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BASIC RESEARCH:

Color Stability and Surface Roughness of Esthetic Resin Composites Following Simulated Toothbrushing with Whitening Toothpastes

Estabilidad del color y rugosidad superficial de resinas compuestas estéticas tras un cepillado dental simulado con dentífricos blanqueadores

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ABSTRACT: This *in vitro* study aimed to evaluate the effects of two whitening toothpastes with different mechanisms and one non-whitening, low-abrasivity toothpaste on the color stability and surface roughness of three anterior esthetic resin composites after coffee staining. Ninety disc-shaped specimens (2 mm × 6 mm) were prepared from three resin composites: Filtek Ultimate, Estelite Sigma Quick, and Neo Spectra ST Effects (n=30 each). After polishing, specimens were stored in distilled water for 24 hours at 37°C. For staining, the specimens were fully immersed in a freshly prepared coffee solution (3.6 g/300 ml) at room temperature for six consecutive days. The solution was renewed every 24 hours to ensure a constant concentration of chromogens, simulating six months of clinical coffee consumption. Color and surface roughness were measured at baseline and after staining. Each composite group was then divided into three subgroups (n=10) and brushed in a simulator with one of three toothpastes—Sensodyne Promine, Opalescence Whitening, or R.O.C.S. Sensation Whitening—for a total of 30 minutes at a 200 g load. Final measurements were taken, and color change (ΔE_{00}) and surface roughness change (ΔRa) were calculated. Data were analyzed using ANOVA and Tukey HSD ($p<0.05$). Composite type significantly influenced color change after staining ($p<0.05$), with Estelite Sigma Quick showing the highest ΔE00 values. Toothpaste type also significantly affected color change ($p<0.05$), with Opalescence Whitening producing greater whitening in certain composite groups. All experimental groups exhibited ΔE_{00} values above the clinical acceptability threshold ($\Delta E_{00} > 1.8$). Surface roughness increased significantly within some groups after brushing, but there were no significant intergroup differences between toothpaste types ($p>0.05$).

KEYWORDS: Coffee staining; Color stability; Resin composites; Surface roughness; Whitening toothpaste; Toothbrushing.

RESUMEN: Este estudio *in vitro* tuvo como objetivo evaluar los efectos de dos dentífricos blanqueadores con diferentes mecanismos de acción y un dentífrico no blanqueador de baja abrasividad sobre la estabilidad del color y la rugosidad superficial de tres resinas compuestas estéticas, posterior a la pigmentación con café. Se prepararon noventa muestrasen forma de disco (2 mm×6 mm) a partir de tres resinas compuestas: Filtek Ultimate, Estelite Sigma Quick y Neo Spectra ST Effects (n=30 cada una). Tras el pulido, las muestras se almacenaron por 24 horas a 37 °C. Para la pigmentación, las muestras se sumergieron en una solución de café por seis días consecutivos. La solución se renovó cada 24 horas, simulando seis meses de consumo de café. El color y la rugosidad superficial se midieron al inicio y después del proceso de pigmentación. Posteriormente, cada grupo se dividió en tres subgrupos (n=10), se sometió a cepillado en un simulador con uno de tres dentífricos. Sensation Whitening—durante un total de 30 min. bajo una carga de 200 g. Se realizaron mediciones finales, se calcularon los cambios de color (ΔE_{00}) y de rugosidad superficial (ΔRa). Los datos se analizaron mediante ANOVA y la prueba de Tukey HSD ($p<0,05$). El tipo de resina influyó en el cambio de color tras la pigmentación ($p<0,05$), Estelite Sigma Quick mostró los valores más altos. El tipo de dentífrico afectó significativamente el cambio de color ($p<0,05$), Opalescence Whitening produjo mayor efecto blanqueador en algunos grupos de resina compuesta. Todos los grupos experimentales presentaron valores de ΔE_{00} superiores al umbral de aceptabilidad clínica ($\Delta E_{00}>1,8$). La rugosidad superficial aumentó significativamente en algunos grupos después del cepillado; sin embargo, no se observaron diferencias significativas entre los tipos de dentífrico ($p>0,05$).

PALABRAS CLAVE: Pigmentación por café; Estabilidad del color; Resinas compuestas; Rugosidad superficial; Dentífrico blanqueador; Cepillado dental.

INTRODUCTION

Resin-based composites are among the most frequently preferred materials in contemporary restorative dentistry due to their esthetic and functional properties (1). However, when exposed to extrinsic factors over time, these materials may exhibit discoloration and surface deterioration (2). Discoloration of resin composites can occur not only due to intrinsic factors such as the type of matrix, filler particle size and content, but also through the effects of extrinsic staining agents such as coffee, tea, and red wine (2). In addition, water absorption, monomer composition, and the quality of surface polishing are other important variables that can negatively affect color stability (3,4).

With the increasing demand for esthetic dental care, tooth whitening procedures have gained significant popularity (5). Initially applied only in clinical settings by dental professionals, whitening procedures have become more accessible through over-the-counter (OTC) products (6). OTC whitening products were introduced to the U.S. market in the early 2000s, offering cost-effective alternatives to professional methods (5). Among these, whitening toothpastes are the most commonly used. These products may reduce surface stains through different mechanisms. Abrasive particles (e.g., silica derivatives) can mechanically remove extrinsic stains, while chemical agents (e.g., hydrogen peroxide, carbamide peroxide) act through oxidation of chromogenic molecules (6,7). Enzymatic agents (e.g., papain, bromelain) can hydrolyze protein-based stains and thereby enhance whitening efficacy. In addition, optical agents (e.g., blue covarine) create a thin film on the enamel surface, altering light reflection and producing an immediate whitening illusion (6,8).

Although whitening toothpastes containing chemical agents or abrasive particles may provide enhanced whitening, it has been reported that such formulations can lead to irreversible surface deterioration and loss of dental hard tissues on both natural teeth and restorative materials (9). The surface characteristics of esthetic restorative materials play a crucial role in esthetics, plaque accumulation, bacterial adhesion, and periodontal health (10). Increased surface roughness may contribute to gingival inflammation, secondary caries, and a reduction in surface gloss (10,11).

This *in vitro* study aimed to evaluate *in vitro* the color stability and surface roughness changes of three different esthetic anterior resin composites that were artificially stained with coffee solution, followed by simulated toothbrushing with two whitening toothpastes (enzymatic-based and peroxide/abrasive-based) and one non-whitening toothpaste (low abrasivity, remineralizing).

Accordingly, the null hypotheses tested in this study were that the type of resin composite would have no statistically significant effect on color stability or surface roughness changes; that brushing with different whitening toothpastes would not significantly influence the color stability or surface roughness of coffee-stained resin composites; and finally, that there would be no statistically significant interaction between the type of composite and the type of toothpaste regarding color or surface roughness alterations.

MATERIALS AND METHODS

In this study, three different esthetic resin composites and three different toothpastes were used (Table 1). A total of 90 specimens were prepared, 30 from each restorative material. The experimental workflow is shown in Figure 1.

SPECIMEN PREPARATION

Cylindrical Teflon molds (2 mm depth × 6 mm diameter) were used to prepare the specimens. The composites were placed into the molds, covered with transparent polyester strips (Mylar strip; SS White Co., Philadelphia, PA, USA) on both the top and bottom surfaces. To ensure a standardized thickness and surface smoothness, the specimens were pressed between two glass slides using constant manual pressure to extrude any excess material. This procedure aimed to achieve a uniform specimen thickness defined by the mold and to minimize the formation of an oxygen-inhibition layer on the surface (12). Polymerization was performed for 20 seconds from both the top and bottom surfaces using a multi-wavelength LED light-curing unit (VALO, Ultradent, South Jordan, UT, USA). The unit was operated in 'Standard Power' mode with a constant irradiance of 1000 mW/cm², which was verified using a radiometer before the procedure. To ensure maximum polymerization and eliminate the distance factor, the light-guide tip was placed in direct contact with the glass slide (0 mm distance). Curing from both surfaces was performed to achieve a uniform degree of conversion throughout the 2 mm thick specimen and to ensure maximum surface hardness on both sides, minimizing any potential gradient in polymerization (12). Following polymerization, all specimens were stored in distilled water at 37°C for 24 hours to ensure the completion of post-irradiation polymerization and to reach a stable state before finishing procedures (12). After this 24-hour storage, finishing and polishing were performed on the top surfaces of all specimens by a single experienced operator to ensure inter-operator consistency. Sequential polishing discs (Sof-Lex; 3M ESPE, St. Paul, MN, USA) were used in descending order of grit size (coarse, medium, fine, and superfine) (13). Each disc was applied for 20 seconds under light manual pressure (approx. 2 N) using a slow-speed handpiece (10,000 rpm) with a constant circular motion and water cooling, following a standardized protocol (12,14). Between each grit change, specimens were rinsed for 10 seconds to remove debris. To maintain orientation, the unpolished bottom surface of each specimen was marked with an indelible waterproof pen, ensuring that all subsequent color and roughness measurements were performed on the standardized top surface (12).

GROUP ALLOCATION

Before measurements, the specimens were randomly divided into groups (Table 2). The first measurements were performed after polishing (Baseline, T0). For staining, specimens were fully immersed in a coffee solution for 24 hours each day, totaling six consecutive days. This 6-day immersion protocol was intended to simulate approximately six months of clinical consumption, based on the literature stating that 24 hours of in vitro immersion corresponds to approximately one month of clinical exposure (15,16). The staining solution was prepared daily by dissolving 3.6 g of instant coffee (Nescafe Classic, Nestlé, Vevey, Switzerland) in 300 ml of boiling water, cooled to room temperature before use. To ensure a standardized and clean surface for staining each day, the specimens were removed from the solution every 24 hours, rinsed with distilled water for 1 minute to remove any surface debris or metabolic byproducts, and then placed into a freshly prepared solution (15). Following immersion, specimens were rinsed with distilled water and measured again (T1) (Figure 2).

Table 1. Materials used in the study.

Material (Shade)	Type of Material	Composition	Manufacturer
Filtek Ultimate (Ena-mel 1)	Nanohybrid composite	Bis-GMA, Bis-EMA, UDMA, TEGDMA; silica and zirconia nanofillers	3M ESPE, St. Paul, MN, USA
Estelite Sigma Quick (A1)	Submicron hybrid composite	Bis-GMA, UDMA, TEGDMA, spherical silica–zirconia fillers	Tokuyama Dental, Tokyo, Japan
Neo Spectra™ ST Effects (E1)	Nanohybrid composite	Bis-GMA, UDMA, TEGDMA, Bis-EMA; pre-polymerized resin filler, barium glass	Dentsply Sirona, Konstanz, Germany
Promine, Sensodyne	Conventional toothpaste (low RDA)	Sodium fluoride, hydrated silica, sorbitol, glycerin (no specific whitening agent)	SPLAT, Moscow, Russia
Opalescence White-ning Toothpaste	Whitening toothpaste	Abrasive silica particles, sodium fluoride, flavoring agents	Ultradent Products, South Jordan, UT, USA
R.O.C.S. Sensation Whitening	Whitening toothpaste	Bromelain enzyme, silica, xylitol, sodium fluoride	EuroCosMed, Stupino, Mos-cow Region, Russia

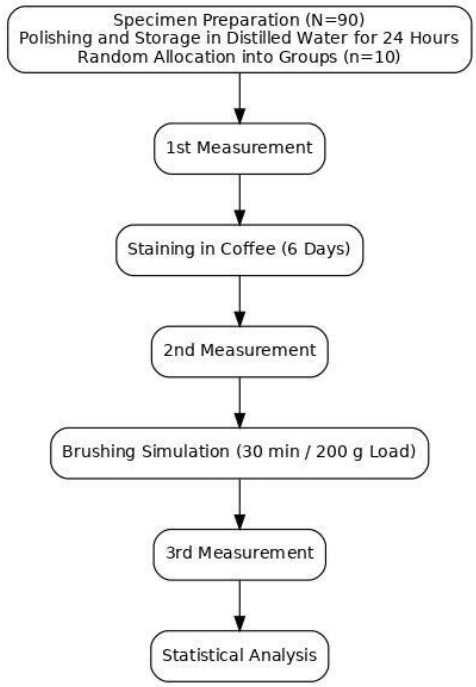

Figure 1. Flowchart of the study design.

Table 2. Experimental groups of composite resins and toothpastes used in the study.

SQP	Tokuyama Estelite Sigma Quick(SQ) / Sensodyne Promine(P)
SQO	Tokuyama Estelite Sigma Quick(SQ) / Opalescence Whitening(O)
SQR	Tokuyama Estelite Sigma Quick(SQ) / R.O.C.S. Sensation Whitening(R)
FUP	3M ESPE Filtek Ultimate(FU) / Sensodyne Promine(P)
FUO	3M ESPE Filtek Ultimate(FU) / Opalescence Whitening(O)
FUR	3M ESPE Filtek Ultimate(FU) / R.O.C.S. Sensation Whitening(R)
NSP	Dentsply Neo Spectra ST Effects(NS) / Sensodyne Promine(P)
NSO	Dentsply Neo Spectra ST Effects(NS) / Opalescence Whitening(O)
NSR	Dentsply Neo Spectra ST Effects(NS) / R.O.C.S. Sensation White-ning(R)

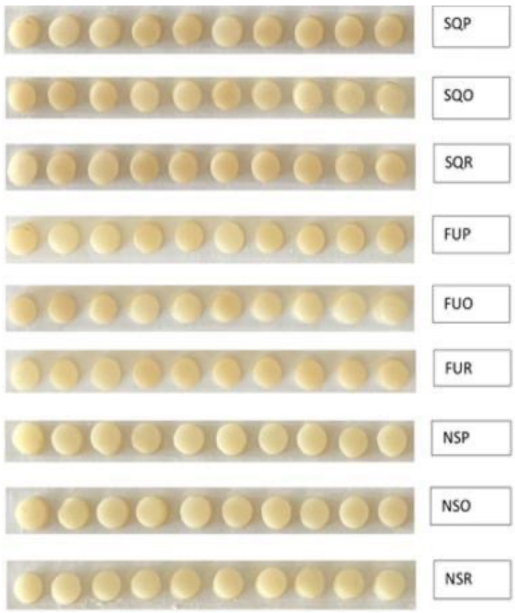

Figure 2. Representative image of the study groups after coffee staining.

BRUSHING SIMULATION

Toothbrushing was performed using a custom-made brushing machine fitted with an electric toothbrush (Oral-B Expert Precision Clean, Procter & Gamble, USA) featuring standardized soft bristles. To ensure a clinically relevant simulation of six months of aging, a protocol of 10,000 brushing cycles was applied (12,17). This was achieved through a total brushing time of 30 minutes, operating at a standardized rate of approximately 333 strokes per minute, following the methodology described by Tritten and Armitage (17,18). The specimens of each restorative material (n=30) were randomly allocated into three toothpaste groups (n=10). To simulate salivary dilution, equal amounts of toothpaste were diluted with distilled water at a ratio of 1:2 (w/w) following established protocols (19). The brushing procedure was standardized under a constant load of 200 g (1.96 N) in accordance with ISO standards. Toothbrush heads were replaced every five minutes to maintain consistent abrasive efficacy and prevent mechanical degradation of the bristles. After the brushing simulation, final color and surface measurements were recorded (T2).

COLOR MEASUREMENT

To minimize dehydration, color measurements were performed immediately after removal from distilled water and gentle drying with an air–water syringe within two minutes (2). Color measurements were performed in a standardized clinical environment under consistent natural daylight conditions. To minimize the influence of ambient light fluctuations, all measurements were conducted at the same time of day in the same room. A spectrophotometer (VITA Easyshade Advance 4.0, VITA Zahnfabrik, Bad Säckingen, Germany) was used with its standardized probe tip held in stable and perpendicular contact with the specimen surface. This contact-based measurement technique ensures that the device's internal light source remains the primary illuminant by effectively sealing the measurement area against external ambient light. The device was calibrated before each session. Each specimen was measured at the central area, with recalibration every five specimens. The CIE L*a*b* values (L0*, a0*, b0* and L1*, a1*, b1*) were recorded.Color differences (ΔE00) were calculated using the CIEDE2000 formula, incorporating the mathematical observations for hue and chroma discontinuities as described by Sharma, Wu, and Dalal (20).

$$\Delta E_{00}=\sqrt{(\Delta L'/kL\cdot SL)^2 + (\Delta C'/kC\cdot SC)^2+(\Delta H'/kH\cdot SH)^2+RT\cdot(\Delta C'/kC\cdot SC)\cdot(\Delta H'/kH\cdot SH)}$$

Where ΔL′, ΔC′, and ΔH′ represent lightness, chroma, and hue differences, respectively; SL, SC, and SH are weighting functions; kL, kC, and kH were all set to 1; and RT is the rotation function accounting for chroma–hue interaction.

The threshold values used for evaluation were the perceptibility threshold (ΔE_{00}=0.8) and the clinical acceptability threshold (ΔE_{00}=1.8)(21).

SURFACE ROUGHNESS MEASUREMENT

Surface roughness was measured with a contact profilometer (Surftest SJ-201, Mitutoyo, Tokyo, Japan). Calibration was performed prior to baseline and before each set of group measurements (λc: 0.8; λs: 2.5). Three measurements were taken across the center of each specimen, and the mean roughness value (Ra, μm) was calculated.

SAMPLE SIZE CALCULATION

The required sample size was determined using G*Power 3.1 software (Heinrich Heine University, Düsseldorf, Germany). Based on an effect size of 0.65, α=0.05, and power=0.80, a minimum of 10 specimens per group was calculated.

STATISTICAL ANALYSIS

Data were analyzed using SPSS version 22.0 (IBM SPSS Inc., Chicago, IL, USA). The normality of distribution was confirmed using the Kolmogorov–Smirnov test. Since the data followed a normal distribution and met the parametric assumptions, Two-way Repeated Measures Analysis of Variance (ANOVA) was employed to evaluate the effects of two independent factors: composite type (three levels) and toothpaste type (three levels). Time (baseline, after staining, and after brushing) was treated as the repeated measures factor to account for measurements obtained from the same specimens at different stages. For surface roughness (ΔRa) and color change (ΔE_{00}), both main effects and their interactions were analyzed. Multiple comparisons were performed using the Tukey's post-hoc test. A significance level of $p<0.05$ was considered statistically significant.

RESULTS

The results of color difference (ΔE_{00}) and surface roughness (Ra) measurements were analyzed using Two-way Repeated Measures ANOVA to evaluate the effects of composite type, toothpaste type, and their interactions over time (Table 3).

COLOR CHANGE (ΔE_{00})

The statistical analysis revealed a significant main effect of composite type on color change ($p<0.001$), whereas the toothpaste type did not show a significant main effect ($p=0.293$). After immersion in coffee solution (ΔE_{00}), the SQP group exhibited significantly higher color change compared with NSP and NSR groups ($p<0.05$). The lowest ΔE_1 values were consistently observed in the Neo Spectra ST Effects (NS) groups (Table 4).

Regarding ΔE_3 (color change after brushing compared with coffee staining), the Neo Spectra (NS) groups demonstrated significantly higher color stability and stain removal resistance compared to Filtek Ultimate (FU) and Estelite Sigma Quick (SQ) groups ($p<0.05$). While the SQO group exhibited high ΔE_3 values, indicating effective stain removal, all experimental groups remained above the clinical acceptability threshold $\Delta E_{00}>1.8$). No significant interaction was found between composite and toothpaste types for color change ($p=0.142$).

SURFACE ROUGHNESS (RA)

For surface roughness, the Two-way Repeated Measures ANOVA showed a highly significant main effect of time ($p<0.001$) and, more importantly, a significant three-way interaction between composite type, toothpaste type, and time (p=0.027) (Table 5).

While ΔRa_1 values (after coffee immersion) were similar across all groups (p>0.05), the brushing stage significantly altered the surface integrity depending on the material-toothpaste combination. In the Filtek Ultimate (FU) group, simulated brushing with toothpastes (especially Promine) led to a more pronounced increase in roughness compared to the Neo Spectra (NS) group.

Within-group comparisons revealed significant increases in surface roughness for SQP, FUP, FUO, FUR, NSR, and NSP groups compared with baseline (p<0.05). However, the significant interaction effect (p=0.027) confirms that the surface degradation caused by whitening toothpastes is not uniform and is significantly influenced by the specific resin composite substrate.

Table 3. Two-way repeated measures ANOVA summary for surface roughness and color change.

Source of Variation	df	Mean Square	F	p-value
Color Change (ΔE00)				
Composite Type (C)	2	17.939	11.763	< 0.001*
Toothpaste Type (T)	2	1.887	1.237	0.293
Interaction (C×T)	4	3.241	2.125	0.080
Surface Roughness (Ra)				
Composite Type (C)	2	0.027	0.624	0.536
Toothpaste Type (T)	2	0.014	0.333	0.717
Interaction (C ×T ×Time)	8	0.095	2.208	0.027*

df: Degrees of freedom. (C): Composite type; (T): Toothpaste type. (C×T): Interaction between composite and toothpaste types. (C×T×Time): Three-way interaction between composite, toothpaste, and time factors. Statistically significant difference (p<0.05).

Table 4. Color change values (ΔE_{00}) of the groups (Mean±SD).

Groups	ΔE_1	ΔE_2	ΔE_3
SQP	4.10 ± 2.08^{b}	3.14 ± 1.86^{b}	2.97 ± 1.61^{ab}
SQO	2.51 ± 1.65^{ab}	2.67 ± 1.73^{ab}	3.84 ± 1.80^{b}
SQR	3.05 ± 1.66^{ab}	2.54 ± 1.59^{ab}	2.96 ± 1.21^{ab}
FUP	2.45 ± 1.40^{ab}	3.00 ± 0.95^{ab}	2.58 ± 1.00^{ab}
FUO	3.49 ± 1.12^{ab}	1.95 ± 0.73^{ab}	3.15 ± 1.05^{ab}
FUR	3.73 ± 0.76^{ab}	1.70 ± 0.71^{ab}	2.70 ± 0.76^{ab}
NSP	2.04 ± 0.93^{a}	1.37 ± 0.74^{a}	1.92 ± 0.93^{a}
NSO	2.52 ± 0.73^{ab}	1.76 ± 1.25^{ab}	2.59 ± 0.95^{ab}
NSR	2.18 ± 0.60^{a}	1.54 ± 0.46^{ab}	1.95 ± 0.38^{a}

SD: Standard Deviation. ΔE_{00}: Color change calculated using the CIEDE2000 formula. ΔE_1: Color change after coffee staining compared to baseline (T1-T0). ΔE_2: Color change after brushing compared to baseline (T2-T0). ΔE_3: Color change after brushing compared to post-coffee staining values (T2-T1). Different superscript lowercase letters in the same column indicate significant differences between toothpaste groups within each composite type (p<0.05).

Table 5. Surface roughness changes (ΔRa) of the groups (Mean±SD).

Groups	ΔRa1	ΔRa2	ΔRa3
SQP	0.11±0.11[a]	0.2±0.15[a]	0.08±0.18[ab]
SQO	0.2±0.15[a]	0.41±0.11[a]	0.21±0.15[ab]
SQR	0.12±0.11[a]	0.44±0.17[a]	0.32±0.19[ab]
FUP	0.12±0.14[a]	0.61±0.92[a]	0.48±0.94[b]
FUO	0.15±0.13[a]	0.3±0.16[a]	0.15±0.18[ab]
FUR	0.18±0.13[a]	0.55±0.17[a]	0.37±0.17[ab]
NSP	0.25±0.14[a]	0.22±0.21[a]	-0.3±0.15[a]
NSO	0.1±0.11[a]	0.4±0.14[a]	0.3±0.16[ab]
NSR	0.23±0.08[a]	0.5±0.17[a]	0.27±0.18[ab]

SD: Standard Deviation. ΔRa1: Change after coffee staining compared to baseline (T1-T0). ΔRa2: Change after brushing compared to baseline (T2-T0). ΔRa3: Change after brushing compared to post-coffee staining values (T2-T1).. Different superscript lowercase letters in the same column indicate statistically significant differences between toothpaste groups within each composite type (p<0.05).

DISCUSSION

Composite restorations in the oral cavity, similar to natural teeth, are prone to discoloration over time due to frequent exposure to dietary chromogens. Beverages with high pigment content such as tea, coffee, red wine, and cola are among the most common extrinsic causes of tooth discoloration (2). Among these, coffee is one of the most frequently used staining agents in research because of both its widespread consumption and strong staining potential (1). However, as Paolone *et al*. emphasized, methodological variations in experimental studies—such as the temperature of the staining solution, immersion period, and renewal frequency—make direct comparison of results difficult (2). To minimize such variability, all parameters were standardized in the present study. Based on reported consumption models, an average daily intake of 3.2 cups of beverages corresponds to approximately 24 hours of immersion under *in vitro* conditions (15,16). Therefore, coffee staining was standardized to simulate long-term clinical exposure, in accordance with previous studies (15,16). Brushing was simulated under standardized conditions to approximate six months of clinical use (17). The applied load was kept within ISO-recommended limits to ensure comparability.

Since ΔE_1 was measured after coffee staining without toothpaste application, it reflected the effect of the composites alone. Two-way repeated measures ANOVA confirmed a significant main effect of composite type ($p<0.001$) on color stability. Specifically, Neo Spectra ST Effects (NS) showed superior color stability compared to Estelite Sigma Quick and Filtek Ultimate throughout the study phases. This finding indicates that the inherent properties of the composite resin, rather than external factors alone, are the primary determinants of long-term color stability.

The difference may be attributed to variations in resin matrix composition and water absorption (2). Composites with more hydrophilic monomers are more prone to water sorption, facilitating stain penetration and increasing susceptibility to discoloration (3,22). Conversely, NSP and NSR groups exhibited lower ΔE_1 values. The color stability of resin composites is not only influenced by extrinsic staining agents but also by intrinsic properties such as the monomer composition and proportion of the resin matrix (3,22,23). Low molecular weight and hydrophilic monomers, such as TEGDMA, have been reported to increase water sorption, which facilitates the diffusion of pigments into the matrix (22). Furthermore, water absorption may promote the formation of microvoids within the matrix, compromising structural integrity and creating sites for pigment retention (2). Loss of filler particles from the surface over time may also contribute to micro-roughness and an increased tendency to stain. Therefore, both filler-related and organic phase-related characteristics must be considered when evaluating long-term color stability. Previous studies have similarly reported that water sorption and matrix degradation play important roles in long-term discoloration (13,22). Berger *et al*. also emphasized that discoloration is influenced not only by surface roughness but also by the chemical composition of the resin matrix (13). Hence, composite selection in esthetic areas should consider not only immediate appearance but also long-term resistance to discoloration. On the other hand, ΔRa_1 values, representing the effect of coffee staining on surface roughness, did not differ significantly among groups ($p>0.05$). The mild increases observed were not clinically meaningful. Bezgin *et al.*(17) investigated the effect of toothbrushing on the discoloration of restorative materials stained in different solutions and applied once-daily brushing for five seconds using an electric toothbrush. In the present study, the brushing protocol was standardized with a six-month equivalent of brushing performed under constant force using a brushing simulator (17). Our ΔE_2 results revealed a significant difference only between SQP and NSP groups, suggesting that certain composite–toothpaste combinations may be more resistant to discoloration. Our findings showed that the efficacy of whitening toothpastes is complex and multi-factorial. While the Two-way repeated measures ANOVA indicated that toothpaste type as a main effect did not reach statistical significance regarding overall color change ($p=0.293$), specific post-hoc comparisons revealed that certain material-toothpaste combinations were more effective than others. Notably, the SQO group (Estelite Sigma Quick brushed with Opalescence) exhibited significantly higher ΔE_3 values compared with NSP and NSR ($p<0.05$). This suggests that the whitening success is not solely dependent on the toothpaste formulation itself, but rather on how the specific chemical or abrasive agents interact with the surface characteristics of the particular resin composite. Peroxide-based and abrasively formulated products, such as Opalescence Whitening, may demonstrate superior cleaning potential only when the composite surface allows for effective stain removal without excessive substrate degradation

Similarly, Patil *et al.*(7) reported that papain-containing enzymatic toothpastes exhibited superior whitening performance compared with abrasive formulations In the present study, while the enzymatic toothpaste (R.O.C.S.) did not show a significantly different main effect compared to other toothpastes, it consistently produced clinically perceptible color changes ($\Delta E_{00}>1.8$) across all composite types (SQR, FUR, and NSR groups).

Bromelain, a cysteine protease, specifically hydrolyzes peptide bonds in protein–pigment complexes, which are responsible for extrinsic stains. In beverages such as coffee, polyphenols interact with salivary proteins to form complexes that adhere to the acquired pellicle and resin surfaces. Bromelain hydrolyzes these proteins, disrupting the complexes and weakening their adhesion to the surface, thereby facilitating stain removal through mechanical brushing. Unlike abrasive agents, bromelain acts selectively on organic components without damaging hard tissues (8). This mechanism may explain the potential clinical advantage of enzymatic whitening toothpastes in maintaining esthetic restorations. Importantly, all experimental groups in this study exhibited ΔE_{00} values above the clinical acceptability threshold of 1.8, indicating that even in the absence of statistically significant differences, clinically noticeable color changes were observed.

Previous literature has reported conflicting findings regarding the relationship between abrasivity and whitening efficacy of toothpastes. Meseli *et al.*(24) suggested that toothpastes with higher RDA values cause greater color change on composite surfaces compared with those with lower abrasivity. In contrast, Gömleksiz and Okumuş reported that charcoal-based toothpastes, despite their high abrasivity, produced limited whitening effects (25). Such discrepancies may be attributed to multiple factors, including the multi-component nature of toothpastes, composite resin type, staining agents, brushing duration, and brushing protocols. Moreover, methodological differences such as controlled brushing load and standardized brushing time, as employed in this study, may also account for variations in results compared with previous research.

In the present study, color measurements were performed using a spectrophotometer. The CIEDE2000 formula was chosen to calculate color differences because it provides more accurate perceptibility and acceptability thresholds in dental research compared with the traditional CIELab formula (21).

With respect to surface roughness, although the main effect of toothpaste type alone was not the primary driver of change, the significant interaction effect (p=0.027) highlights that material-specific responses are critical. While the standardized brushing protocol (fixed duration and load) and microstructural similarities among nanohybrid composites contributed to overall controlled changes, the specific combination of Filtek Ultimate and Promine, for example, resulted in higher roughness increases compared to Neo Spectra ST Effects combinations. This finding aligns with the idea that filler-matrix interface stability plays a critical role when exposed to specific abrasive challenges. Colak and Katirci similarly reported that composites with different filler structures may respond differently to whitening toothpastes, which supports the present interpretation that comparable filler–matrix characteristics contributed to the similar results (26).

Nonetheless, some differences with previously reported studies were noted. Meseli *et al*. reported increased roughness in composites brushed with high-RDA toothpastes (24). In contrast, Gömleksiz and Okumuş observed limited whitening despite the high abrasivity of charcoal-containing toothpastes (25). Such variations may be explained by differences in composite material type, filler morphology, toothpaste composition, and brushing methodology. It has been suggested that manual brushing at uncontrolled high loads may cause greater abrasion, whereas powered brushing operating at constant, lower loads provides more controlled surface abrasion. The standardized, constant-load protocol used herein likely contributed to minimal surface deterioration compared with manual brushing. Therefore, when evaluating the effects of whitening toothpastes on composite surfaces, not only toothpaste composition but also composite properties and brushing protocols should be considered. For example, Türkün *et al*. reported that toothpastes with similar compositions produced different roughness outcomes depending on the composite type, largely due to filler size and matrix properties (12). Similarly, Bagis *et al*. emphasized that application parameters such as brushing duration and load significantly influence abrasivity outcomes (27). In the present study, the use of standardized load and duration, along with comparable composite microstructures, likely contributed to the lack of significant intergroup differences in surface roughness when assessed with a contact profilometer—a reliable and widely used method in dental materials research.A significant three-way interaction was identified between composite type, toothpaste type, and time regarding surface roughness changes (p=0.027). This indicates that the impact of whitening toothpastes on surface integrity is not uniform but is significantly influenced by the specific restorative material it is applied to. This synergistic interaction suggests that certain abrasive or chemical components in toothpastes may react differently with the specific monomer matrices or filler coupling systems of each resin composite, leading to varied levels of surface degradation over time (3,27).

These findings demonstrate that whitening toothpastes may alter the properties of composite surfaces, but the magnitude of these changes is influenced not only by toothpaste formulation but also by the intrinsic structural properties of composites. Hydrophilic monomers such as TEGDMA increase water sorption, which in turn promotes microvoid formation and surface degradation, contributing to roughness changes. Paolone reported that water sorption compromises the microstructural integrity of composites, leading to surface deterioration and increased susceptibility to staining (2). Lopes-Rocha *et al*. also emphasized that resin matrix composition and filler–matrix interface stability play critical roles in both mechanical durability and surface integrity (3). Bagis *et al*. further reported that nanohybrid composites produce lower surface roughness than microhybrids, attributable to differences in filler size and distribution (27). In line with these findings, the specific variations in responses observed in our study may be related to the distinct ways in which the filler and matrix characteristics of each composite interacted with the different toothpaste formulations, despite the standardized brushing protocol.This study has certain limitations. First, the in vitro design cannot fully reproduce the complex oral environment, where saliva, biofilm, pH fluctuations, and temperature changes may influence outcomes. In addition, only three resin composites and three toothpaste formulations were tested, which does not represent the full range of available materials. The brushing protocol was performed under constant force and duration, which does not reflect the variability of manual brushing habits in daily life. Surface roughness was evaluated only with a contact profilometer; complementary analyses such as SEM or AFM could have provided more detailed information. Another limitation concerns the device used for color measurements. Although the VITA Easyshade Advance 4.0 has also been applied in previous in vitro studies for composite and ceramic specimens, it was originally designed for natural tooth shade assessment. Since the device's algorithms are optimized for natural enamel, its use on restorative materials should be considered a methodological limitation when interpreting the results. Furthermore, toothpaste slurries were diluted with distilled water at a 1:2 ratio (w/w) to simulate salivary dilution; however, the absence of salivary proteins, ions, and dynamic pH cycling limits full reproduction of the oral environment (28).

CONCLUSION

Within the limitations of this *in vitro* study, whitening toothpastes were found to influence the color stability of resin composites. While the main effect of toothpastes on surface roughness was limited, a significant interaction was identified between composite type and toothpaste type, indicating that surface degradation is material-dependent. Composite type remains a primary factor for color stability, and the choice of whitening toothpaste should be carefully considered based on the specific resin composite substrate to maintain long-term surface integrity.

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