to the Ra value, other parameters such as Rq, Rp, Rv, Rz, and RSm should be evaluated when the surface roughness of ceramic materials are investigated. The results in this study were dependent on the ceramic materials and the surface treatment methods.

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