

Article

The Effect of Different Surface Treatments on the Color and Translucency of Zirconia: An In Vitro Study

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Abstract

Background/Objectives: To compare the effects of different surface treatments on the color and translucency of three types of zirconia ceramics. **Methods:** Ninety CAD/CAM-milled zirconia disks (10 mm diameter, 1 mm thickness) were fabricated from Cercon HT (3-YTZP), IPS e.max ZirCAD MT (4-YTZP), and Cercon XT (5-YTZP). Baseline CIE Lab* coordinates were measured using a digital spectrophotometer. The disks underwent one of three surface treatments: 50 μ m alumina air-particle abrasion (AAA), Zircos-E etching (ZE), or 100 μ m glass bead air-particle abrasion (GBA). Post-treatment CIE Lab* measurements were obtained, and color change (ΔE_{00} , CIEDE2000) and translucency change (ΔTP_{00}) were calculated. **Results:** Regarding color change (ΔE_{00}), 50 μ m AAA produced the greatest change, followed by ZE, while GBA caused the smallest change. Surface treatment and its interaction with material type were found to exert a significant effect, whereas material type alone was not significant. Cercon XT showed the highest numerical ΔE_{00} value among the materials, although the difference was not statistically significant. All ΔE_{00} values were below the clinical acceptability threshold (<1.8). No significant effects of surface treatment, material type, or their interaction were observed for translucency change (ΔTP_{00}) after surface treatment. Baseline translucency values (TP_{00}) differed significantly, with Cercon XT being the most translucent, followed by ZirCAD MT and Cercon HT, but these differences did not result in significant ΔTP_{00} changes post treatment. **Conclusions:** Surface treatments and their interaction with material type significantly affected zirconia color change, with 50 μ m alumina air-particle abrasion producing the most pronounced effect. Material type alone did not significantly influence ΔE_{00} , though Cercon XT showed the highest numerical value. Translucency change (ΔTP_{00}) after treatment was unaffected by surface treatment or material–treatment interaction.



Academic Editors: João Paulo Mendes Tribst and Marco Cicciu

Received: 14 April 2026

Revised: 3 August 2026

Accepted: 4 August 2026

Published: 7 August 2026

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Keywords: surface treatment; zirconia ceramics; alumina air abrasion; Zircos-E etching; glass bead abrasion; optical properties

1. Introduction

Zirconia ceramics are widely used in dentistry due to their high flexural strength, fracture toughness, and biocompatibility. Traditional metal–ceramic restorations are being

replaced by all-ceramic restorations because ceramics offer superior esthetics and chemical stability. Zirconia can exist in monoclinic, tetragonal, and cubic phases; the addition of yttria stabilizes the tetragonal and cubic phases. Increasing the yttria content from 3 mol% to 5 mol% improves translucency but reduces mechanical strength [1,2].

Bonding zirconia to the tooth structure requires surface roughening and chemical activation because zirconia lacks a glass phase. Conventional acid etching and silane application, effective for glass ceramics, are ineffective for zirconia. Thus, mechanical treatments such as air abrasion, grinding, and glass bead blasting are commonly used to increase surface roughness and improve micromechanical interlocking. However, defects introduced to the surface can also weaken fully stabilized zirconia if the treatment is too aggressive [3,4].

Zirconia conditioning techniques can be categorized as physical, physicochemical, or chemical. Examples include mechanical roughening with aluminum-oxide (Al_2O_3) particles, tribochemical silica coating, Er:YAG laser irradiation, nano-silica deposition, and application of phosphate ester monomers such as MDP primers. Among these, sandblasting with alumina followed by MDP primer is widely regarded as the most reliable approach for improving adhesion. Nonetheless, researchers continue to explore new conditioners [5,6]. Zircos-E etching solution—a mixture of hydrofluoric, hydrochloric, sulfuric, nitric and phosphoric acids—creates a microporous surface by ionizing zirconia and can be applied to enhance adhesion [7].

Understanding optical measurements is crucial for evaluating how treatments alter color. The CIE $L^*a^*b^*$ system quantifies color in three coordinates: L^* represents lightness, a^* represents chromaticity along the red–green axis, and b^* represents chromaticity along the yellow–blue axis. Spectrophotometers measure these coordinates; color change can then be calculated using the ΔE_{ab} or the more recent ΔE_{00} formula [1]. ΔE_{00} provides better performance, especially for blue and gray colors, by including weighting factors for lightness, chroma, and hue, as well as a rotation term for blue hue interactions [2]. Perceptibility and acceptability thresholds for ΔE_{00} have been established; a 50:50 perceptibility threshold (PT) of 0.8 and an acceptability threshold (AT) of 1.8 represent the smallest differences that 50% of observers can perceive and consider acceptable [8,9].

Translucency is another key aesthetic parameter. It lies on a continuum from transparency to opacity and is influenced by light reflection, absorption, and scattering within the material [10]. The translucency parameter (TP) quantifies how much light passes through; a TP near zero indicates an opaque material [11,12]. The TP_{00} variant of this parameter uses the CIEDE 2000 formula to compare differences between white and black backgrounds. Surface roughness, grain size, fluorescence, and thickness all influence translucency. For example, as grain size increases, fewer grain boundaries scatter light, resulting in higher translucency. Conversely, a rougher surface increases scattering and opacity [13,14].

Finally, the rationale for this study stems from a gap in the literature—although previous research has shown that Zircos-E etching improves bond strength and alters surface roughness, little is known about its effect on the optical properties (color and translucency) of zirconia. This work therefore seeks to determine whether mechanical and chemical surface treatments—including alumina air abrasion, glass bead abrasion, and the novel method of Zircos-E etching—alter the color and translucency of three generations of zirconia ceramics. The following null hypotheses were tested in this study: (1) The color of the tested zirconia ceramic materials is not altered by different surface treatments. (2) The translucency of the tested zirconia ceramic materials is not altered by different surface treatments. (3) There is no difference in color stability between different types of zirconia ceramics.

2. Materials and Methods

2.1. Ethical Approval and Study Design

The research protocol was submitted to the Research Center at Riyadh Elm University and approved by the Institutional Review Board (IRB; registration FPGRP/2023/755/1015, approval number FPGRP/2023/755/1015/918). A total of 90 zirconia disks were fabricated and divided equally among three materials (Cercon HT, ZirCAD MT, and Cercon XT). Sample size calculations (G*Power v3.1.9.4) indicated that 63 samples were required to detect differences with an effect size of 2.16 at a power of 95% and $\alpha = 0.05$; 10 specimens per group ($n = 90$) were used to increase the statistical power of the investigation.

2.2. Specimen Preparation

Pre-sintered zirconia blocks (shade A2, 14 mm thickness) of Cercon HT (3-YTZP) (Dentsply Sirona, Bensheim, Germany), IPS e.max ZirCAD MT (4-YTZP) (Ivoclar Vivadent, Schaan, Liechtenstein), and Cercon XT (5-YTZP) (Dentsply Sirona, Bensheim, Germany) were used. A total of 90 disks (10 mm diameter $\times$ 1 mm thickness) were milled using CAD/CAM technology (Zirkonzahn M5 milling machine, Gias, Italy) and sintered (Zirkonofen600; Zirkonzahn GmbH, Gias, Italy) according to the manufacturers' instructions. All disks were polished using a polishing machine and ultrasonically cleaned in distilled water. An overview of the experimental workflow is shown in Figure 1.

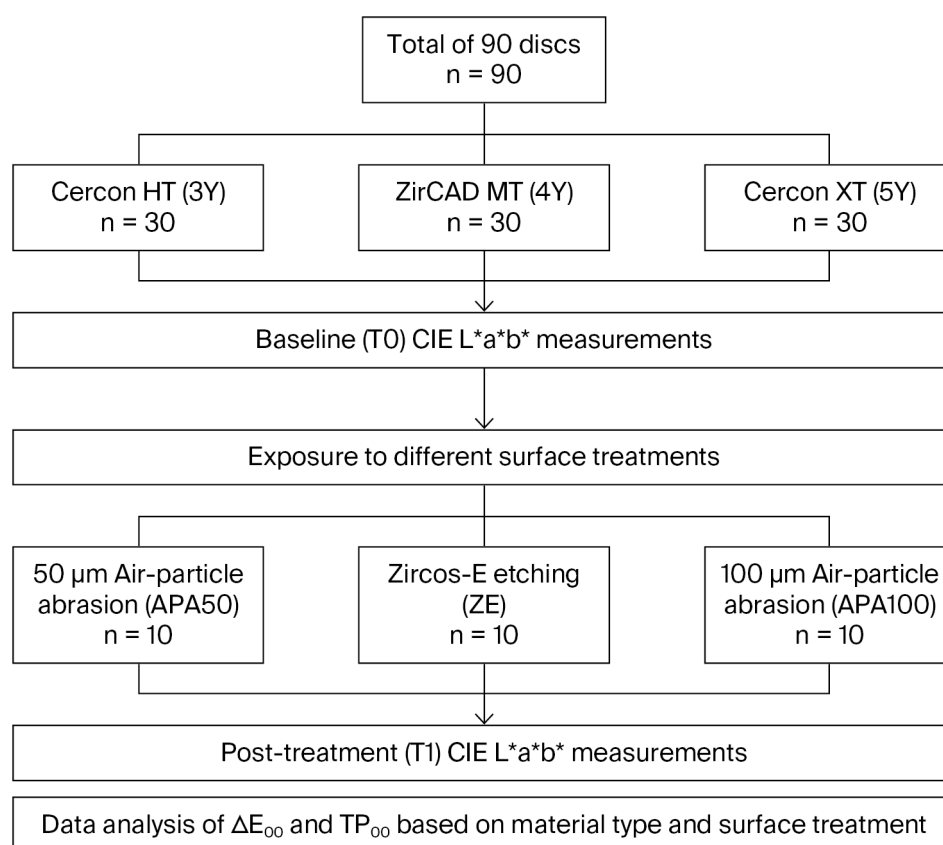


Figure 1. An overview of the experimental workflow of the study.

2.3. Optical Measurements

Baseline CIE L^* , a^* , and b^* values for each disk were recorded using a LabScan® XE spectrophotometer (Murnau am Staffelsee, Germany) standardized with white and black reference tiles.

2.4. Surface Treatments

Specimens from each material group were randomly assigned to one of three surface treatment groups ($n = 10$ each):

Alumina Air-Particle Abrasion (AAA; 50 μm)—Sandblasting with 50 μm alumina particles using a Cobra air-abrasion unit (Cobra, Renfert, Hilzingen, Germany) at a 10 mm distance and 90° angle.

Glass Bead Air-Particle Abrasion (GBA; 100 μm)—Sandblasting with 100 μm glass beads (Rolloblast, Renfert, Hilzingen, Germany) performed under the same parameters as AAA (10 mm distance and 90° angle) (Figure 2).

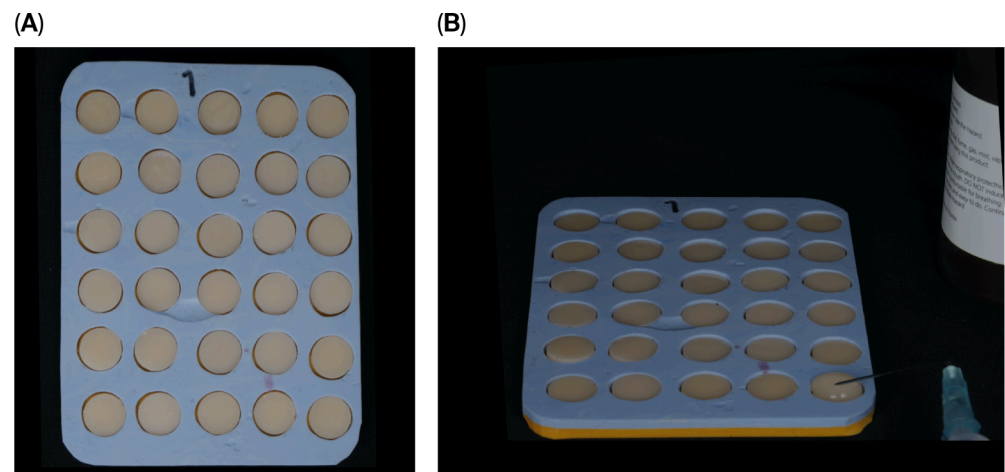


Figure 2. Photo showing (A) putty index fabricated to contain the disks, (B) the dispersion of Zircos-E Etching over one of the disks.

Zircos-E Etching (Bio Den Co., Ltd., Seoul, Republic of Korea)—Performed by applying the solution to the intaglio surface for 30 min, then rinsing the restoration thoroughly under running water for 3 min to neutralize and remove all lingering acids.

2.5. Post-Treatment Optical Measurement

Following the surface treatments, the specimens underwent a second CIE L^* , a^* , and b^* measurement using the same spectrophotometer setup. The color change (ΔE_{00}) and change in the translucency parameter (ΔTP_{00}) were calculated according to the CIEDE 2000 formula.

2.6. Statistical Analysis

All measurements were imported for statistical analysis into the Statistical Package for the Social Sciences (SPSS) software, version 25.0 (IBM Corp., Armonk, NY, USA).

The Shapiro–Wilk test was used to assess the normality of the color coordinate (L^* , a^* , b^*) and translucency parameter (TP_{00}) data, confirming a near-normal distribution ($p > 0.05$). Descriptive statistics (mean $\pm$ standard deviation) were calculated for the individual color coordinates (L^* , a^* , b^*) and translucency parameters at baseline (T0) and after surface treatment (T1) with the three protocols applied to the three zirconia materials (Cercon HT, ZirCAD MT, and Cercon XT): 50 μm alumina air abrasion, Zircos-E etching, and 100 μm glass bead air abrasion. Mean $\pm$ standard deviation values were also calculated for the color differences (ΔL , Δa , Δb), overall color change (ΔE_{00}), and change in the translucency parameter (ΔTP_{00}).

Paired-samples t -tests were performed to compare baseline and post-treatment values within the same specimens for L^* , a^* , b^* , and TP_{00} . One-way ANOVA was used for single-factor comparisons of ΔL , Δa , Δb , and ΔE_{00} across material types and across

surface treatment protocols, as well as for TP_{00} values within each material before and after treatment.

Two-way ANOVA was used to examine the main effects of material type and surface treatment, and their interaction effects, on ΔE_{00} , TP_{00} at baseline, and ΔTP_{00} . When significant main effects or interactions were found in the two-way ANOVA, Tukey's HSD post hoc test was applied for pairwise group comparisons.

For all statistical tests, the significance level was set at $p < 0.05$.

3. Results

Color Change (ΔE_{00})

The descriptive statistics (Tables 1–3) and paired-samples *t*-test (Table 4) showed that all individual color coordinates (L^* , a^* , b^*) changed significantly after surface treatment ($p < 0.001$), indicating measurable alterations in lightness and the red–green and yellow–blue axes. Cercon XT exhibited the highest ΔE_{00} values across surface treatments, indicating the greatest overall color change (Figure 3). Among the surface treatment protocols, 50 μm alumina air abrasion (AAA) produced the greatest color change, followed by Zircos-E etching (ZE) and 100 μm glass bead abrasion (GBA). Two-way ANOVA (Table 5) revealed that surface treatment exerted a significant effect on color change ($p < 0.001$) and that the interaction between material type and surface treatment was also significant ($p < 0.001$). Material type alone did not significantly influence color change ($p = 0.197$). Although statistically significant, all ΔE_{00} values were below the clinical acceptability threshold (< 1.8) (Table 1).

Table 1. Mean and standard deviation values for color and translucency parameters.

Variables	L^*		a^*		b^*		ΔE_{00}		TP	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Baseline (T0)	65.82	1.77	0.22	0.96	12.79	2.02	-	-	4.14	0.67
After ST (T1)	64.84	1.82	-0.35	0.85	12.10	1.85	-	-	3.77	0.62
Change (Δ)	-0.98	1.12	-0.57	0.16	-0.70	0.54	1.37	0.70	-0.37	0.27

ST = Surface treatment.

Table 2. Descriptive statistics for materials' color and translucency parameters.

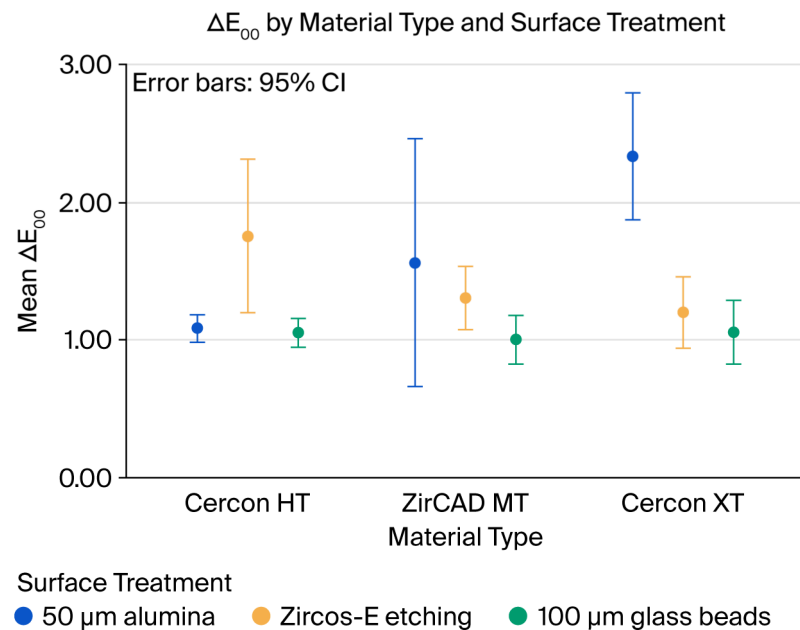
		ΔE_{00}		Baseline TP		TP After ST		ΔTP_{00}	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Material Type	Cercon HT	1.30	0.56	3.32	0.14	3.03	0.16	-0.29	0.18
	ZirCAD MT	1.29	0.77	4.29	0.27	3.87	0.25	-0.42	0.27
	Cercon XT	1.53	0.74	4.82	0.30	4.42	0.32	-0.41	0.33

Table 3. Descriptive statistics for color and translucency parameters based on surface treatment protocols.

		ΔE_{00}		Baseline TP		TP After ST		ΔTP_{00}	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Surface Treatment	50 μm Alumina	1.66	0.95	4.06	0.69	3.70	0.57	-0.36	0.28
	Zircos-E Etching	1.42	0.57	4.19	0.68	3.81	0.64	-0.38	0.30
	100 μm Glass Beads	1.04	0.25	4.19	0.67	3.81	0.67	-0.38	0.24

Table 4. Paired-samples *t*-test—changes in L*, a*, and b* coordinates from baseline to after surface treatment.

		Paired Differences					t	df	p
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	L* (T0)–L* (T1)	0.98	1.12	0.12	0.75	1.22	8.32	89	<0.001
Pair 2	a* (T0)–a* (T1)	0.57	0.16	0.02	0.54	0.60	33.07	89	<0.001
Pair 3	b* (T0)–b* (T1)	0.69	0.54	0.06	0.58	0.81	12.26	89	<0.001

**Figure 3.** The chart shows the ΔE_{00} values by material type and surface treatment.**Table 5.** Two-way ANOVA of ΔE_{00} across all material types and surface treatments.

Dependent Variable: ΔE_{00}					
Source	Type III Sum of Squares	df	Mean Square	F	p
Corrected Model	15.666 ^a	8	1.958	5.748	0.000
Intercept	169.305	1	169.305	496.970	0.000
Surface Treatment	5.931	2	2.965	8.705	<0.001
Material Type	1.131	2	0.565	1.659	0.197
Surface Treatment $\times$ Material Type	8.604	4	2.151	6.314	<0.001
Error	27.595	81	0.341		
Total	212.565	90			
Corrected Total	43.260	89			

^a. R Squared = 0.362 (Adjusted R Squared = 0.299). Bold values indicate statistically significant differences ($p < 0.05$).

The baseline (T0) and post-treatment (T1) translucency values (TP_{00}) for each material and surface treatment protocol are presented in Tables 6–8. Cercon XT exhibited the highest mean TP_{00} at baseline, followed by ZirCAD MT and Cercon HT.

Table 6. Comparison of the relative translucency parameter (TP₀₀) at baseline and after surface treatment of **Cercon HT**.

		N	Mean	SD	Std. Error	95% Confidence Interval for Mean		F	p
						Lower Bound	Upper Bound		
Baseline	50 μm AAA	10	3.27	0.16	0.05	3.15	3.38	1.12	0.341
	Zircos-E Etching	10	3.33	0.17	0.05	3.21	3.46		
	100 μm GBAA	10	3.36	0.06	0.02	3.31	3.40		
	Total	30	3.32	0.14	0.03	3.26	3.37		
After ST	50 μm AAA	10	3.05	0.17	0.05	2.93	3.17	0.47	0.627
	Zircos-E Etching	10	3.06	0.14	0.04	2.96	3.16		
	100 μm GBAA	10	2.99	0.18	0.06	2.86	3.12		
	Total	30	3.03	0.16	0.03	2.97	3.09		

Table 7. Comparison of the relative translucency parameter (TP₀₀) at baseline and after surface treatment of **ZirCAD MT**.

		N	Mean	SD	Std. Error	95% Confidence Interval for Mean		F	p
						Lower Bound	Upper Bound		
Baseline	50 μm AAA	10	4.12	0.17	0.05	4.00	4.24	3.678	0.039
	Zircos-E Etching	10	4.41	0.29	0.09	4.20	4.61		
	100 μm GBAA	10	4.34	0.27	0.09	4.15	4.53		
	Total	30	4.29	0.27	0.05	4.19	4.39		
After ST	50 μm AAA	10	3.79	0.26	0.08	3.60	3.97	0.797	0.461
	Zircos-E Etching	10	3.88	0.21	0.07	3.73	4.03		
	100 μm GBAA	10	3.93	0.27	0.09	3.73	4.12		
	Total	30	3.87	0.25	0.05	3.77	3.96		

Table 8. Comparison of the relative translucency parameter (TP₀₀) at baseline and after surface treatment of **Cercon XT**.

		N	Mean	SD	Std. Error	95% Confidence Interval for Mean		F	p
						Lower Bound	Upper Bound		
Baseline	50 µm AAA	10	4.79	0.40	0.13	4.51	5.08	0.118	0.889
	Zircos-E Etching	10	4.82	0.27	0.09	4.62	5.01		
	100 µm GBAA	10	4.86	0.25	0.08	4.68	5.04		
	Total	30	4.82	0.30	0.06	4.71	4.94		
After ST	50 µm AAA	10	4.26	0.35	0.11	4.01	4.51	1.895	0.117
	Zircos-E Etching	10	4.49	0.32	0.10	4.26	4.72		
	100 µm GBAA	10	4.50	0.25	0.08	4.33	4.68		
	Total	30	4.42	0.32	0.06	4.30	4.54		

The two-way ANOVA for baseline translucency (Table 9) revealed that the effect of material type was statistically significant ($p < 0.001$), with post hoc comparisons (Table 10) confirming that all pairwise differences between the three materials were also statistically significant ($p < 0.001$). Neither surface treatment ($p = 0.075$) nor the interaction between material type and surface treatment ($p = 0.496$) had a significant effect at baseline, which is to be expected since these values were obtained before any surface treatments had been applied.

Table 9. Tests of between-subject effects.

Dependent Variable: TP ₀₀ (T0)						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	35.477 ^a	8	4.435	73.783	<0.001	0.879
Intercept	1544.718	1	1544.718	25,700.766	<0.001	0.997
Material Type	34.951	2	17.475	290.753	<0.001	0.878
Surface Treatment	0.322	2	0.161	2.676	0.075	0.062
Material Type × Surface Treatment	0.205	4	0.051	0.852	0.496	0.040
Error	4.868	81	0.060			
Total	1585.063	90				
Corrected Total	40.346	89				

^a. R Squared = 0.879 (Adjusted R Squared = 0.867).

Table 10. Multiple comparisons of material types at baseline.

Dependent Variable: TP ₀₀ (T0)							
	(I) Material Type	(J) Material Type	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Cercon HT	ZirCAD MT	−0.9687 *	0.06330	<0.001	−1.1198	−0.8175
		Cercon XT	−1.5060 *	0.06330	<0.001	−1.6571	−1.3549
	ZirCAD MT	Cercon HT	0.9687 *	0.06330	<0.001	0.8175	1.1198
		Cercon XT	−0.5373 *	0.06330	<0.001	−0.6885	−0.3862
	Cercon XT	Cercon HT	1.5060 *	0.06330	<0.001	1.3549	1.6571
		ZirCAD MT	0.5373 *	0.06330	<0.001	0.3862	0.6885

* The mean difference is significant at the 0.05 level.

When assessing translucency change (ΔTP_{00}), the two-way ANOVA (Table 11) indicated no statistically significant effect of surface treatment, material type, or their interaction (all $p > 0.05$). Post hoc analysis (Table 12) similarly showed no significant pairwise differences. These findings indicate that while baseline translucency varied significantly among the materials, the application of the different surface treatments did not result in a statistically significant change in translucency for any of the groups.

Table 11. Tests of between-subject effects.

Dependent Variable: ΔTP_{00}						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.858 ^a	8	0.107	1.522	0.163	0.131
Intercept	12.462	1	12.462	176.793	<0.001	0.686
Material Type	0.319	2	0.159	2.261	0.111	0.053
Surface Treatment	0.005	2	0.003	0.037	0.964	0.001
Material Type × Surface Treatment	0.534	4	0.134	1.894	0.119	0.086
Error	5.710	81	0.070			
Total	19.030	90				
Corrected Total	6.568	89				

^a. R Squared = 0.131 (Adjusted R Squared = 0.045).

Table 12. Showing multiple comparisons—post hoc of ΔTP_{00} .

Dependent Variable: ΔTP_{00}						
Tukey HSD						
(I) Material Type	(J) Material Type	Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Cercon HT	ZirCAD MT	0.1327	0.06855	0.135	−0.0310	0.2963
	Cercon XT	0.1187	0.06855	0.200	−0.0450	0.2823
ZirCAD MT	Cercon HT	−0.1327	0.06855	0.135	−0.2963	0.0310
	Cercon XT	−0.0140	0.06855	0.977	−0.1777	0.1497
Cercon XT	Cercon HT	−0.1187	0.06855	0.200	−0.2823	0.0450
	ZirCAD MT	0.0140	0.06855	0.977	−0.1497	0.1777

The trends in baseline and post-treatment TP_{00} values for each material are illustrated in Figures 3–6.

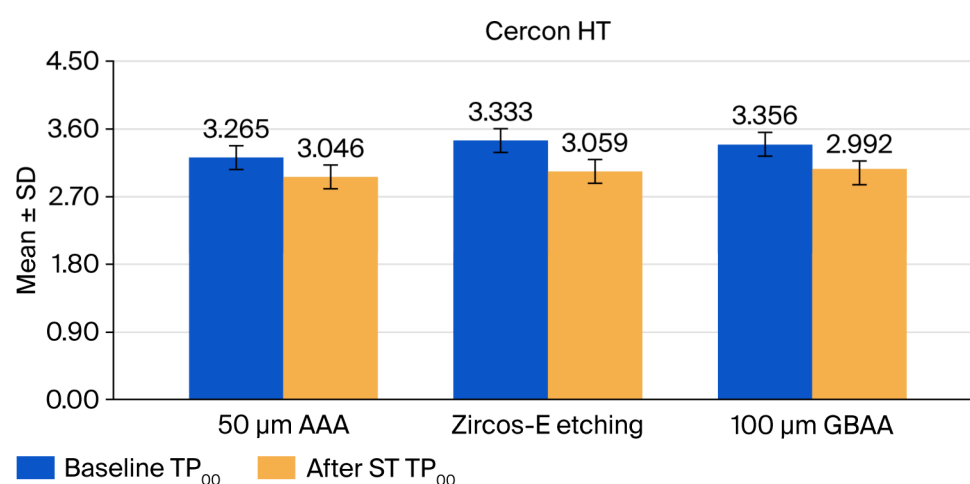


Figure 4. This figure shows the relative translucency parameter (TP_{00}) for **Cercon HT** both at baseline (T_0) and after different surface treatments (T_1).

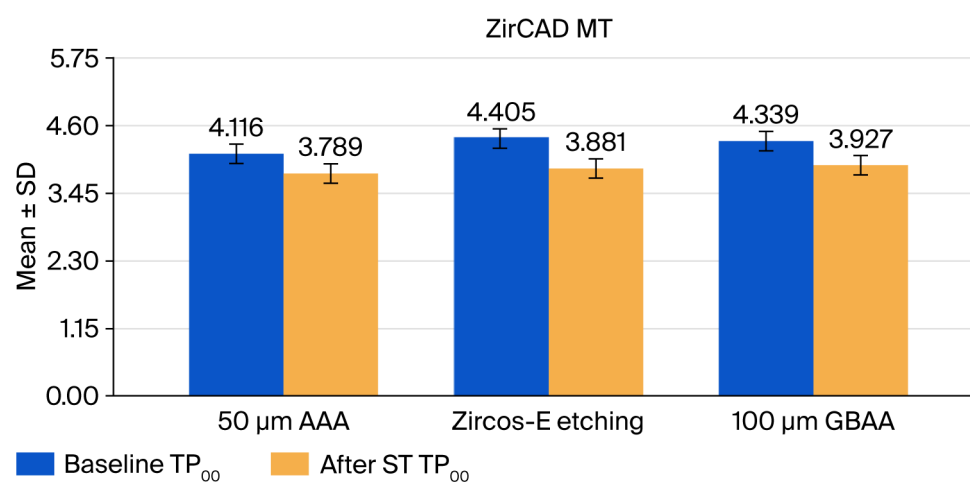


Figure 5. This figure shows the relative translucency parameter (TP_{00}) for **ZirCAD MT** both at baseline (T_0) and after different surface treatments (T_1).

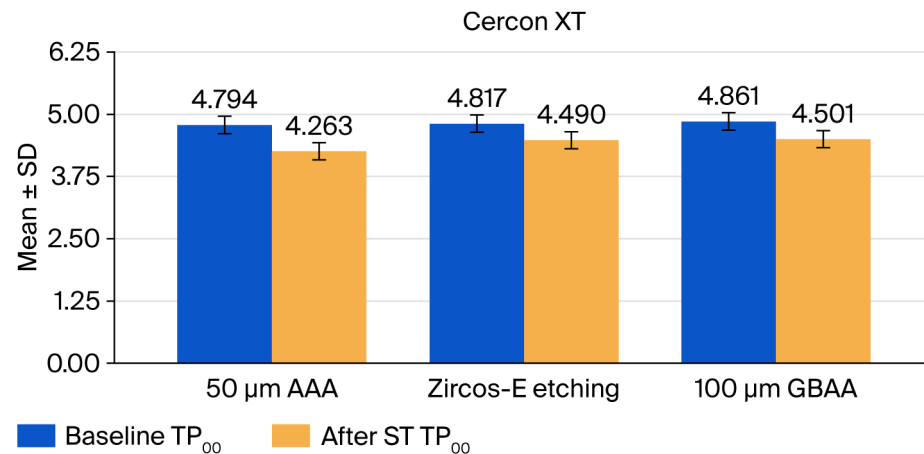


Figure 6. This figure shows the relative translucency parameter (TP_{00}) for **Cercon XT** both at baseline (T_0) and after different surface treatments (T_1).

4. Discussion

The transition from metal–ceramic restorations to all-ceramic systems has been driven by the superior esthetics and biocompatibility of the latter [15]. Zirconia ceramics offer high strength and toughness but traditionally lack translucency. To improve translucency, manufacturers have increased the yttria content, producing third- and fourth-generation zirconias (4-YTZP and 5-YTZP); however, a higher yttria content reduces mechanical strength [16].

Bonding zirconia remains challenging because zirconia lacks a glass phase. Mechanical treatments such as air-particle abrasion create micro-retentive surfaces and improve bonding, while chemical etching has been less successful. Recently, Zircos-E etching, a mixture of nitric and hydrofluoric acids, has been introduced and shows promise in terms of improving bond strength [17].

Among the surface treatments, 50 µm alumina air abrasion produced the greatest color change and 100 µm glass bead abrasion the smallest, while material type alone did not significantly affect ΔE_{00} . No surface treatment produced a significant change in translucency (ΔTP_{00}) for any material. These two results, taken together, are the empirical findings of this study; the explanation for why they occurred is addressed critically below.

Previous publications have attributed treatment-dependent color differences in this kind to differences in the aggressiveness of particle impact and the resulting surface roughness. This explanation is plausible and consistent with the relative abrasiveness of the three protocols tested here, but it cannot be confirmed by the present data: no direct surface characterization (SEM, AFM, or profilometry) was performed, so surface roughness itself was not measured, and its relationship to the observed color changes is inferred from prior literature rather than demonstrated experimentally in this study. We regard this as the principal limitation of the present work, and we present the roughness-based explanation as a hypothesis rather than an established mechanism. An equally plausible, and currently indistinguishable, alternative is that the intrinsic microstructure of each zirconia—yttria content, grain size, and phase composition—governs its optical response to a given treatment independently of surface topography [18]. Distinguishing between these possibilities will require pairing optical measurements with direct surface characterization in future work.

To contextualize these findings, it is useful to consider how sample thickness and measurement thresholds affect color. Previous research has shown that even a 0.1 mm reduction in a 2 mm thick zirconia sample can produce perceptible color changes; a minimum thickness of about 1 mm is needed for a satisfactory final color [19]. The present study

therefore used 1 mm thick samples to standardize baseline color and translucency. Color differences were evaluated using the CIEDE 2000 formula (ΔE_{00}), and the resulting values (around 1.4–1.66) fell between the 50:50 perceptibility threshold (0.8) and the established acceptability threshold (1.8). This means that while observers may detect a color change after treatment, it remains clinically acceptable [20,21].

The main effect of surface treatment on ΔE_{00} ($p < 0.001$) and its interaction with material type ($p < 0.001$) indicate that the impact of a given treatment differed across the three zirconia generations tested; alumina air abrasion (mean $\Delta E_{00} = 1.66$) produced roughly 1.6 times the color change in glass bead abrasion (mean $\Delta E_{00} = 1.04$). This pattern is broadly consistent with reports by Kim et al. (2013) and Kurtulmus-Yilmaz et al. (2019), who also observed perceptible color changes after abrasive surface treatments, but neither those studies nor the present one directly measured the surface features responsible for the change [22,23]. Agreement in outcome does not, by itself, establish a shared mechanism: abrasion-related color change could equally reflect differences in residual particle embedment, microcrack formation, or subsurface damage that were not assessed here [22,23].

Translucency followed a different pattern. At baseline, Cercon XT (5-YTZP) was significantly more translucent than ZirCAD MT and Cercon HT, consistent with the known translucency-enhancing effect of higher yttria content, but none of the three surface treatments produced a significant change in TP_{00} (ΔTP_{00}) for any material, and the changes observed stayed within the perceptibility and acceptability thresholds established for TP_{00} (0.62 and 2.62). This dissociation—treatment altering color but not translucency—argues against a single, simple roughness-based explanation for both outcomes, since a rougher surface would generally be expected to scatter more light and reduce translucency as well as shift color; we did not measure roughness directly, so this remains an inference. Schabach et al. similarly reported no significant change in transmittance after sandblasting [24]. Nonetheless, conflicting findings exist: some studies report that surface treatments affect translucency via changes in surface roughness [25]. We cannot adjudicate between these findings and ours with the present data; the discrepancy may reflect differences in zirconia brand, treatment parameters, specimen thickness, or measurement method between studies, and, as above, it underscores the need for direct surface characterization to test whether roughness is in fact the operative variable.

Several limitations should be acknowledged. Most importantly, no direct surface characterization (SEM, AFM, or profilometry) was performed; consequently, the roughness-based explanation offered above for the observed color changes is a hypothesis grounded in prior literature rather than a mechanism demonstrated in this study, and it should be read accordingly. The study also used only three surface treatments on three zirconia types at a single thickness, limiting direct comparison with other studies. The *in vitro* design does not replicate intra-oral conditions—oral fluids, pH fluctuations, temperature changes, and chewing forces could affect both color and translucency *in vivo*. Future work that pairs optical measurements with SEM, AFM, or profilometry across a range of thicknesses, treatments, and zirconia brands is needed to directly test the roughness hypothesis and to confirm these findings *in vivo*.

5. Conclusions

Within the limits of this *in vitro* study, the following conclusions were drawn:

Surface treatments and material–treatment interactions significantly affected color change (ΔE_{00}) in zirconia ceramics; these changes were perceptible but clinically acceptable ($\Delta E_{00} < 1.8$). The 50 μm alumina air abrasion treatment produced the greatest color change, followed by Zircos-E etching and 100 μm glass bead abrasion.

Material type alone did not significantly influence color change.

Surface treatment, material type, and their interaction did not significantly affect translucency (ΔTP_{00}). At baseline, Cercon XT had the highest translucency, followed by ZirCAD MT and Cercon HT.

The proposed explanation linking these color changes to differences in surface roughness among treatments is plausible but was not directly tested here and requires confirmation by surface characterization (SEM, AFM, or profilometry) in future work. In vivo studies are also needed to validate these findings.

Author Contributions: Conceptualization, K.M.A. (Khaled M. AlZahrani), K.M.A. (Khalid Mohammed Alnajjar) and L.Y.M.A.; methodology, M.F.A. and D.A.A., formal analysis, M.F.A., D.A.A. and K.M.A. (Khaled M. AlZahrani) Investigation, L.T.A. and G.S.A.; data curation, M.F.A., D.A.A. and K.M.A. (Khaled M. AlZahrani); writing—original draft preparation, K.M.A. (Khalid Mohammed Alnajjar) and L.Y.M.A.; writing—review and editing, K.M.A. (Khaled M. AlZahrani), K.M.A. (Khalid Mohammed Alnajjar), L.T.A. and G.S.A.; supervision, K.M.A. (Khaled M. AlZahrani) All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This research was submitted to the Research Center at Riyadh Elm University (REU) (protocol code FPGRP/2023/755/1015/918 and date of approval 25 September 2023).

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors extend their appreciation to Prince Sattam bin Abdulaziz University and the IADR Saudi Arabian Division for their generous support.

Conflicts of Interest: The authors disclose no conflicts of interest.

References

1. Della Bona, A.; Nogueira, A.D.; Pecho, O.E. Optical properties of CAD–CAM ceramic systems. *J. Dent.* **2014**, *42*, 1202–1209. [[CrossRef](#)] [[PubMed](#)]
2. Della Bona, A.; Pecho, O.E.; Alessandretti, R. Zirconia as a dental biomaterial. *Materials* **2015**, *8*, 4978–4991.
3. Qeblawi, D.M.; Muñoz, C.A.; Brewer, J.D.; Monaco, E.A., Jr. The effect of zirconia surface treatment on flexural strength and shear bond strength to a resin cement. *J. Prosthet. Dent.* **2010**, *103*, 210–220. [[CrossRef](#)] [[PubMed](#)]
4. Sulaiman, T.A.; Abdulmajeed, A.A.; Shahramian, K.; Lassila, L. Effect of different treatments on the flexural strength of fully versus partially stabilized monolithic zirconia. *J. Prosthet. Dent.* **2017**, *118*, 216–220. [[CrossRef](#)] [[PubMed](#)]
5. Mattiello, R.D.L.; Coelho, T.M.K.; Insaurralde, E.; Coelho, A.A.K.; Terra, G.P.; Kasuya, A.V.B.; Favarão, I.N.; Gonçalves, L.d.S.; Fonseca, R.B. A review of surface treatment methods to improve the adhesive cementation of zirconia-based ceramics. *ISRN Biomater.* **2013**, *2013*, 185376. [[CrossRef](#)]
6. Dal Piva, A.M.; Carvalho, R.L.; Lima, A.L.; Bottino, M.A.; Melo, R.M.; Valandro, L.F. Silica coating followed by heat-treatment of MDP-primer for resin bond stability to yttria-stabilized zirconia polycrystals. *J. Biomed. Mater. Res. Part B Appl. Biomater.* **2019**, *107*, 104–111.
7. Sadid-Zadeh, R.; Strazzella, A.; Li, R.; Makwoka, S. Effect of zirconia etching solution on the shear bond strength between zirconia and resin cement. *J. Prosthet. Dent.* **2021**, *126*, 693–697. [[CrossRef](#)] [[PubMed](#)]
8. Lee, Y.-K.; Powers, J.M. Comparison of CIE lab, CIEDE 2000, and DIN 99 color differences between various shades of resin composites. *Int. J. Prosthodont.* **2005**, *18*, 150. [[PubMed](#)]
9. Paravina, R.D.; Ghinea, R.; Herrera, L.J.; Bona, A.D.; Igiel, C.; Linninger, M.; Sakai, M.; Takahashi, H.; Tashkandi, E.; Mar Perez, M.d.; et al. Color difference thresholds in dentistry. *J. Esthet. Restor. Dent.* **2015**, *27*, S1–S9. [[CrossRef](#)] [[PubMed](#)]
10. Baldissara, P.; Llukacej, A.; Ciocca, L.; Valandro, F.L.; Scotti, R. Translucency of zirconia copings made with different CAD/CAM systems. *J. Prosthet. Dent.* **2010**, *104*, 6–12. [[CrossRef](#)] [[PubMed](#)]
11. de Azevedo Cubas, G.B.; Camacho, G.B.; Demarco, F.F.; Pereira-Cenci, T. The effect of luting agents and ceramic thickness on the color variation of different ceramics against a chromatic background. *Eur. J. Dent.* **2011**, *5*, 245–252. [[CrossRef](#)]

12. Kim, H.K.; Kim, S.H.; Lee, J.B.; Ha, S.R. Effects of surface treatments on the translucency, opalescence, and surface texture of dental monolithic zirconia ceramics. *J. Prosthet. Dent.* **2016**, *115*, 773–779. [[CrossRef](#)] [[PubMed](#)]
13. Chung, K.-h. Effects of finishing and polishing procedures on the surface texture of resin composites. *Dent. Mater.* **1994**, *10*, 325–330. [[CrossRef](#)] [[PubMed](#)]
14. Lee, Y.K.; Lim, B.S.; Kim, C.W. Effect of surface conditions on the color of dental resin composites. *J. Biomed. Mater. Res. Off. J. Soc. Biomater. Jpn. Soc. Biomater. Aust. Soc. Biomater. Korean Soc. Biomater.* **2002**, *63*, 657–663. [[CrossRef](#)] [[PubMed](#)]
15. Anusavice, K.J.; Shen, C.; Rawls, H.R. *Phillips' Science of Dental Materials*; Elsevier Health Sciences: London, UK, 2012.
16. Güth, J.-F.; Stawarczyk, B.; Edelhoff, D.; Liebermann, A. Zirconia and its novel compositions: What do clinicians need to know? *Quintessence Int.* **2019**, *50*, 512. [[CrossRef](#)] [[PubMed](#)]
17. Sales, A.; Rodrigues, S.J.; Mahesh, M.; Ginjupalli, K.; Shetty, T.; Pai, U.Y.; Saldanha, S.; Hegde, P.; Mukherjee, S.; Kamath, V.; et al. Effect of different surface treatments on the micro-shear bond strength and surface characteristics of zirconia: An in vitro study. *Int. J. Dent.* **2022**, *2022*, 1546802. [[CrossRef](#)] [[PubMed](#)]
18. Mihali, S.G.; Hiller, A. State-of-the-art zirconia and glass-ceramic materials in restorative dentistry: Properties, clinical applications, challenges, and future perspectives. *Appl. Sci.* **2025**, *15*, 12841. [[CrossRef](#)]
19. Kim, H.K.; Kim, S.H.; Lee, J.B.; Han, J.S.; Yeo, I.S.; Ha, S.R. Effect of the amount of thickness reduction on color and translucency of dental monolithic zirconia ceramics. *J. Adv. Prosthodont.* **2016**, *8*, 37–42. [[CrossRef](#)] [[PubMed](#)]
20. Prott, L.S.; Spitznagel, F.A.; Bonfante, E.A.; Malassa, M.A.; Gierthmuehlen, P.C. Monolithic zirconia crowns: Effect of thickness reduction on fatigue behavior and failure load. *J. Adv. Prosthodont.* **2021**, *13*, 269–280. [[CrossRef](#)] [[PubMed](#)]
21. Kang, C.M.; Peng, T.Y.; Huang, H.H. Effects of thickness of different types of high-translucency monolithic multilayer precolored zirconia on color accuracy: An in vitro study. *J. Prosthet. Dent.* **2021**, *126*, 587.e1–587.e8. [[CrossRef](#)] [[PubMed](#)]
22. Kim, H.-K.; Kim, S.-H.; Lee, J.-B.; Han, J.-S.; Yeo, I.-S. Effect of polishing and glazing on the color and spectral distribution of monolithic zirconia. *J. Adv. Prosthodont.* **2013**, *5*, 296. [[CrossRef](#)] [[PubMed](#)]
23. Kurtulmus-Yilmaz, S.; Cengiz, E.; Ongun, S.; Karakaya, I. The effect of surface treatments on the mechanical and optical behaviors of CAD/CAM restorative materials. *J. Prosthodont.* **2019**, *28*, e496–e503. [[CrossRef](#)] [[PubMed](#)]
24. Schabbach, L.M.; Dos Santos, B.C.; De Bortoli, L.S.; Fabris, D.; Fredel, M.C.; Henriques, B. Translucent multi-layered zirconia: Sandblasting effect on optical and mechanical properties. *Dent. Mater.* **2023**, *39*, 807–819. [[CrossRef](#)] [[PubMed](#)]
25. Li, S.; Zhang, X.; Xia, W.; Liu, Y. Effects of surface treatment and shade on the color, translucency, and surface roughness of high-translucency self-glazed zirconia materials. *J. Prosthet. Dent.* **2022**, *128*, 217.e1–217.e9. [[CrossRef](#)] [[PubMed](#)]

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