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The effects of different surface treatments on the surface properties and microstructure of restorative materials: an *in vitro* study

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Introduction: This study aims to systematically evaluate the differential effects of ultrasonic treatment, erythritol sandblasting, sodium bicarbonate sandblasting, and polishing on the surface roughness (Ra), volume loss, and surface microtopography of four dental restorative materials: composite resin, glass ionomer, ceramic, and titanium.

Methods: Specimens of each material were randomly assigned to the following treatment groups ($n = 16$, for each group): Group A (ultrasonic treatment), Group B (erythritol sandblasting), Group C (sodium bicarbonate sandblasting), Group D (polishing), and Group E (non-surface treated control group). Ra was measured before and after treatment using a surface profilometer. Volume loss was quantified with an electronic micrometer, and surface morphology was examined by scanning electron microscopy (SEM). Data were analyzed using paired t-tests, one-way ANOVA, and two-way ANOVA to examine the main effects and interactions.

Results: Two-way ANOVA revealed a significant interaction between material type and treatment method for both volume loss and Ra ($p < 0.001$), indicating that the treatment efficacy was material-dependent. Both sandblasting methods resulted in significantly greater surface improvement, when compared to ultrasonic treatment and polishing ($p < 0.05$). Sodium bicarbonate sandblasting yielded the greatest improvement for titanium ($\Delta Ra = -0.295$) and glass ionomer ($\Delta Ra = -0.211$). Erythritol sandblasting provided effective surface leveling with more uniform and milder morphological changes. SEM confirmed the uniform abrasion after sandblasting versus scratches or residual debris after polishing or ultrasonic treatment, respectively. Glass ionomer had the highest volume loss (139–153 μm), while ceramic had the lowest volume loss (14–17 μm).

Conclusion: Sandblasting was overall superior to ultrasonic and polishing treatments, as evidenced by the improved Ra, controlled volume loss, and supporting micro-topographical observations. Sodium bicarbonate sandblasting is suitable for reducing aggressive roughness, while erythritol sandblasting is preferable for minimal and uniform surface treatment. Among the tested

materials, ceramic had the best wear resistance and surface stability across all surface treatments.

KEYWORDS

erythritol, sandblasting, sodium bicarbonate, surface roughness, volume loss

1 Introduction

Surface treatment is a critical factor that influences the clinical performance and longevity of dental restorative materials (Liu et al., 2024). Restorations are required to function for a prolonged period within the complex dynamic oral environment, where smooth surfaces not only improve aesthetics, but also reduce plaque adhesion, minimize staining, and delay the material's biodegradation, thereby extending its service life (Nascimento et al., 2021; Martins et al., 2023). Furthermore, the wear resistance of various restorative materials varies, depending on the composition, type, and size of fillers (Nayyer et al., 2019). In clinical practice, ultrasonic scaling and sandblasting are commonly used for restoration maintenance (Divnic-Resnik et al., 2022). Ultrasonic cleaning relies on high-frequency oscillations and cavitation effects to remove surface deposits. However, its impact on the substrate surface, particularly the microstructural alterations induced in different materials, remains inadequately investigated (Babina et al., 2020; Kruse et al., 2024; Németh et al., 2022). Sandblasting, which propels abrasive particles at high velocity *via* compressed air, enables efficient cleaning. However, various factors, such as the choice of abrasive particles (sodium bicarbonate and erythritol) and operational parameters (*e.g.*, pressure and angle), can lead to markedly different outcomes on material surfaces (G et al., 2023; Jentsch et al., 2020; Onisor et al., 2022). Furthermore, there are few systematic studies, and there is a lack of systematic studies that directly compare the effects of these mainstream treatment methods on the surface properties of common restorative materials (Reinhart et al., 2022). Therefore, the present study aimed to systematically evaluate and compare the effects of various surface treatments on the surface properties of four dental restorative materials, in order to provide scientific evidence for selecting the optimal clinical treatment protocol.

2 Materials and methods

2.1 Materials and instruments

2.1.1 Instruments and consumables

The primary instruments used for the present study were as follows: sandblasting machine (EMS Air-Flow Master, Switzerland), scanning electron microscope (TESCAN MIRA3 LMH, Czech Republic), roughness tester (Siderixin TR230, China), digital micrometer (Mitutoyo, Japan), and light-curing lamp (Yihuoja, Liechtenstein). The consumables comprised of erythritol sandblasting powder (EMS AIR-FLOW PLUS, Switzerland) and sodium bicarbonate sandblasting powder (EMS AIR-FLOW Powder CLASSIC, Switzerland), Ultrasonic scaler (Woodpecker UDS-J, China), and a standard polishing system (Belmont Clesta, China).

The restorative materials were paste resin (3M Z350XT A2, United States), glass ionomer (Fuji IX A2, Japan), a titanium block (Enburi, China), and a ceramic block (Enburi, China).

2.1.2 Restorative materials

Four dental restorative materials were investigated, and the primary chemical compositions were, as follows: composite resin (3M Filtek™ Z350XT, shade A2, United States) (The main components were silanized ceramics, silanized zirconia and silica, dimethyl acrylate, bisphenol A diglycidyl ether dimethyl acrylate, and ethoxylated bisphenol A dimethyl acrylate polybis ester), glass ionomer cement (GC Fuji IX GP Extra, Japan) (Powder: silica-alumina-fluorine glass, and polyacrylic acid; Liquid: polyacrylic acid, distilled water, and polycarboxylic acid), pre-sintered ceramic block (Enburi, China) (Primary composition: 3 mol% yttria-stabilized tetragonal zirconia polycrystal, 3Y-TZP), and commercially pure titanium block (Enburi, China) (titanium grade $\geq 99.5\%$).

2.2 Sample preparation

The sample size of the present study ($n = 16$) was determined based on the commonly used range for similar *in vitro* studies in the field of prosthodontic materials science (Yoshida, 2020; Mirt et al., 2024), combined with the laboratory's conditions and experimental feasibility. To assess the statistical power of the sample size, a post-hoc power analysis (using G*Power 3.1 software) was performed. The analysis is based on the observed effect sizes derived from this study (specifically, Cohen's $\eta^2 = 10.21$ for the material principal effect, which is well above the conventional large-effect threshold). The probability of error in the setting α was 0.05, the total sample size was $N = 256$. The analysis showed that the statistical power ($1 - \beta$) of this study was >0.999 for the detection of the main effect of the material. This indicates that the current sample size provides extremely adequate testing power.

Among the four restorative materials, the titanium and ceramic blocks were custom-made to the dimensions of $8 \times 8 \times 5$ mm, while the composite resin (3M Z350) and glass ionomer cement (Fuji IX) were prepared using polytetrafluoroethylene (PTFE) molds ($8 \times 8 \times 5$ mm, with five cavities). For the resin composite, an incremental filling technique was employed, in which each layer was ≤ 2 mm thick, and light-cured using a dental light-curing unit (Yihuoja, Liechtenstein) at an intensity of $1,200 \text{ mW/cm}^2$, according to the manufacturer's instructions. A glass slide was used to flatten the surface before final curing. The glass ionomer cement was mixed according to the manufacturer's guidelines, and allowed to self-cure in the molds at room temperature. For each sample, four rectangular sides ($8 \text{ mm} \times 5 \text{ mm}$) were defined as experimental surfaces. Specimens with visible bubbles under magnification were

discarded. Ultimately, 16 valid specimens were obtained for each material, yielding a total of 64 experimental surfaces (four per specimen).

2.3 Experimental grouping and treatment

The specimens for each material were randomly allocated into four treatment groups. Four specimens were assigned to each treatment group per material, and with each specimen contributing four experimental surfaces, this resulted in 16 surfaces per group per material. The surface of each specimen was marked with a pen. For each group, the following surface treatments were applied until the markings were completely removed under visual inspection.

- Group A (ultrasonic): the treatment was performed using an ultrasonic scaler (Woodpecker UDS-J, China) with a sweeping motion for 30 s;
- Group B (erythritol sandblasting): the surfaces were treated with erythritol powder (EMS AIR-FLOW PLUS, Switzerland) at a pressure of 0.4 MPa, with the nozzle maintained at a 4 mm distance and a 45° angle;
- Group C (sodium bicarbonate sandblasting): the surfaces were treated using sodium bicarbonate powder (EMS AIR-FLOW Powder CLASSIC, Switzerland) with the same parameters as Group B;
- Group D (polishing): the surfaces were sequentially polished using a standard polishing system (Belmont Clesta, China);
- Group E (control group): non-surface treated control group.

The experimental design is schematically illustrated in [Figure 1](#).

2.4 Surface roughness (Ra) measurement

For each group, the Ra value was measured after surface treatment using a profilometer (Siderixin TR230, China) in contact mode. The measurement parameters were set, as follows: probe tip diameter, 2 μm ; pressure, 0.75 mN; feed rate, 1 mm/s. For each sample, three measurements were taken on the central surface area, and the average value was recorded as the final Ra.

2.5 Volume loss determination

The central thickness of each specimen was measured using an electronic micrometer (Mitutoyo, Japan) before and after treatment. Three measurements were taken and averaged. The volume loss (μm) was calculated as the difference between the pre- and post-treatment thickness values.

2.6 Surface morphology observation

Following the surface treatment, the samples were ultrasonically cleaned, dried, and sputter-coated with gold. Then, the surface microtopography (TESCAN MIRA3 LMH, Czech Republic) was examined by scanning electron microscopy (SEM) at an acceleration voltage of 15 kV and a working distance of 15 mm.

2.7 Statistical analysis

Statistical analysis was performed using the SPSS 25.0 software (SPSS Corporation, Chicago, IL, United States). Quantitative data were expressed in mean \pm standard deviation ($\bar{x} \pm s$). In order to comprehensively evaluate the impact of material type and treatment method on volume loss and Ra, the present study employed a multi-level statistical strategy. Initially, two-way ANOVA was conducted to test the main effects and interactions between materials and treatment methods. Then, the effect size (partial η^2) was calculated for significant effects. If the interactions were significant, a simple effect analysis was further performed (*i.e.*, one-way ANOVA was conducted for each material separately). Next, post-hoc multiple comparisons were performed using the Tukey HSD test when significant differences were observed, in order to clarify the specific differences among treatment groups. The post-hoc comparison results were labeled with superscript letters in the relevant tables. In addition, paired-sample *t*-test was used to compare the changes in Ra before and after treatment within each group.

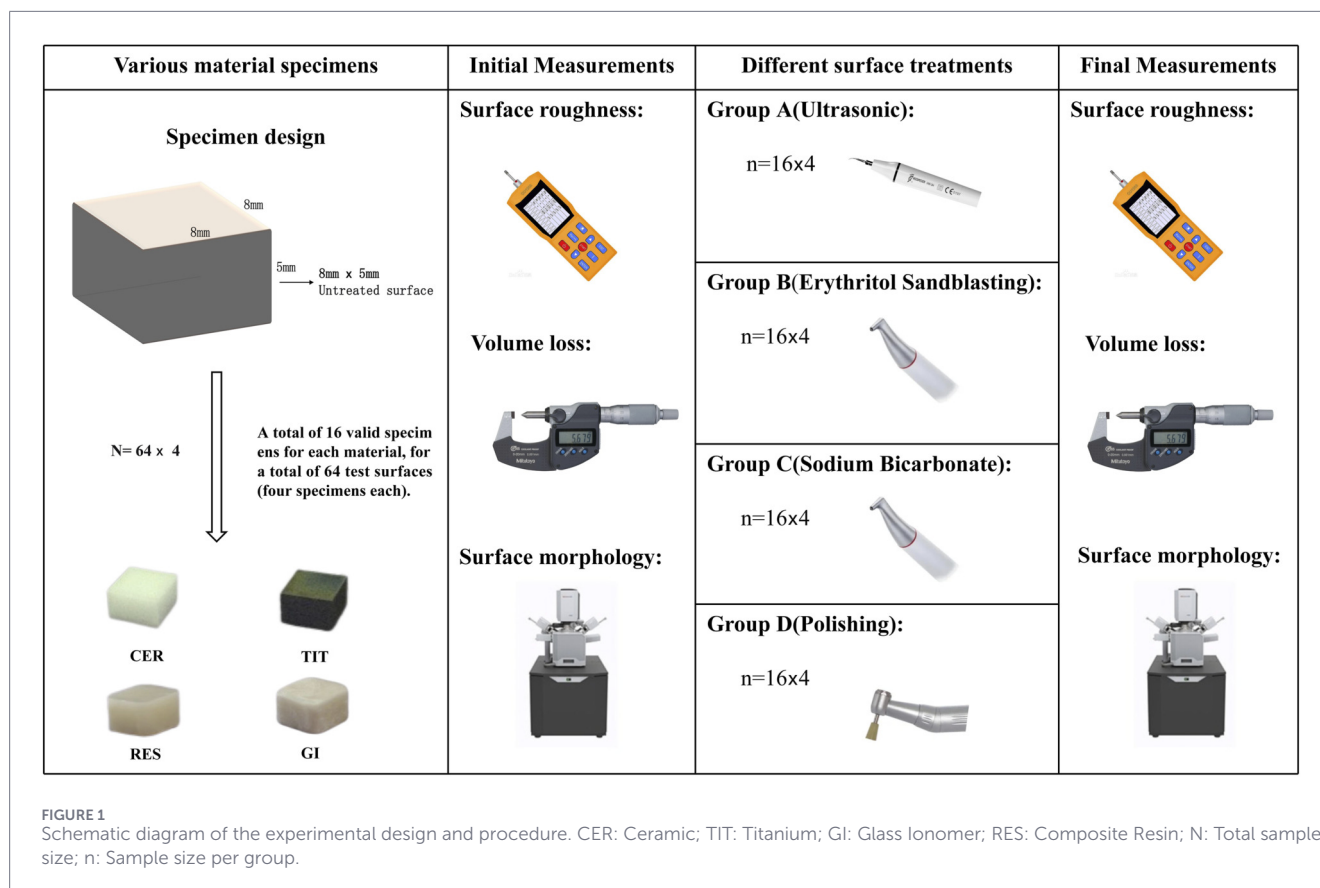
2.8 Statistical independence

We acknowledge that measurements obtained from multiple surfaces of the same specimen are not completely independent. In this study, the main statistical analyses (*e.g.*, two-way ANOVA and subsequent comparisons) were designed to examine differences between different ‘material-treatment’ combinations. Therefore, we use the average of the measurements of the 16 individual specimens under each combination as the basic unit of analysis. This strategy effectively handles potential within-sample correlations at the between-group-comparison level. In addition, the effect size observed in this study is extremely large (*e.g.*, the partial $\eta^2 > 0.99$ for the main effect of the material). The post-hoc power analysis shows that the statistical power was close to 1.000, indicating that the main conclusions are extremely robust and not subject to the substantive effects of potential minor correlations at the measurement level.

3 Results

3.1 Interaction between material and treatment

In order to comprehensively evaluate the influence of material type and surface treatment on the experimental results, two-way analysis of variance was initially carried out. For volume loss, the main effects of material type ($F = 8369.234, p < 0.001, \eta^2 = 0.991$) and surface treatment method ($F = 78.472, p < 0.001$) were extremely significant. More importantly, there was a significant interaction between the two ($F = 10.097, p < 0.001$), indicating that the impact of different surface treatments on volume loss varied with the material type ([Table 1](#)). Furthermore, the model had an extremely high degree of fit ($R^2 > 0.99$). For post-treatment Ra, the main effects of material type ($F = 15637.941, p < 0.001, \eta^2 = 0.995$) and treatment method ($F = 21.942, p < 0.001$) were both highly significant. Furthermore, a significant interaction effect between these two factors was



observed ($F = 5.931$, $p < 0.001$) (Table 2). This confirms that the improvement of surface treatment on roughness is highly dependent on the specific restorative material. The simple effect analysis revealed that the sandblasting treatment was generally better than the mechanical treatment in volume loss, and that the effect of sandblasting on roughness differed according to the material. That is, some materials were sensitive to the sandblasting treatment, while some materials were tolerant to the sandblasting treatment. The marginal means plots in Figures 2, 3 visually illustrate the above interaction. The curves that represented the different treatments were clearly non-parallel and intersecting, clearly indicating that there is no “one-size-fits-all” treatment that is optimal for all materials.

3.2 Paired sample *t*-test: Changes in Ra before and after treatment in each group

On the basis of confirming the presence of significant interactions, the specific effects of various treatments on the Ra of each material were further analyzed by paired sample *t*-test (Table 3).

The paired *t*-test results (Table 3) indicated that the Ra was significantly altered ($p < 0.05$) following treatment in all groups, except for the titanium specimens in Group A ($p = 0.394$). Furthermore, the ultrasonic treatment (group A) significantly increased the Ra value of glass ionomer (from 3.758 ± 0.104 to 3.956 ± 0.152 , $p < 0.001$). In contrast, both sandblasting methods (Groups B and C) significantly reduced the Ra across all materials.

3.3 One-way analysis of variance: Specific comparisons and between-group differences

One-way analysis of variance was conducted to further explore the differences in effects across treatment methods within specific materials.

3.3.1 Between-group comparison of volume loss

The ANOVA (Table 4; Figure 4) results revealed significant differences in volume loss among the treatment groups for all materials: porcelain ($F = 7.15$, $p < 0.001$), titanium ($F = 28.49$, $p < 0.001$), glass ionomer ($F = 38.58$, $p < 0.001$), and resin ($F = 12.63$, $p < 0.001$). Overall, Groups A (ultrasonic) and D (polishing) resulted in greater volume loss, while Groups B (erythritol sandblasting) and C (sodium bicarbonate sandblasting) induced significantly less volume loss, when compared to Groups A and D. The post-hoc comparisons (Tukey HSD) confirmed this pattern, showing that sandblasting induced significantly less volume loss, when compared to the ultrasonic or polishing treatments, for every material tested (all, $p < 0.05$), with no significant difference between the two sandblasting methods. Specific to materials, ceramics had the smallest volume loss ($14\text{--}17\ \mu\text{m}$) under all treatments, and the differences between groups were relatively small. Next was the volume loss of the resin ($51\text{--}57$). The titanium material had a large volume loss ($79\text{--}100\ \mu\text{m}$), which peaked under the ultrasonic and polishing treatments. Among all the materials, glass

TABLE 1 Inter-subject effect test table for volume loss.

Tests of between-subjects effects					
Dependent variable: Volume loss					
Source	Type III sum of squares	Degrees of freedom	Mean square	F	<i>p</i>
Corrected model	597268.215 ^a	15	39817.881	1695.599	0.000***
Intercept	1482762.848	1	1482762.848	63141.772	0.000***
Material	589605.980	3	196535.327	8369.234	0.000***
Group	5528.293	3	1842.764	78.472	0.000***
Material*group	2133.941	9	237.105	10.097	0.000***
Error	5635.938	240	23.483		
Total	2085667.000	256			
Corrected total	602904.152	255			
aR ² = 0.991 (adjusted R ² = 0.990)					

****p* < 0.001. Material *Group, represents the interaction between material types and how these are processed. aR² = 0.991 (adjusted R² = 0.990), indicates that the model has a high degree of interpretation of dependent variable variation.

TABLE 2 Test table of roughness intersubject-subject effects.

Tests of between-subjects effects					
Dependent variable: Roughness after treatment					
Source	Type III sum of squares	Degrees of freedom	Mean square	F	<i>p</i>
Corrected model	855.203 ^a	15	57.014	3135.535	0.000***
Intercept	2072.412	1	2072.412	113975.016	0.000***
Material	853.036	3	284.345	15637.941	0.000***
Group	1.197	3	0.399	21.942	0.000***
Material*group	0.971	9	0.108	5.931	0.000***
Error	4.364	240	0.018		
Total	2931.979	256			
Corrected total	859.567	255			
aR ² = 0.995 (adjusted R ² = 0.995)					

****p* < 0.001. Material *Group, represents the interaction between material types and how these are processed. aR² = 0.995 (adjusted R² = 0.995), indicates that the model has a high degree of interpretation of dependent variable variation.

ionomer had the largest volume loss (139–153 μm). These results indicate that the surface treatment method significantly affected the volume loss of the restorative material. Furthermore, the statistical analysis (Table 5; Figure 5) results revealed the significant effect of the treatment method on material volume loss (*p* < 0.001). Notably, the volume loss in the sandblasted groups (Groups B and C) was consistently and significantly lower, when compared to that observed in both the ultrasonic (Group A) and polishing (Group D) groups.

3.3.2 Comparison between groups for change in surface roughness (ΔRa)

The ANOVA (Tables 6, 7) results revealed that the surface treatment methods had a statistically significant effect on the

ΔRa for all four materials (*p* < 0.001). Specifically, the ultrasonic treatment (Group A) significantly increased the roughness of glass ionomer (ΔRa = +0.197 ± 0.137), while the other treatments reduced it. The sandblasting treatment (Groups B and C) produced the most significant roughness reduction effect on titanium materials (ΔRa was approximately −0.294 and −0.295, respectively). Except for the ultrasonic treatment (Group A), all treatments reduced the Ra value, with the sodium bicarbonate sandblasting treatment (Group C) showing slightly better results than the other groups (ΔRa = −0.023 ± 0.012). Notably, the post-hoc analysis indicated that for titanium and composite resin, the differences in ΔRa among the four treatment groups were not statistically significant, suggesting that these materials exhibit greater surface tolerance to the tested protocols. Furthermore, the type of restorative material significantly influenced

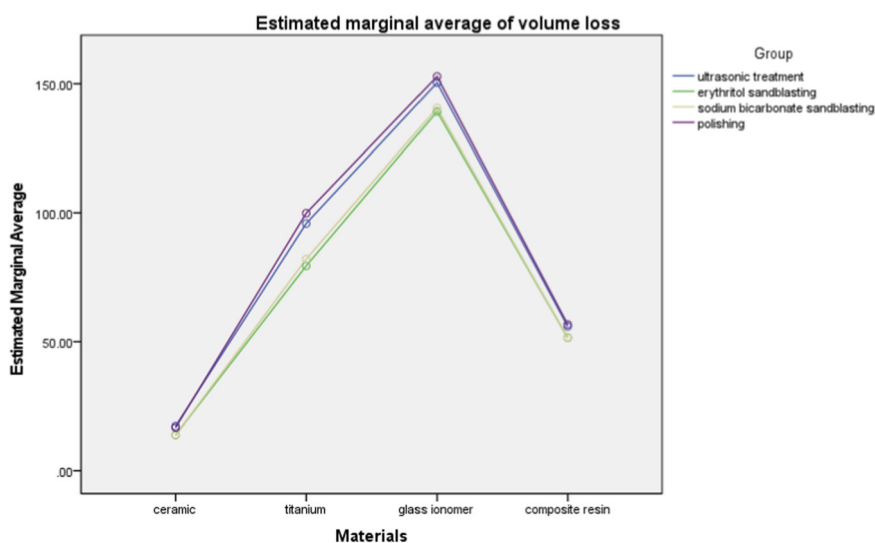


FIGURE 2 Effect of material type and surface treatment on volume loss (Two-way ANOVA, marginal means \pm SE). Blue: ultrasonication; Green: erythritol sandblasting; Yellow: sodium bicarbonate blasting; Purple: polished. Error bars represent the standard errors.

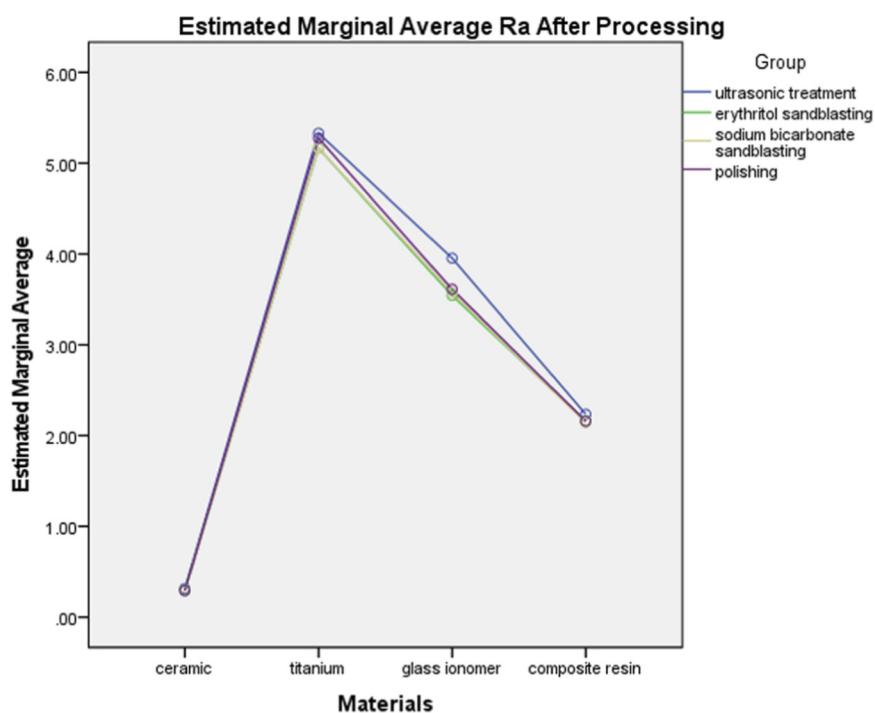


FIGURE 3 Effect of material type and surface treatment on surface roughness (Two-way ANOVA, marginal means \pm SE). Blue: ultrasonication; Green: erythritol sandblasting; Yellow: sodium bicarbonate blasting; Purple: polished. Error bars represent the standard errors.

the ΔRa outcome within each treatment group ($p < 0.001$). These results indicate the significant interaction between the surface treatment methods and materials, highlighting that the material's inherent physical properties are a key determinant of its response to surface treatment.

3.4 Surface morphology observation

The SEM results revealed distinct microstructural alterations that resulted from the different surface treatments (Figure 6). The untreated surfaces (Group E) had an inherent material morphology,

TABLE 3 Paired-samples *t*-test analysis results for surface roughness before and after treatment.

Group	Material	Pair ($\bar{x} \pm s$)		<i>t</i>	<i>p</i>
		Pre-treatment Ra	Post-treatment Ra		
A	Ceramic pre-post	0.310 ± 0.009	0.316 ± 0.011	-2.395	0.030*
	Titanium pre-post	5.350 ± 0.244	5.331 ± 0.188	0.877	0.394
	Glass ionomer pre-post	3.758 ± 0.104	3.956 ± 0.152	-5.757	0.000***
	Composite resin pre-post	2.272 ± 0.139	2.236 ± 0.135	14.590	0.000***
B	Ceramic pre-post	0.311 ± 0.010	0.300 ± 0.010	3.350	0.004**
	Titanium pre-post	5.460 ± 0.218	5.166 ± 0.232	23.935	0.000***
	Glass ionomer pre-post	3.743 ± 0.103	3.544 ± 0.116	17.736	0.000***
	Composite resin pre-post	2.252 ± 0.082	2.159 ± 0.082	12.382	0.000***
C	Ceramic pre-post	0.312 ± 0.009	0.289 ± 0.005	7.587	0.000***
	Titanium pre-post	5.462 ± 0.162	5.166 ± 0.232	6.520	0.000***
	Glass ionomer pre-post	3.792 ± 0.109	3.579 ± 0.097	14.605	0.000***
	Composite resin pre-post	2.247 ± 0.153	2.140 ± 0.137	5.548	0.000***
D	Ceramic pre-post	0.311 ± 0.010	0.293 ± 0.006	8.105	0.000***
	Titanium pre-post	5.467 ± 0.211	5.277 ± 0.167	6.022	0.000***
	Glass ionomer pre-post	3.808 ± 0.089	3.613 ± 0.091	19.053	0.000***
	Composite resin pre-post	2.253 ± 0.154	2.159 ± 0.148	16.253	0.000***

p* < 0.05, *p* < 0.01, ****p* < 0.001. Ra, surface roughness.

TABLE 4 Analysis of variance for volume loss in different materials across surface treatment groups.

Group ($\bar{x} \pm s$)	Ceramic	Titanium	Glass ionomer	Composite resin
A (<i>n</i> = 16)	17 ± 4a	96 ± 12a	150 ± 5a	56 ± 3a
B (<i>n</i> = 16)	14 ± 2b	79 ± 7b	139 ± 5b	52 ± 4b
C (<i>n</i> = 16)	14 ± 3b	82 ± 5b	141 ± 4b	51 ± 3b
D (<i>n</i> = 16)	17 ± 2a	100 ± 3a	153 ± 4a	57 ± 2a
<i>F</i>	7.151	28.491	38.583	12.627
<i>p</i>	0.000***	0.000***	0.000***	0.000***

p* < 0.05, *p* < 0.01, ****p* < 0.001. For a given treatment method, the differences between groups labeled with different lowercase letters are statistically significant (*p* < 0.05).

serving as the baseline for comparison. Surfaces subjected to ultrasonic treatment (Group A) had minor, uneven deposits, suggesting incomplete cleaning. In contrast, both sandblasting groups (Groups B and C) had significantly improved surface uniformity and flatness, with original irregularities effectively removed to form a homogeneously abraded surface morphology. This observation is consistent with the quantitative roughness data, confirming the efficacy of sandblasting. Although the polished group (Group D) achieved general smoothness, distinct directional scratches were evident on the glass ionomer and resin surfaces, indicating that mechanical polishing can induce new micro-defects in comparatively softer materials. In summary, sandblasting produced the most favorable surface topography, while ultrasonic and polishing methods were associated with residual debris and scratching, respectively.

4 Discussion

4.1 Discussion on the mechanism of material response difference

The present study confirmed the significant interaction between the type of restorative material and the surface treatment method (*p* < 0.001), indicating that there is no universal optimal treatment scheme. The difference in the response of materials to surface treatment stems from the matching relationship between its inherent properties and the treatment mechanism. Sandblasting treatment can generally reduce the Ra value (Petersilka, 2000). However, the specific effect varies with the material: erythritol particles with moderate hardness and regular morphology can achieve the uniform micro-cutting of titanium materials, and obtain the

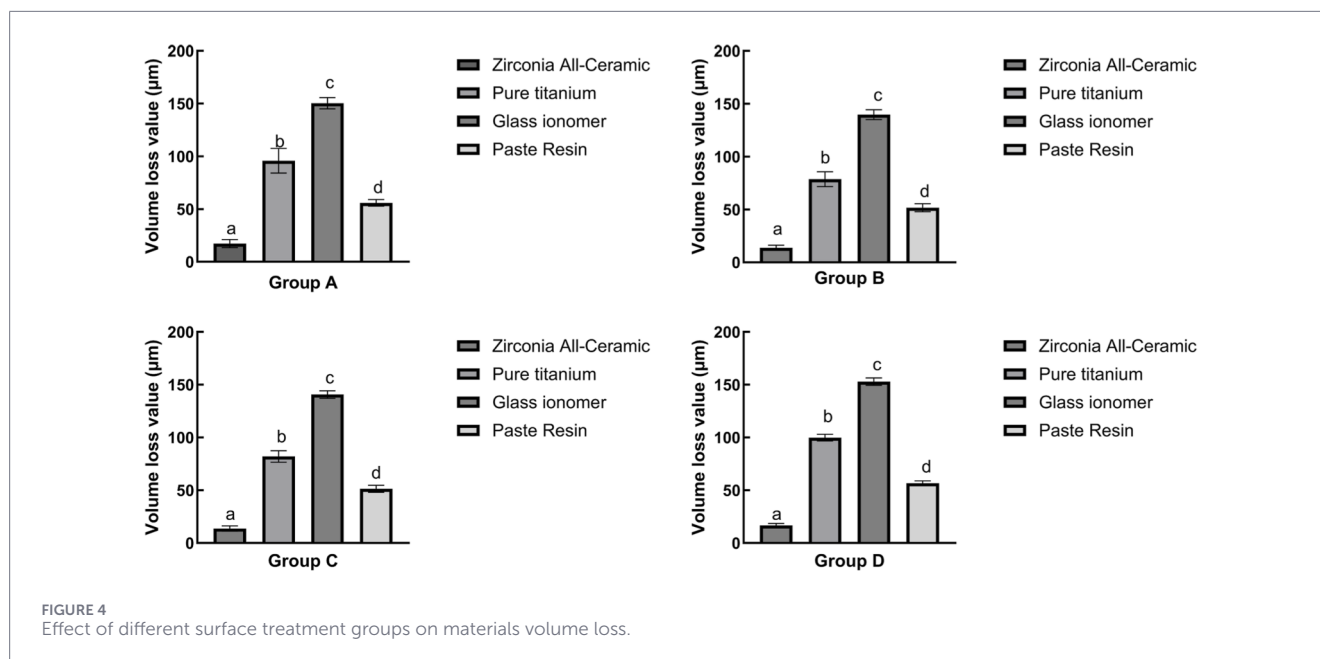


TABLE 5 Analysis of variance for the effect of different surface treatment groups on material volume loss.

Group ($\bar{x} \pm s$)	A (ultrasonic)	B (erythritol)	C (NaHCO ₃)	D (polishing)
Composite resin ($n = 16$)	56 ± 3c	52 ± 4c	51 ± 3c	57 ± 2c
Glass ionomer ($n = 16$)	150 ± 5a	139 ± 5a	141 ± 4a	153 ± 4a
Ceramic ($n = 16$)	17 ± 4d	14 ± 2d	14 ± 3d	17 ± 2d
Titanium ($n = 16$)	96 ± 12b	79 ± 7b	82 ± 5b	100 ± 3b
<i>F</i>	1,102.692	1,818.865	3,128.263	7,185.913
<i>p</i>	0.000***	0.000***	0.000***	0.000***

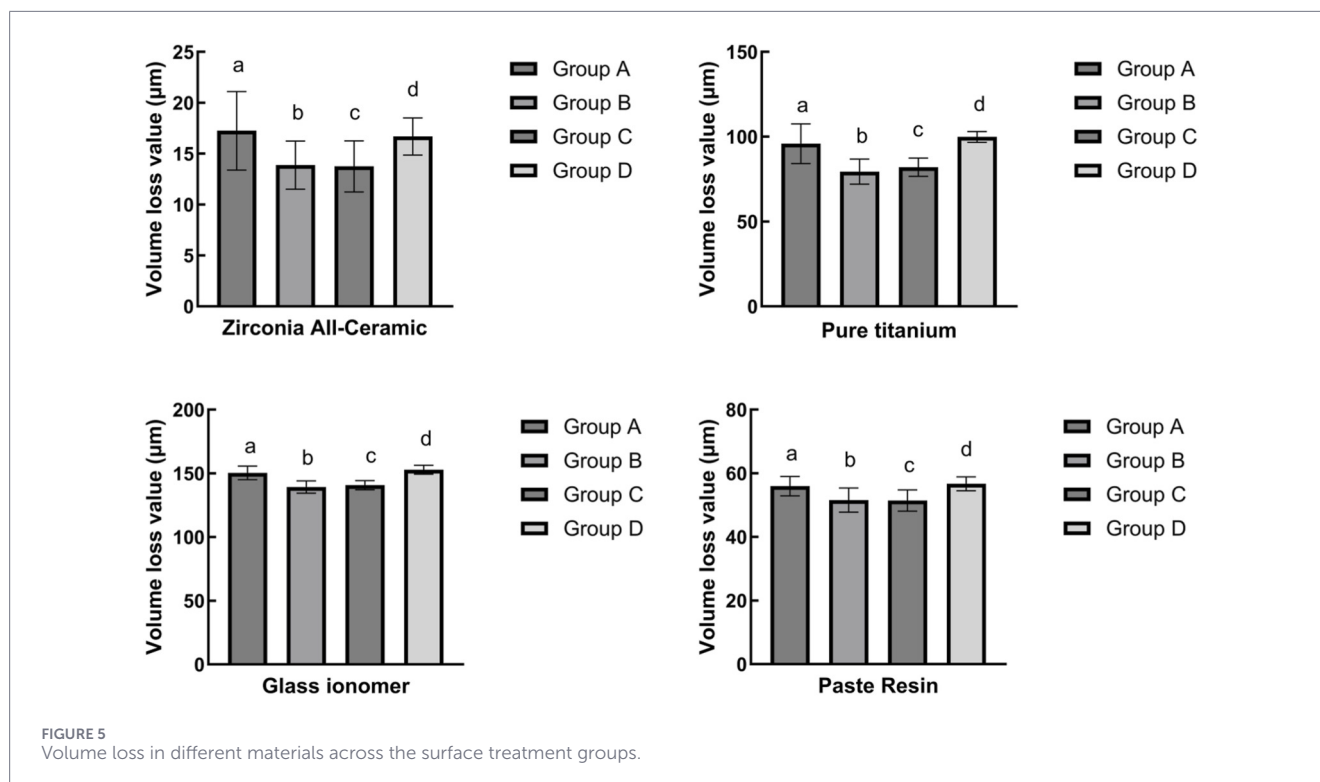
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. For a given material, groups labeled with different lowercase letters are considered statistically significant ($p < 0.05$).

best smoothing effect ($\Delta Ra = -0.295 \pm 0.181$) (Atagün and Kalyoncuoğlu, 2025). Furthermore, sodium bicarbonate particles with higher hardness and irregular shape can level the surface of softer glass ionomer more effectively ($\Delta Ra = -0.199 \pm 0.045$) (Amin et al., 2021). The negative effect of ultrasonic treatment on glass ionomer cement ($\Delta Ra = +0.197 \pm 0.137$) revealed that its porous matrix was prone to packing shedding or microcrack propagation under high-frequency oscillation (Mensi et al., 2024; Mohammadi et al., 2023). The volume loss data further confirmed the role of the material's intrinsic properties. Ceramic materials have extremely high hardness and dense microstructures, thereby exhibiting minimal volume loss (14–17 μm) and optimal wear resistance in all treatments (Martins et al., 2023). In contrast, due to its low hardness and multiphase structure, glass ionomer cement is prone to plastic deformation and interfacial failure under mechanical stress, resulting in the largest volume loss (139–153 μm) (Worthington et al., 2021). Although abrasive blasting removes the material, this generally leads to less volume loss, when compared to ultrasonic or polishing. This suggests that sandblasting may preferentially remove the prefabricated defect layer of the surface, and form a denser and more durable surface

transition layer through uniform micro-deformation or micro-forging (Sekino et al., 2020). In contrast, ultrasound can cause subsurface damage, while the directional scratches left by polishing on softer materials can become new stress concentration points and wear initiators (Okumuş et al., 2023).

4.2 Clinical significance and translational value

The present study correlated the *in vitro* experimental data with the key evaluation indicators of long-term clinical performance of restorations, providing an empirical basis for clinical decision-making. There is a broad consensus that increased Ra promotes the attachment and maturation of dental plaque biofilms, thereby elevating the risk of secondary caries, marginal discoloration, and peri-implantitis, and may also affect the long-term retention of dental restorations (Alnazzawi et al., 2025; Al Hatem et al., 2025). Therefore, achieving and maintaining a low Ra value is an important goal for clinical maintenance. The results of the present study show that sandblasting treatment has clear advantages in reducing the surface Ra value of different materials. For example, the

TABLE 6 Effect of different surface treatment groups on the change in surface roughness (ΔRa).

Group ($\bar{x} \pm s$)	Ceramic	Titanium	Glass ionomer	Composite resin Ra
A ($n = 16$)	0.006 ± 0.011	-0.018 ± 0.083	0.197 ± 0.137	-0.036 ± 0.010
B ($n = 16$)	-0.011 ± 0.013	-0.294 ± 0.049	-0.199 ± 0.045	-0.093 ± 0.030
C ($n = 16$)	-0.023 ± 0.012	-0.295 ± 0.181	-0.199 ± 0.021	-0.106 ± 0.077
D ($n = 16$)	-0.018 ± 0.009	-0.160 ± 0.065	-0.195 ± 0.041	-0.093 ± 0.023
<i>F</i>	20.608	24.113	108.980	8.468
<i>p</i>	0.000***	0.000***	0.000***	0.000***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Ra, surface roughness.

surface Ra value of ceramics, titanium, and composite resins after sandblasting can be reduced to less than $0.3 \mu\text{m}$. In contrast, the surface Ra value of ultrasonically treated glass ionomer cement (approximately $3.96 \mu\text{m}$) is much higher than this threshold, suggesting that the ultrasonic maintenance of the material may be detrimental to long-term oral health, and potentially shorten its lifespan (Eram et al., 2024).

In terms of material preservation, sandblasting technology shows a better balance. Although there is a controllable loss of micron-sized material, it is significantly lower than that of polishing and ultrasonic treatments, which can introduce microscopic scratches or cause subsurface damage (Harman and Murchie, 2025). For materials with excellent intrinsic properties such as ceramics, the extremely low volume loss ($14\text{--}17 \mu\text{m}$) combined with the ideal smooth surface after sandblasting support its application in areas where high durability is required, such as the posterior tooth area (Al-Akhali et al., 2025; Schubert et al., 2019). For glass ionomer cement, despite its relatively large volume loss, sodium bicarbonate

blasting, rather than ultrasonic treatment, is a more reasonable clinical compromise between “controlled material removal” and “avoiding severe surface roughening”, which may help extend its service time in low-stress zones (Sekino et al., 2020).

In summary, clinicians may be able to achieve more predictable maintenance outcomes by considering the material properties when selecting a restoration surface treatment method, and prioritizing sandblasting techniques that better match the material (Saraç Atagün et al., 2025; Janiszewska-Olszowska et al., 2020).

4.3 Research limitations and future directions

4.3.1 Study limitations

Although the present study yielded some findings, its inherent limitations should be considered when interpreting the conclusions. First, the *in vitro* model used in the present study did not fully

TABLE 7 Comparison of change in surface roughness (ΔRa) among different materials across treatment groups.

Material/Group ($\bar{x} \pm s$)	A (ultrasonic)	B (erythritol)	C (NaHCO ₃)	D (polishing)
Composite resin Ra ($n = 16$)	-0.036 ± 0.010	-0.093 ± 0.030	-0.106 ± 0.077	-0.093 ± 0.023
Glass ionomer Ra ($n = 16$)	0.197 ± 0.137	-0.199 ± 0.045	-0.211 ± 0.049	-0.195 ± 0.041
Ceramic Ra ($n = 16$)	0.006 ± 0.011	-0.011 ± 0.013	-0.023 ± 0.012	-0.018 ± 0.009
Titanium Ra ($n = 16$)	-0.018 ± 0.083	-0.294 ± 0.049	-0.295 ± 0.181	-0.187 ± 0.116
<i>F</i>	28.930	177.009	22.009	28.691
<i>p</i>	0.000***	0.000***	0.000***	0.000***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Ra, surface roughness.

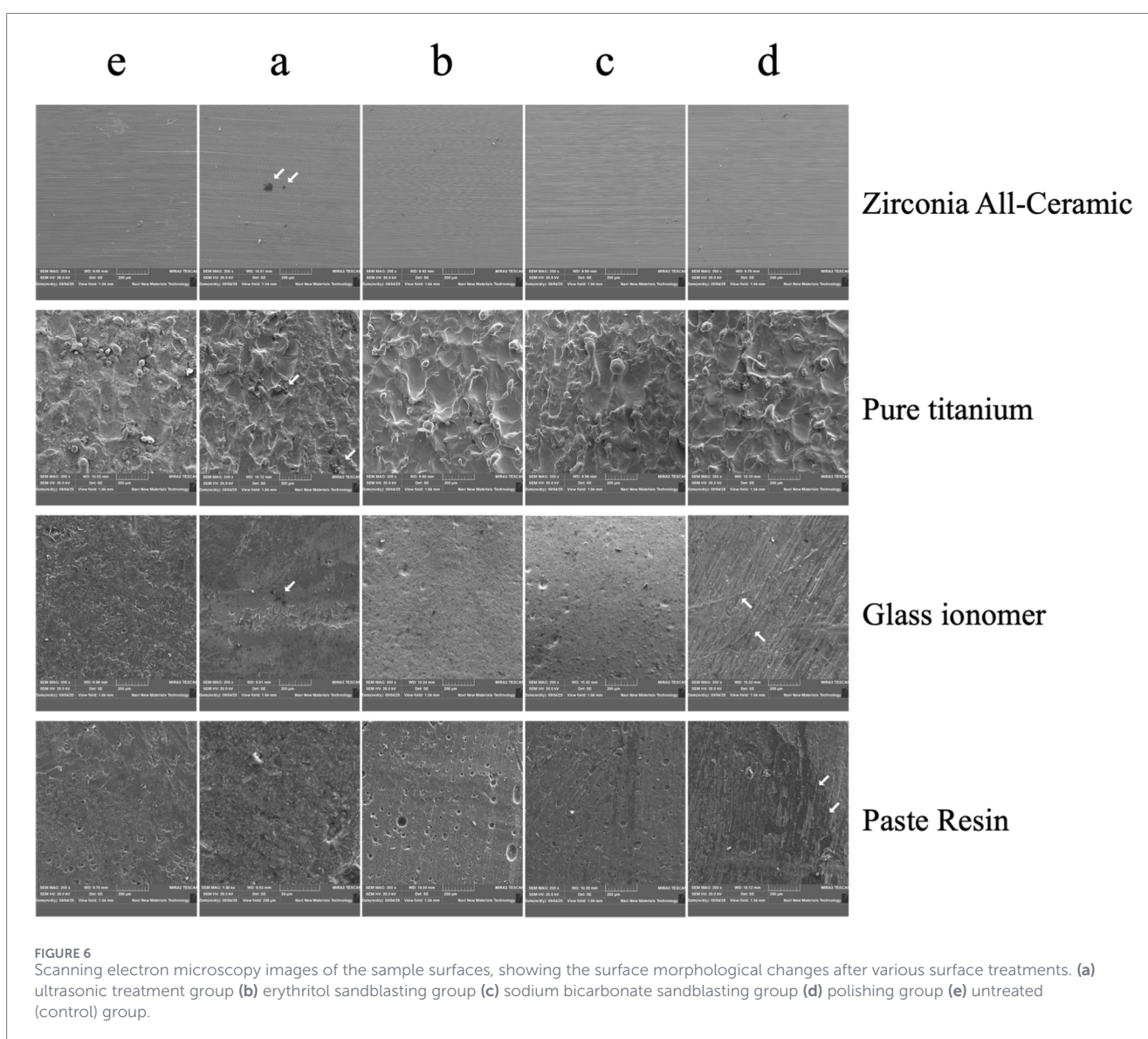


FIGURE 6 Scanning electron microscopy images of the sample surfaces, showing the surface morphological changes after various surface treatments. (a) ultrasonic treatment group (b) erythritol sandblasting group (c) sodium bicarbonate sandblasting group (d) polishing group (e) untreated (control) group.

reproduce the complex dynamic biological and physicochemical conditions in the oral cavity, such as saliva wetting, pH fluctuations, temperature cycling, microbial colonization, and long-term masticatory load, which may affect the accurate evaluation of the long-term performance of the surface treatment of the restorative material. Second, all surface treatments were performed by a single investigator to ensure operational consistency. However, the impact of this clinical variability on treatment effects has not been evaluated in the present study. In addition, the present study mainly focused on the changes in surface physical properties (e.g., roughness, morphology, and volume loss). That is, it did not further explore the effects of material chemical properties (e.g., oxidation state and functional group changes) or biological properties (e.g., biocompatibility and bacterial adhesion) that may be induced by surface treatment, which are closely correlated to the long-term biological stability of restorations. Finally, in terms of statistical design, the sample size ($n = 16/\text{group}$) was mainly based on literature practice and experimental feasibility, and no prior power analysis was conducted. The design of multiple measurement surfaces from the same sample may introduce statistical non-independence. However, the two-way ANOVA results revealed that the main effect and interaction effect of the material and treatment method reached a very high statistically significant level ($p < 0.001$). The model had strong explanatory power ($R^2 > 0.99$), indicating that the observed treatment effect was of great research significance, and was basically not disturbed by potential intra-sample correlations.

4.3.2 Future direction

Future studies should employ long-term simulated aging models to assess the durability of different surface treatment protocols. Furthermore, multi-center clinical trials are recommended to verify the reproducibility of the techniques. Moreover, the effects of surface treatment on the chemical and biological properties of materials warrant comprehensive evaluation. In addition, more advanced statistical approaches, such as mixed-effects models accounting for the non-independence of multiple surfaces from the same specimen, can be applied to further validate the robustness of the findings. Finally, the development of novel low-abrasion, highly biocompatible sandblasting materials can further optimize the balance between cleaning efficacy and substrate preservation. These approaches are expected to advance both the fundamental understanding and clinical translation of surface treatment strategies in restorative dentistry.

5 Conclusion

1. Considering the significant material-dependent effects of the surface treatment, the clinical selection of treatment method must carefully consider the type of restorative materials and the specific clinical objectives, and carefully weigh the need to seek Ra improvement and avoid the risk of potential volume loss.
2. Sandblasting techniques demonstrated overall superiority over ultrasonic cleaning and mechanical polishing in improving Ra.

3. Ultrasonic treatment significantly increased the Ra of glass ionomer materials. Therefore, this should be used with caution on glass ionomer restorations.
4. Material type significantly influenced volume loss, with glass ionomer exhibiting the poorest wear resistance, and ceramic exhibiting the best wear resistance.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

QL: Conceptualization, Formal Analysis, Investigation, Writing – original draft, Writing – review and editing. QH: Conceptualization, Writing – review and editing. XW: Methodology, Writing – original draft. MC: Methodology, Writing – original draft. ZL: Validation, Writing – original draft. HH: Validation, Writing – original draft. YX: Validation, Writing – original draft. LZ: Supervision, Writing – original draft. YW: Supervision, Writing – original draft.

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