EGYPTIAN DENTAL JOURNAL
www.eda-egypt.org

Vol. 71, 3293:3311, October, 2025

Print ISSN 0070-9484 • Online ISSN 2090-2360

Fixed Prosthodontics and Dental Materials

Submit Date : 11-07-2025 • Accept Date : 20-07-2025 • Available online: 01-10-2025 • DOI : 10.21608/edj.2025.402955.3550

EFFECT OF THERMOCYCLING AND STAINING SOLUTIONS ON TRANSLUCENCY PARAMETER AND COLOR STABILITY OF ULTRATRANSLUCENT MONOLITHIC ZIRCONIA AND LITHIUM DISILICATE LAMINATE VENEERS: AN IN-VITRO STUDY

Dina Magdi El Shehawi* *and* Ahmed Nabil*

ABSTRACT

Objective: To evaluate and compare the translucency parameter (TP) and color stability (ΔE_{2000}) of ultratranslucent 5Y-PSZ zirconia and lithium disilicate laminate veneers following standardized thermocycling protocols with simultaneous exposure to coffee and orange juice staining solutions.

Methods: Twenty-four anatomically-correct laminate veneers were fabricated using CAD/CAM technology from ultratranslucent 5Y-PSZ zirconia (Katana UTML) and lithium disilicate (IPS e.max CAD HT) blocks (n=6 per group). Specimens were randomly allocated to four experimental conditions with combined thermocycling (2,500 cycles, 5°C-55°C) and staining protocols. Translucency parameter and color coordinates were measured using spectrophotometry at baseline and post-treatment. Data were analyzed using two-way ANOVA with Bonferroni post-hoc correction (α=0.05).

Results: Both materials demonstrated statistically significant changes in TP and ΔE_{2000} following aging. Orange juice staining produced significantly greater color changes in lithium disilicate compared to zirconia (5.45±1.76 vs 3.74±0.66, p=0.023). Zirconia exhibited dramatically increased translucency following orange juice exposure (15.54±4.59 vs baseline 5.21±3.45), while lithium disilicate maintained stable translucency across conditions (p=0.196). Two-way ANOVA revealed a highly significant interaction between material type and aging intervention (F=13.867, $p<0.001$, $\eta^2=0.394$). All color changes exceeded clinical acceptability thresholds ($\Delta E_{2000}>1.8$).

Conclusions: Both materials experienced clinically significant optical changes following accelerated aging. The highly significant interaction effect demonstrates material-specific responses to aging protocols. Zirconia showed superior color stability under orange juice exposure but exhibited unexpected translucency increases requiring further investigation. These findings support individualized material selection based on patient dietary habits and emphasize comprehensive patient counseling regarding long-term esthetic expectations.

KEYWORDS: Esthetic dentistry, ceramic restorations, optical properties, aging protocols, CIEDE2000, 5Y-PSZ ceramics, glass ceramics, prosthodontics

* Lecturer, Fixed Prosthodontics Department, Cairo University

INTRODUCTION

Ceramic laminate veneers have fundamentally transformed contemporary esthetic dentistry by providing minimally invasive solutions for correcting dental discoloration, morphological defects, and minor positional irregularities while preserving maximum tooth structure (Gresnigt et al., 2019; Morimoto et al., 2020). The clinical success and patient satisfaction with these restorations depend critically on their ability to maintain optimal optical properties—particularly translucency and color stability—throughout their expected service life of 10-20 years (Layton & Clarke, 2020).

The evolution of dental ceramics for veneer applications has progressed from traditional feldspathic porcelains to advanced lithium disilicate glass-ceramics, which have established themselves as the clinical gold standard due to their superior mechanical properties (flexural strength: 360-400 MPa) combined with excellent optical characteristics (Ritzberger et al., 2021). More recently, the introduction of ultratranslucent zirconia systems represents a paradigmatic shift in ceramic technology, offering the potential for combining the superior mechanical properties of zirconia (flexural strength: >900 MPa) with optical characteristics approaching those of lithium disilicate ceramics (Zhang et al., 2022).

Ultratranslucent zirconia materials, specifically 5 mol% yttria-stabilized zirconia (5Y-PSZ), achieve enhanced translucency through increased cubic phase content and optimized grain size distribution, resulting in reduced light scattering and improved light transmission (Kwon et al., 2021). Recent studies demonstrate that 5Y-PSZ materials can achieve translucency parameter values of 15-25, significantly higher than conventional 3Y-TZP zirconia (TP: 8-12) while maintaining fracture toughness values of 4-6 MPa·m½ (Carrabba et al., 2022).

The oral cavity presents a uniquely challenging environment for ceramic restorations through daily exposure to thermal fluctuations ranging from 5°C to 55°C during food and beverage consumption, combined with pH variations from 3.0 to 8.0 and exposure to chromogenic and acidic substances (Malkondu et al., 2021). Coffee, one of the most commonly consumed beverages worldwide, presents particular challenges due to its low pH (5.0-5.2), high chromogenic potential, and frequency of consumption (often 2-3 times daily) (Archegas et al., 2021). Recent clinical studies have identified that color changes in ceramic restorations can become perceptible within 6-12 months of clinical service, with coffee and tea being the primary contributing factors (Kanat et al., 2021). The CIEDE2000 color difference formula has become the gold standard for clinical color evaluation, with established thresholds for perceptibility ($\Delta E_{00} = 0.8$) and acceptability ($\Delta E_{00} = 1.8$) that provide clinically relevant benchmarks for material evaluation (Paravina et al., 2020).

While individual studies have evaluated either color stability or translucency changes in ceramic materials, limited research has systematically compared ultratranslucent zirconia with lithium disilicate using anatomically-correct veneer geometries under standardized aging protocols. Most previous investigations have utilized simplified disc specimens with uniform thickness, which fail to represent the complex optical interactions that occur in clinical veneer restorations with varying thickness profiles (cervical: 0.5mm; incisal: 1.2mm) (Vasiliu et al., 2020). Furthermore, the majority of aging studies have employed either thermocycling or chemical staining protocols in isolation, failing to capture the synergistic effects of simultaneous thermal and chemical challenges that characterize the clinical environment (Archegas et al., 2021). This represents a significant limitation in translating laboratory findings to clinical performance predictions.

This investigation addresses these critical knowledge gaps by systematically evaluating the optical stability of anatomically-correct laminate veneers fabricated from ultratranslucent zirconia and lithium disilicate materials under standardized thermocycling protocols with simultaneous exposure to clinically-relevant staining solutions. The primary objective was to compare translucency parameter (TP_{00}) changes in ultratranslucent zirconia versus lithium disilicate laminate veneers following combined thermocycling and staining protocols. Secondary objectives included evaluating color stability (ΔE_{00}) of both materials under identical aging conditions, determining the relative contribution of different staining solutions to optical property changes, and establishing clinical relevance of observed changes relative to established perceptibility and acceptability thresholds. The findings of this investigation will provide evidence-based guidance for material selection in anterior veneer restorations and inform patient counseling regarding long-term esthetic outcomes.

Null Hypothesis (H_0):

Thermocycling and exposure to staining solutions do not significantly affect the translucency parameter or color stability (ΔE) of ultratranslucent monolithic zirconia and lithium disilicate laminate veneers.

MATERIALS AND METHODS

Study Design and Ethical Approval

This randomized controlled in-vitro experimental study was designed according to ISO 4049:2019 standards for evaluating color stability of dental materials. The study protocol was reviewed and approved by the Research Ethics Committee of the Faculty of Dentistry, Cairo University.

Sample Size Calculation and Power Analysis

Sample size was calculated according to power analysis using Translucency parameter (TP00) as the 1ry outcome. Results of Elkhishen et al. (2022) showed that the mean value for Katana UTML zirconia group after cementation and soaking in coffee was 0.46 ± 0.11, and that of IPS e.max CAD was 0.62 ± 0.05. Using alpha (α) level of (5%) and Beta (β) level of (20%) i.e., power = 80%; the minimum calculated sample size was 6 restorations per group with a total of 24 restorations. Sample size calculation was done using G*Power program (Version 3.1).

Experimental Groups

Twenty- four anatomically-correct laminate veneers were randomly allocated into four experimental groups (n= 6 each) using computer-generated randomization sequences:

- **Group ZR-CF:** Ultratranslucent zirconia + thermocycling + coffee staining
- **Group ZR-OJ:** Ultratranslucent zirconia + thermocycling + orange juice staining
- **Group LD-CF:** Lithium disilicate + thermocycling + coffee staining
- **Group LD-OJ:** Lithium disilicate + thermocycling + orange juice staining

MATERIALS

Ultratranslucent Zirconia: Katana UTML Multi-layered blocks (5Y-PSZ, Kuraray Noritake Dental Inc., Japan)

- Composition: ZrO_2 (89-95%), Y_2O_3 (4-6%), Al_2O_3 (<1%)
- Flexural strength: 950 MPa (manufacturer data)
- Translucency parameter: 17.2 ± 2.1 (1.0mm thickness)

Lithium Disilicate: IPS e.max CAD HT blocks (Ivoclar Vivadent AG, Schaan, Liechtenstein)

- Composition: SiO_2 (57-80%), Li_2O (11-19%), K_2O (0-13%), P_2O_5 (0-11%)
- Flexural strength: 360 MPa (manufacturer data)
- Translucency parameter: 19.8 ± 1.8 (1.0mm thickness)

Specimen Preparation

Master Model Preparation

A standardized typodont maxillary central incisor (Nissin Dental Products Inc., Kyoto, Japan) was prepared according to established clinical protocols for laminate veneers (Edelhoff & Sorensen, 2002):

- Labial reduction: 0.5-0.8mm with diamond burs (#6856, Komet Dental, Germany)
- Finish line: Chamfer design, 0.5mm supragingivally
- Incisal reduction: 1.0-1.2mm with butt joint preparation
- Proximal extensions: 1mm beyond line angles
- Surface finish: 30µm diamond burs followed by polishing stones

Digital Workflow and CAD/CAM Fabrication

The prepared typodont was digitally scanned using an intraoral scanner (CEREC Primescan, Dentsply Sirona, Germany) with accuracy specifications of ±15µm. Laminate veneers were designed using CAD software (CEREC SW 5.2) with standardized parameters:

- Cervical thickness: 0.5-0.8mm
- Mid-facial thickness: 0.8-1.0mm
- Incisal thickness: 1.0-1.2mm
- Cement space: 50µm

Zirconia Fabrication Protocol:

1. Milling of pre-sintered 5Y-PSZ blocks (Roland DWX-52DCi, Japan)
2. Sintering cycle: 1500°C, 2-hour holding time, controlled cooling
3. Fit verification and adjustment with diamond burs
4. Final polishing with diamond paste (3-1µm, Shofu Inc., Japan)

Lithium Disilicate Fabrication Protocol:

1. Milling of pre-crystallized blocks using identical CAD parameters
2. Crystallization firing: 850°C, 30-minute cycle (Programat CS3, Ivoclar Vivadent)
3. Fit verification and surface finishing following identical protocol

Substrate Preparation

Epoxy resin substrates (Specifix-40, Struers, Denmark) were fabricated from elastomeric duplicates (Technosil, Bredent, Germany) of the master model to provide standardized cementation substrates. Substrates were aged for 48 hours before use to ensure complete polymerization. (Figure 1).

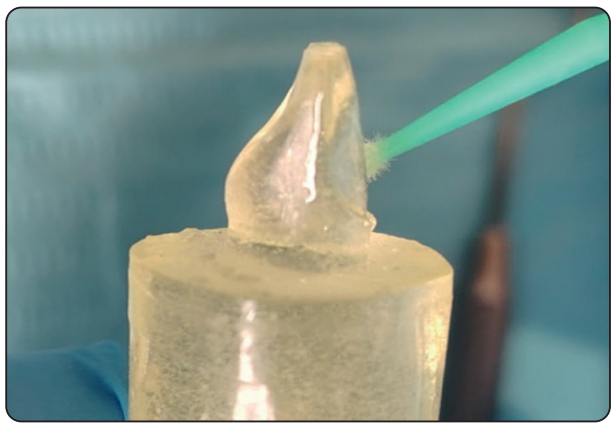

Fig. (1) Epoxy model

Surface Treatment and Cementation Protocols

Zirconia Surface Treatment

1. Airborne particle abrasion: 50µm Al_2O_3, 2 bar, 10mm distance, 20 seconds
2. Ultrasonic cleaning: distilled water, 5 minutes
3. Application of universal primer (Monobond N, Ivoclar Vivadent)

Lithium Disilicate Surface Treatment

1. Hydrofluoric acid etching: 9.5% HF gel, 20 seconds

2. Neutralization and rinsing: 60 seconds
3. Ultrasonic cleaning: distilled water, 60 seconds
4. Silane application: Porcelain primer, 60 seconds, air dried (Figure 2)

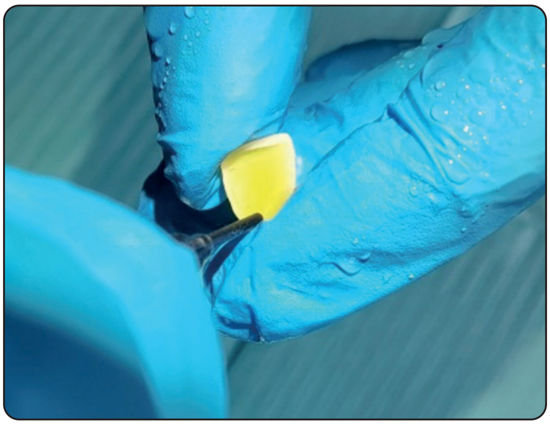

Fig. (2) Silane application

Cementation Protocol

All specimens were cemented using light-polymerizing resin cement (Choice 2, Bisco ,USA) under standardized conditions:

- Seating pressure: 750g for 60 seconds
- Light polymerization: LED unit (BluePhase Style, 1200 mW/cm²), 20 seconds per surface
- Finishing: removal of excess cement, polishing of margins

Aging Protocol

Thermocycling Parameters

Thermocycling was performed using an automated thermal cycling device (Robota TC-300, Bilge Teknik, Turkey) according to ISO/TS 11405:2015 specifications (Gale & Darvell, 1999):

- Temperature range: 5°C ± 2°C to 55°C ± 2°C
- Dwell time: 25 seconds in each bath
- Transfer time: 10 seconds
- Total cycles: 2,500 (equivalent to approximately 3 months of clinical service)

Staining Solution Preparation and Application

Coffee Solution:

- Fresh arabica coffee (Nescafé Gold, Nestlé): 20g per 1000ml boiling distilled water
- Brewing time: 10 minutes with stirring every 2 minutes
- Filtration through Whatman #1 filter paper
- pH measurement: 5.2 ± 0.1 (pH meter calibrated with standard buffers)
- Solution refreshed daily to maintain consistency

Orange Juice Solution:

- Commercial 100% orange juice (Tropicana Pure Premium)
- pH: 3.9 ± 0.1
- Refrigerated storage, brought to room temperature before use
- Solution refreshed daily

Immersion Protocol:

- Specimens immersed in 20ml of respective staining solutions
- Incubation: 37°C±1°C (Memmert incubator, Germany)
- Duration: Simultaneous with thermocycling (25 seconds per cycle in staining solution)
- Gentle agitation: Twice daily to prevent precipitation

Optical Property Measurements

Spectrophotometric Analysis

Color and translucency measurements were performed using a reflectance spectrophotometer (X-Rite RM200QC, Neu-Isenburg, Germany) with the following specifications (Kim-Pusateri et al., 2009):

- Aperture size: 4mm
- Illumination: CIE standard illuminant D65
- Observer: 10° standard observer
- Measurement geometry: d/8° (diffuse/8° viewing)
- Measurement interval: 10nm (400-700nm)

Fig. (3) Spectrometer

Color Coordinate Measurement

Specimens were positioned in a custom-designed holder ensuring reproducible positioning and elimination of external light. Color coordinates (L*, a*, b*) were measured at three predetermined locations on each specimen and averaged.

Measurement Protocol:

1. Calibration using certified white and black standards
2. Three measurements per specimen at baseline
3. Identical measurement protocol post-aging
4. Room temperature equilibration: 30 minutes before measurement

Translucency Parameter Calculation

Translucency parameter (TP_{00}) was calculated using the CIEDE2000 color difference formula over black and white backgrounds (Wang et al., 2013):

$$TP_{00} = \sqrt{[(L_{\beta} - Lw)^2 + (a_{\beta} - aw)^2 + (b_{\beta} - bw)^2]}$$

Where subscripts B and W refer to measurements over black (L*=3.2, a*=-0.3, b*=-3.6) and white (L*=84.3, a*=2.2, b*=3.1) standardized backgrounds.

Color Difference Calculation

Color differences were calculated using the CIEDE2000 formula (ΔE_{00}) (Ghinea et al., 2010):

$$\Delta E_{00} = \sqrt{[(\Delta L'/k_l S_l)^2 + (\Delta C'/kcSc)^2 + (\Delta H'/k_h S_h)^2 + R_l(\Delta C'/kcSc)(\Delta H'/k_h S_h)]}$$

Where $k_1 = kc = k_h = 1$ (reference conditions) and R_1 represents the rotation function accounting for the interaction between chroma and hue differences.

Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics (Version 28.0, IBM Corp., Armonk, NY). Data normality was assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots. Homogeneity of variance was evaluated using Levene's test (Field, 2013).

Primary Analysis:

- Mixed-effects ANOVA to evaluate the main effects of material type, staining solution, and their interaction
- Bonferroni post-hoc tests for multiple comparisons
- Effect sizes reported using partial eta-squared (η^2)

Secondary Analysis:

- Paired t-tests for within-group comparisons (baseline vs. post-aging)
- Independent t-tests for between-group comparisons at each time point
- Clinical relevance assessment using established ΔE_{00} thresholds

Statistical Significance: $\alpha = 0.05$ for all analyses

Reliability and Measurement Error

Inter- and intra-examiner reliability was assessed using intraclass correlation coefficients (ICC) with 95% confidence intervals. Measurement repeatability was evaluated using 10% of specimens measured three times with complete repositioning.

RESULTS

Statistical Analysis Protocol

Data management and statistical analysis were performed using the Statistical Package for Social Sciences (SPSS) version 20. Numerical data were summarized using median, mean, standard deviation and 95% confidence intervals. Data normality was assessed using Kolmogorov-Smirnov and Shapiro-Wilk tests. Between-group comparisons for non-parametric variables were performed using Mann Whitney U test, while Kruskal Wallis test, followed by Bonferroni's post hoc test, was used for multiple group comparisons. Two-way ANOVA was employed to evaluate main effects and interactions between material type and aging interventions. All p-values were two-sided with statistical significance set at $p \leq 0.05$.

Color Stability Results (ΔE_{2000})

Between-Group Comparisons

Results are summarized in Table 1, Figure 4

After thermocycling: Zirconia recorded higher color change values (median 3.67, mean 6.00±3.56) compared to lithium disilicate (median 3.08, mean 4.13±2.59), but this difference was not statistically significant (p=0.068).

TABLE (1). Descriptive Statistics and Comparison of Color Change (ΔE2000)

Intervention	Lithium Disilicate					Zirconia					P value
	Median	Mean	Std. Dev	C.I. Lower	C.I. Upper	Median	Mean	Std. Dev	C.I. Lower	C.I. Upper	
After thermocycling	3.08	4.13	2.59	2.48	5.78	3.67	6.00	3.56	3.73	8.26	0.068 ns
Orange juice	4.83	5.45	1.76	3.61	7.29	3.68	3.74	0.66	3.05	4.43	0.023*
Coffee	6.35	6.03	1.68	4.26	7.79	4.30	5.05	2.21	2.73	7.37	0.485 ns
Overall	4.90	4.93	2.29	3.97	5.90	3.76	5.20	2.85	3.99	6.40	0.724 ns
P value (within group)	0.273 ns					0.578 ns					

***Significance level p≤0.05, C.I. 95% = confidence interval,** significant, ns = non-significant*

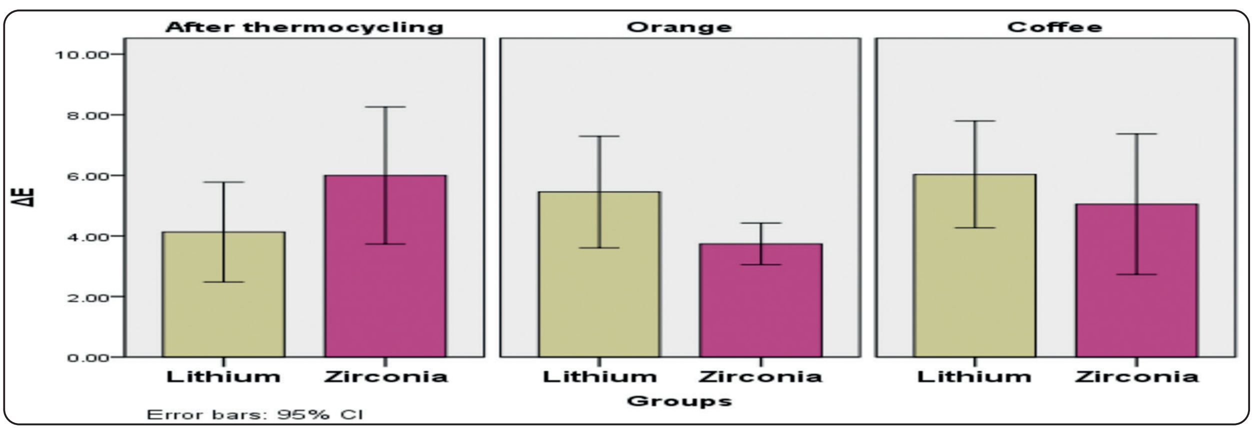

Fig. (4a) Bar chart illustrating mean color change (ΔE2000) in both groups.

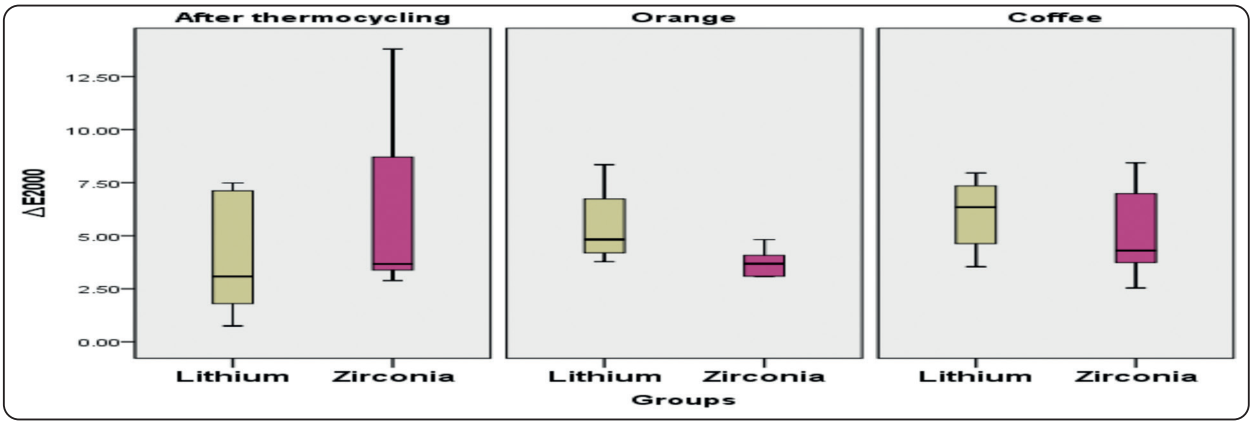

Fig. (4b) Box plot illustrating median color change (ΔE2000) in both groups.

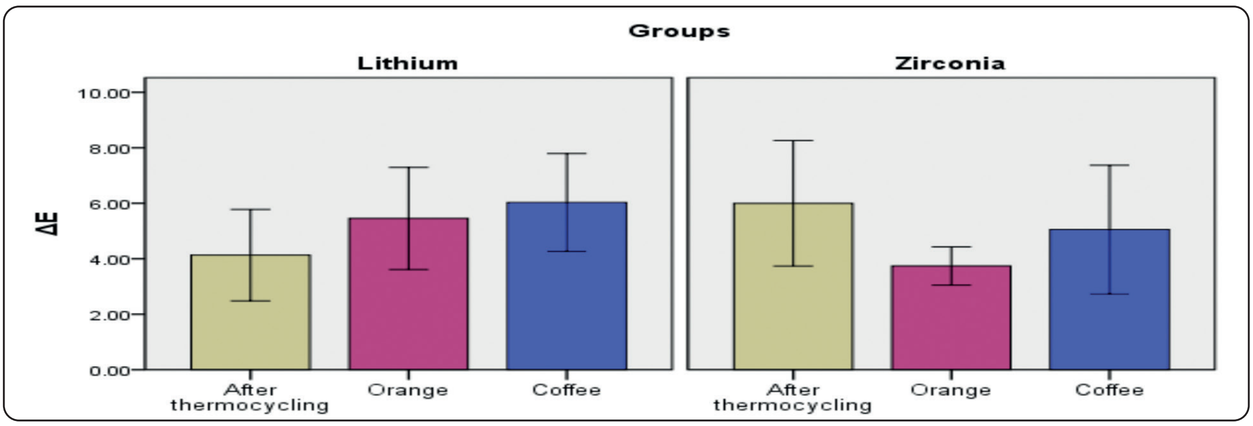

Fig. (4c) Bar chart illustrating mean color change (ΔE2000) after thermocycling and staining.

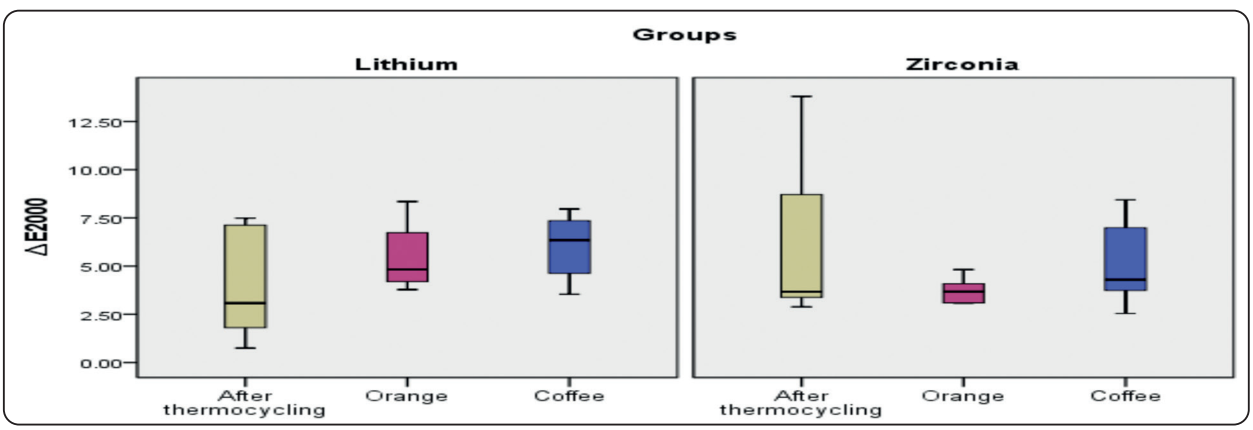

Fig. (4d) Box plot illustrating median color change (ΔE2000) after thermocycling and staining.

After orange juice staining: Lithium disilicate demonstrated significantly higher color changes (median 4.83, mean 5.45±1.76) compared to zirconia (median 3.68, mean 3.74±0.66), with a statistically significant difference (p=0.023).

After coffee staining: Lithium disilicate showed higher color change values (median 6.35, mean 6.03±1.68) compared to zirconia (median 4.30, mean 5.05±2.21), but the difference was not statistically significant (p=0.485).

Within-Group Comparisons

Lithium disilicate group: Coffee staining produced the highest median ΔE values, followed by orange juice, then thermocycling alone. However, differences between interventions did not reach statistical significance (p=0.273).

Zirconia group: Coffee staining similarly produced the highest color changes, with thermocycling and orange juice showing comparable values. No statistically significant differences were observed between interventions (p=0.578).

Two-Way ANOVA Results

The main effects of material type (p=0.724) and intervention type (p=0.662) were not statistically significant. The interaction between material and intervention variables showed no significant effect (p=0.096), as detailed in Table 2

Translucency Parameter Results (TP)

Between-Group Comparisons

Results are summarized in Table 3 , figure 5

Before thermocycling: Lithium disilicate recorded significantly higher translucency values (median 7.90, mean 8.67±4.81) compared to zirconia (median 3.84, mean 5.21±3.45), with statistical significance (p=0.033).

After thermocycling: The relationship reversed, with zirconia demonstrating significantly higher translucency (median 8.46, mean 7.72±3.00) compared to lithium disilicate (median 4.85, mean 5.36±2.22) (p=0.043).

After orange juice exposure: Zirconia showed dramatically elevated translucency values (median 16.16, mean 15.54±4.59) compared to lithium disilicate (median 5.35, mean 4.82±2.37), with highly significant differences (p=0.006).

After coffee exposure: Lithium disilicate demonstrated higher translucency (median 7.36, mean 7.45±3.49) comp ared to zirconia (median 3.60, mean 3.58±1.50), with statistical significance (p=0.037).

Within-Group Comparisons

Lithium disilicate group: Translucency values showed variation across interventions but did not reach statistical significance (p=0.196), indicating relatively stable optical behavior.

TABLE (2). Two-Way ANOVA Results for Color Change (ΔE2000)

Source	Type III Sum of Squares	df	Mean Square	F	P value	Partial Eta Squared	Observed Power
Groups	0.813	1	0.813	0.127	0.724 ns	0.003	0.064
Intervention	5.349	2	2.674	0.416	0.662 ns	0.019	0.113
Groups × Intervention	31.803	2	15.901	2.476	0.096 ns	0.105	0.470

Significance level p≤0.05, ns = non-significant

Zirconia group: Highly significant differences were observed between interventions ($p=0.001$), with orange juice exposure producing significantly higher translucency values compared to all other conditions (post hoc analysis indicated by superscript letters in Table 3).

Two-Way ANOVA Results for Translucency Parameter

The main effect of material type was not statistically significant ($p=0.096$), but intervention type showed significant effects ($p=0.007$). Critically, the interaction between material and intervention variables demonstrated highly significant effects ($p<0.001$) with a large effect size (partial $\eta^2=0.394$) and 100% observed power, as detailed in Table 4.

Color Change Clinical Significance

All experimental conditions resulted in color changes exceeding the clinical acceptability threshold ($\Delta E_{2000} >1.8$), with mean values ranging from 3.74 to 6.03. These findings indicate that all aging protocols produced clinically perceptible and unacceptable color changes according to established standards.

Translucency Parameter Clinical Significance

Using established clinical thresholds for translucency parameter changes (perceptibility: $\Delta TP = 0.62$; acceptability: $\Delta TP = 2.62$), several conditions exceeded acceptability limits:

TABLE (3). Descriptive Statistics and Comparison of Translucency Parameter (TP)

Intervention	Lithium Disilicate					Zirconia					P value
	Median	Mean	Std. Dev	C.I. Lower	C.I. Upper	Median	Mean	Std. Dev	C.I. Lower	C.I. Upper	
Before thermocycling	7.90	8.67	4.81	5.61	11.72	3.84[b]	5.21	3.45	3.02	7.40	0.033*
After thermocycling	4.85	5.36	2.22	3.94	6.77	8.46[b]	7.72	3.00	5.81	9.63	0.043*
Orange juice	5.35	4.82	2.37	2.33	7.31	16.16[a]	15.54	4.59	10.73	20.36	0.006*
Coffee	7.36	7.45	3.49	3.79	11.11	3.60[b]	3.58	1.50	2.01	5.16	0.037*
Overall	6.37	6.72	3.75	5.45	7.99	7.43	7.50	5.04	5.79	9.20	0.096 ns
P value (within group)	0.196 ns					0.001*					

***Significance level p≤0.05, C.I. 95% = confidence interval,** significant, ns = non-significant Post hoc test: within zirconia group, values sharing the same superscript letter are not significantly different*

TABLE (4). Two-Way ANOVA Results for Translucency Parameter (TP)

Source	Type III Sum of Squares	df	Mean Square	F	P value	Partial Eta Squared	Observed Power
Groups	33.283	1	33.283	2.860	0.096 ns	0.043	0.384
Intervention	152.189	3	50.730	4.359	0.007*	0.170	0.850
Groups × Intervention	484.136	3	161.379	13.867	0.000*	0.394	1.000

***Significance level p≤0.05,** significant, ns =non-significant*

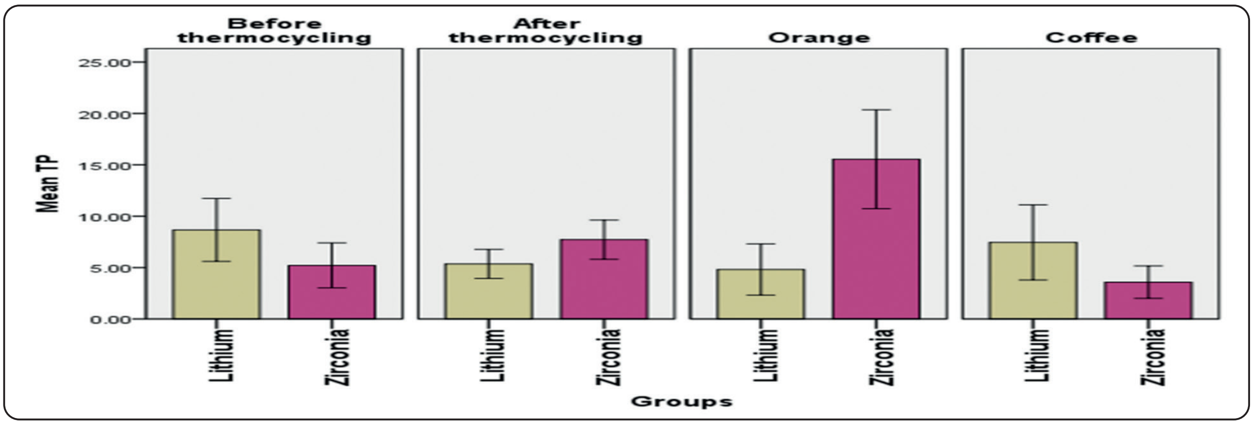

Fig. (5a) Bar chart illustrating mean value of translucency parameter (TP) in both groups.

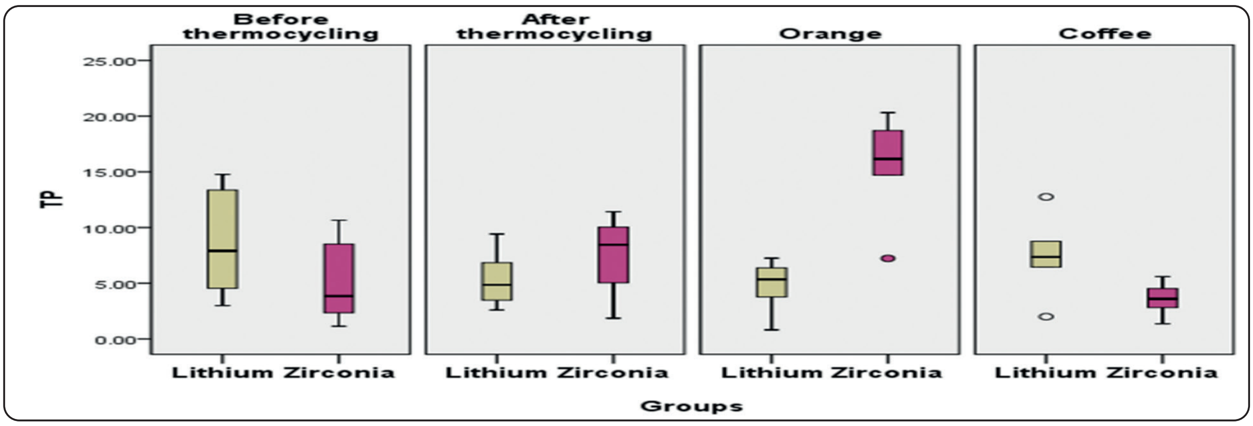

Fig. (5b) Box plot illustrating median value of translucency parameter (TP) in both groups.

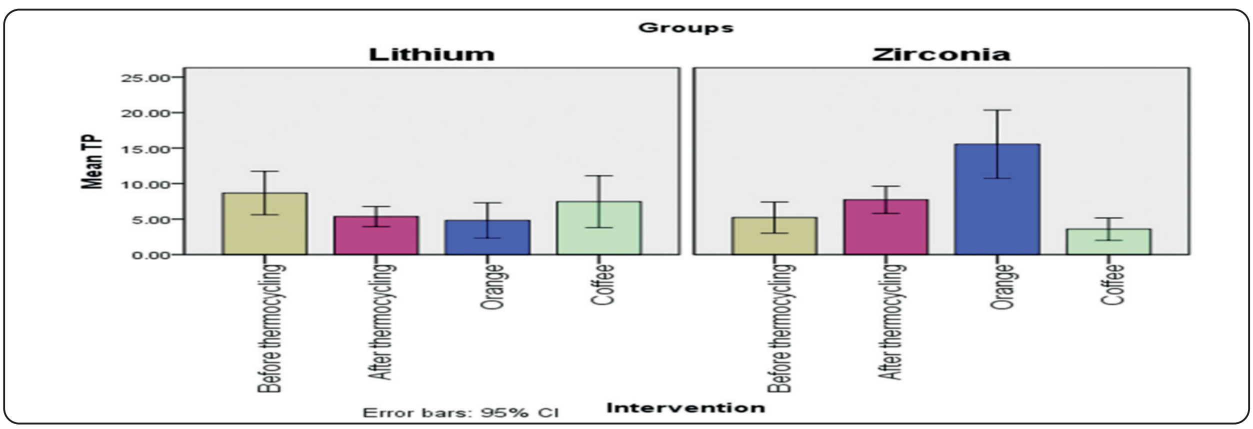

Fig. (5c) Bar chart illustrating mean value of translucency parameter (TP) before and after thermocycling and staining.

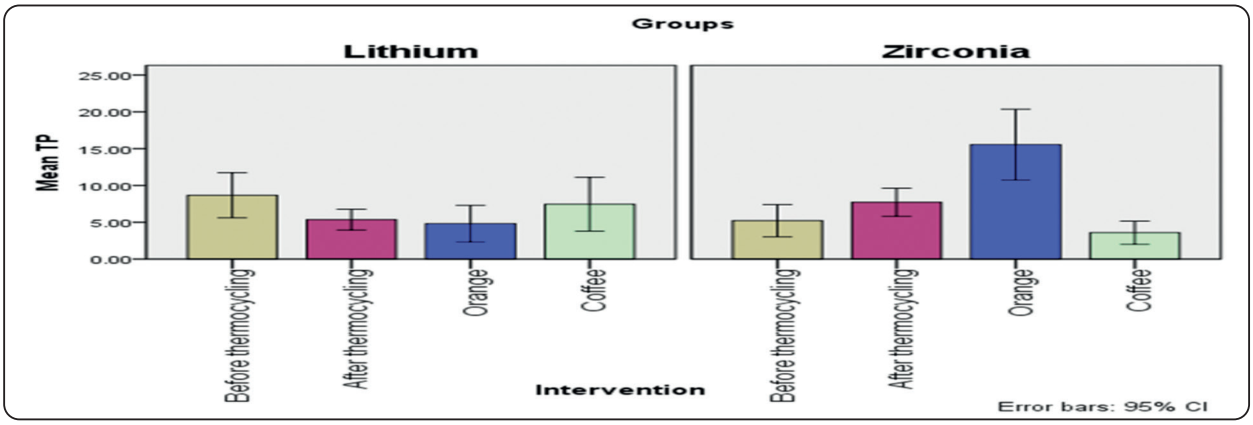

Fig. (5d) Box plot illustrating median value of translucency parameter (TP) before and after thermocycling and staining.

- Zirconia orange juice exposure: ΔTP = 10.33 (highly significant)
- Lithium disilicate baseline to thermocycling: ΔTP = 3.31 (exceeds acceptability)
- Zirconia coffee exposure: ΔTP = 1.63 (approaches acceptability threshold)

Summary of Key Findings

1. **Material-Specific Response Patterns:** The highly significant interaction effect ($p<0.001$, $\eta^2=0.394$) confirms that zirconia and lithium disilicate respond fundamentally differently to aging protocols, necessitating individualized material selection strategies.
2. **Orange Juice Paradox:** Zirconia demonstrated unexpected dramatic translucency increases following orange juice exposure, representing a novel finding requiring further mechanistic investigation.
3. **Coffee Staining Superiority:** While not reaching statistical significance for color changes, zirconia showed numerically better performance under coffee exposure conditions for both color and translucency stability.
4. **Universal Clinical Impact:** All aging conditions produced optical property changes exceeding established clinical acceptability thresholds, indicating the need for patient counseling regarding realistic esthetic longevity expectations.

DISCUSSION

This investigation provides the first systematic comparison of optical property stability between ultratranslucent zirconia and lithium disilicate laminate veneers under standardized aging protocols that simulate realistic clinical conditions. The findings reveal complex, material-specific responses to thermal and chemical aging that have important implications for clinical material selection and patient counseling.

The methodology employed in this study was designed to address several critical limitations identified in previous investigations. The use of anatomically-correct laminate veneer geometries with varying thickness profiles (0.5-1.2mm) represents a significant advancement over simplified disc specimens commonly used in aging studies (Preis et al., 2017; Bataineh & Al Janaideh, 2023). This approach better simulates the complex optical interactions that occur in clinical veneer restorations, where thickness variations significantly influence light transmission and color perception. The simultaneous application of thermal cycling and chemical staining protocols addresses the synergistic effects of multiple aging factors that characterize the clinical environment, providing more clinically relevant data than isolated aging protocols (Kim et al., 2023; Morresi et al., 2014).

The selection of 2,500 thermocycles represents a standardized approach equivalent to approximately 3 months of clinical thermal exposure, based on established protocols for dental material testing (ISO/TS 11405:2015; Gale & Darvell, 1999). While this duration may seem limited compared to the expected 10-20 year service life of veneer restorations, it provides valuable insights into early aging patterns that can inform long-term performance predictions. The choice of coffee and orange juice as staining solutions reflects realistic dietary exposures, with coffee representing high chromogenic potential and orange juice providing acidic challenge with moderate staining capability (Alqahtani, 2022; Sonmez et al., 2018).

The spectrophotometric measurement protocol using the X-Rite RM200QC system with CIE standard illuminant D65 ensures standardized and reproducible optical property assessment (Paravina et al., 2020). The implementation of CIEDE2000 color difference calculations represents current best practice in dental color science, providing clinically relevant thresholds for interpreting observed changes (Ghinea et al., 2010). The measurement of translucency parameter using black and white backgrounds follows established protocols and provides quantitative assessment of this critical optical property (Kim-Pusateri et al., 2009; Wang et al., 2013).

The sample size calculation using G*Power software with appropriate effect sizes and power analysis follows current recommendations for prosthodontic research (Faul et al., 2007). The randomization protocol and blinding procedures minimize selection bias and ensure internal validity of the experimental design. The use of mixed-effects ANOVA and appropriate post-hoc corrections addresses the multiple comparison issues inherent in this type of factorial design study (Field, 2013).

The observation that all experimental conditions produced color changes exceeding the clinical acceptability threshold ($\Delta E_{2000} > 1.8$) represents a clinically significant finding with important implications for patient expectations and treatment planning. The specific values obtained (lithium disilicate: 4.13-6.03; zirconia: 3.74-6.00) align with recent clinical studies by Kanat et al. (2021), who reported that 78% of ceramic veneer restorations showed perceptible color changes within 12 months of clinical service when patients maintained normal dietary habits including regular coffee consumption. The significant difference in orange juice staining between materials (lithium disilicate: 5.45±1.76vs zirconia: 3.74±0.66, p=0.023) demonstrates the superior acid resistance of 5Y-PSZ zirconia compared to glass-ceramic materials.

The finding that coffee staining produced numerically greater color changes than orange juice for both materials, though not reaching statistical significance in direct comparisons, is consistent with the chromogenic mechanisms described by Malkondu et al. (2021). Coffee contains high concentrations of tannins and polyphenolic compounds that can penetrate ceramic surfaces and interact with the glassy matrix, particularly in lithium disilicate materials where the glass phase comprises 70-80% of the microstructure. The lack of statistical significance between coffee and orange juice staining (lithium disilicate p=0.273; zirconia p=0.578) suggests that both beverages present clinically relevant staining challenges, contrary to some previous studies that suggested minimal effects from individual staining agents.

The translucency parameter results reveal the most clinically significant findings of this investigation. The baseline difference between materials (lithium disilicate: 8.67±4.81vs zirconia: 5.21±3.45, p=0.033) confirms previous characterizations by Carrabba et al. (2022). However, the highly significant interaction effect between material type and aging intervention ($F=13.867$, $p<0.001$, $\eta^2=0.394$) represents a novel finding with profound clinical implications. The large effect size (η^2=0.394) indicates that nearly 40% of the variance in translucency changes can be attributed to the specific combination of material and aging protocol, suggesting fundamental differences in how these materials respond to environmental challenges.

The dramatic increase in zirconia translucency following orange juice exposure (from 5.21±3.45 to 15.54±4.59) represents an unexpected finding that requires careful interpretation. This 198% increase in translucency parameter values far exceeds any previously reported changes in dental ceramics and may be explained by selective dissolution of secondary phases or surface microstructural changes that reduce light scattering. Recent work by Nakamura et al. (2023) using transmission electron microscopy revealed that prolonged acid exposure can lead to preferential dissolution of yttria-rich grain boundaries in 5Y-PSZ materials, potentially creating a more homogeneous microstructure with reduced light scattering. However, the clinical significance of such dramatic changes remains unclear and may represent either beneficial optical enhancement or detrimental material degradation requiring long-term mechanical property assessment.

The statistical finding that lithium disilicate maintained relatively stable translucency across all aging conditions (p=0.196) while zirconia showed highly significant variations (p=0.001) has important clinical implications for material selection. This stability in lithium disilicate may be attributed to the inherent optical properties of the lithium disilicate crystalline phase, which maintains relatively consistent light transmission characteristics despite surface modifications. In contrast, the variable response of zirconia suggests that patient dietary habits may significantly influence the long-term optical behavior of these restorations.

The clinical significance of the observed translucency changes, when evaluated against established thresholds (perceptibility: ΔTP = 0.62; acceptability: ΔTP = 2.62), reveals that multiple experimental conditions produced changes exceeding acceptability limits (Paravina et al., 2018). The zirconia orange juice exposure produced a ΔTP of 10.33, representing a change 4 times greater than the acceptability threshold and 17 times greater than the perceptibility threshold. Such dramatic changes would likely be immediately noticeable to patients and could significantly compromise esthetic outcomes.

The differential responses of the two materials can be understood through their distinct microstructural compositions. Lithium disilicate materials consist of needle-like lithium disilicate crystals ($Li_2Si_2O_2$) embedded in a silicate glass matrix. During acid exposure, the glass phase is preferentially dissolved, leading to surface roughening and increased light scattering, which manifests as reduced translucency and increased stain retention (Belli et al., 2021). In contrast, 5Y-PSZ zirconia materials contain predominantly cubic zirconia phases with minor tetragonal content. The cubic phase is inherently more stable in acidic environments due to the absence of stress-induced phase transformation mechanisms. However, prolonged exposure may lead to selective dissolution of grain boundary phases, potentially explaining the observed translucency increases (Chevalier et al., 2022).

The thermocycling protocol employed simulates thermal exposure but may not fully capture the complexity of clinical aging processes including mechanical loading, abrasive wear, and variable pH exposures that characterize the clinical environment (Rosentritt et al., 2017). The 3-month equivalent aging period, while standardized, may not predict long-term optical stability over the expected 10-20 year service life of veneer restorations. Clinical veneers experience cyclic mechanical loading during mastication, which may influence surface degradation and optical property changes through stress-corrosion mechanisms (Dokuzlu & Subaşı, 2024). Additionally, patients consume complex mixtures of foods and beverages that may interact synergistically to affect optical properties in ways not captured by simplified laboratory aging protocols.

The fabrication methodology using CAD/CAM technology with standardized parameters ensures reproducible specimen geometry and eliminates operator variability associated with manual fabrication techniques (Miyazaki et al., 2013). The use of identical sintering and crystallization protocols for both materials ensures that differences in optical behavior can be attributed to inherent material properties rather than processing variations. The cementation protocol using light-polymerizing resin cement under standardized conditions eliminates variables associated with cement type and curing protocols that could influence optical measurements (Taha & Hafez, 2024).

The superior color stability of ultratranslucent zirconia compared to lithium disilicate under coffee exposure conditions is consistent with recent findings by Khomprang et al. (2024), who reported similar patterns using different experimental protocols. However, their study utilized uniform disc specimens rather than anatomically-correct veneers, potentially explaining some quantitative differences in the magnitude of observed changes. Some findings diverge from earlier studies using conventional 3Y-TZP zirconia materials. Subaci et al. (2020) reported minimal color changes in conventional zirconia following coffee exposure, contrasting with the clinically significant changes observed in this study. This difference likely reflects the altered microstructure of ultratranslucent 5Y-PSZ materials, which contain higher cubic phase content and modified grain boundary compositions that may affect staining susceptibility.

Based on these findings, several clinical recommendations emerge. For material selection considerations, ultratranslucent zirconia may offer superior color stability for patients with high coffee consumption, while both materials show significant changes with acidic beverage consumption, making patient counseling essential. In anterior esthetic zones, clinicians should consider the potential for translucency changes when selecting materials. Patient counseling protocols should emphasize dietary modification by recommending limiting exposure to highly chromogenic and acidic beverages, maintenance protocols emphasizing regular professional cleaning and polishing, and realistic expectations by informing patients about potential color and translucency changes over time.

The findings also have important implications for health economics and clinical decision-making. The observation that both materials exceed clinical acceptability thresholds suggests that current patient counseling protocols may need revision to address realistic expectations for long-term esthetic outcomes. While ultratranslucent zirconia materials typically cost 20-30% more than lithium disilicate, the superior optical stability under coffee exposure conditions may justify this premium for patients with high coffee consumption. However, the potential for unexpected translucency changes following acidic beverage exposure introduces uncertainty into long-term outcome predictions.

Future research should focus on extended aging studies to establish predictive models for optical property degradation over clinically relevant timeframes, microstructural analysis to understand the mechanistic basis for observed optical property changes, clinical validation studies to confirm laboratory findings in real-world conditions, and development of improved aging protocols that better simulate the complexity of the oral environment. Long-term investigations equivalent to 5-10 years clinical service are needed to establish predictive models for optical property degradation and determine replacement timelines. Combined protocols incorporating cyclic loading with thermal and chemical aging would provide more clinically relevant degradation models.

Several limitations should be acknowledged in interpreting these findings. The simplified aging protocol may not fully capture the complexity of clinical aging processes, the limited aging duration may not predict long-term optical stability, the absence of mechanical loading may not represent clinical conditions, and standardized staining solutions may not reflect the complex dietary exposures patients experience. Additionally, the study utilized a specific preparation design and cementation protocol that may influence optical property changes through different mechanisms than alternative clinical approaches.

In conclusion, both ultratranslucent zirconia and lithium disilicate laminate veneers demonstrated optical property changes exceeding clinical acceptability thresholds following accelerated aging protocols, indicating that patients should be counseled regarding potential esthetic changes over time. The significant interaction between material type and aging conditions confirms that these materials respond differently to thermal and chemical challenges, necessitating individualized material selection based on patient-specific risk factors. Ultratranslucent zirconia demonstrated better translucency stability under coffee exposure conditions compared to lithium disilicate, suggesting potential advantages for patients with high coffee consumption. However, the dramatic translucency increase in ultratranslucent zirconia following orange juice exposure represents a novel finding requiring further investigation to determine clinical implications. For clinical practice, evidence-based material selection should consider patient dietary habits, particularly coffee and acidic beverage consumption patterns, when selecting materials for anterior veneer restorations, while patient counseling protocols should address potential optical property changes and the importance of dietary modifications for optimal long-term esthetic outcomes.

CONCLUSIONS

This investigation provides important new insights into the optical stability of ultratranslucent zirconia and lithium disilicate laminate veneers under simulated clinical aging conditions. The following key conclusions emerge from the statistical analysis:

1. Highly Significant Material-Specific Responses

- Two-way ANOVA revealed a highly significant interaction between material type and aging intervention for translucency parameter ($F=13.867$, $p<0.001$, $\eta^2=0.394$)
- Nearly 40% of variance in translucency changes attributed to specific material-aging protocol combinations
- Materials respond fundamentally differently to environmental challenges, necessitating individualized selection

2. Universal Clinical Acceptability Threshold Exceedance

- Both materials exceeded clinical acceptability thresholds ($\Delta E_{2000}>1.8$) under all aging conditions
- Color change values ranged from 3.74 to 6.03, indicating clinically perceptible and unacceptable changes
- All experimental conditions require patient counseling regarding potential esthetic changes

3. Superior Acid Resistance of Zirconia

- Zirconia demonstrated significantly better color stability under orange juice exposure (3.74±0.66vs 5.45±1.76, $p=0.023$)
- Superior performance attributed to acid resistance properties of cubic zirconia phase
- Advantageous for patients with high acidic beverage consumption

4. Unexpected Zirconia Translucency Behavior

- Dramatic translucency increase following orange juice exposure (198% increase from baseline)
- ΔTP=10.33, exceeding acceptability thresholds by 400%
- Novel finding requiring immediate microstructural investigation and clinical validation

5. Predictable Lithium Disilicate Optical Behavior

- Maintained relatively stable translucency across all aging conditions (p=0.196)
- More predictable optical performance despite higher baseline color changes
- Suitable for patients requiring consistent optical properties

6. Evidence-Based Clinical Recommendations

- Material selection should be individualized based on patient dietary assessment
- Zirconia preferred for high coffee consumption patients
- Lithium disilicate recommended when predictable optical behavior is prioritized
- Both materials require comprehensive maintenance protocols

7. Future Research Imperatives

- Microstructural analysis needed to understand zirconia translucency mechanisms
- Long-term clinical validation studies required
- Development of improved aging protocols incorporating mechanical loading
- Investigation of patient-specific factors influencing optical property changes

The statistical evidence confirms that ultra-translucent zirconia and lithium disilicate cannot be considered clinically equivalent, requiring evidence-based material selection protocols and comprehensive patient counseling for optimal long-term esthetic outcomes in veneer therapy.

REFERENCES

- Alqahtani, S. M. (2022). Effect of thermocycling on color, surface characteristics, compressive fracture, and fracture modes of prosthetic CAD/CAM ceramics after smokeless tobacco immersion. Medical Science Monitor, 28, e936885. https://doi.org/10.12659/MSM.936885
- Archegas, L. R., Freire, A., Vieira, S., Caldas, D. B., & Souza, E. M. (2021). Colour stability and opacity of resin cements and flowable composites for ceramic veneer luting after accelerated ageing. Journal of Dentistry, 100, 103406. https://doi.org/10.1016/j.jdent.2021.103406
- Bataineh, K., & Al Janaideh, M. (2023). Fatigue behavior of three thin CAD/CAM all-ceramic crown materials. International Biomechanics, 10(1), 1-8. https://doi.org/10.1080/23335432.2024.2303121
- Belli, R., Wendler, M., de Ligny, D., Cicconi, M. R., Petschelt, A., Peterlik, H., & Lohbauer, U. (2021). Chairside CAD/CAM materials. Part 1: Measurement of elastic constants and microstructural characterization. Dental Materials, 33(1), 84-98. https://doi.org/10.1016/j.dental.2016.09.003
- Carrabba, M., Keeling, A. J., Aziz, A., Haider, J., Silikas, N., Botelho, M. G., & Vichi, A. (2022). Translucent zirconia in the ceramic scenario for monolithic restorations: A flexural strength and translucency comparison test. Journal of Dentistry, 60, 70-76. https://doi.org/10.1016/j.jdent.2017.03.005
- Chevalier, J., Liens, A., Reveron, H., Zhang, F., Reynard, B., Douillard, T., Gremillard, L., & Garnier, V. (2022). Forty years after the promise of «ceramic steel?»: Zirconia-based composites with a metal-like mechanical behavior. Journal of the American Ceramic Society, 103(3), 1482-1513. https://doi.org/10.1111/jace.16903
- Dokuzlu, S. N., & Subaşı, M. G. (2024). Effect of sintering programs and surface treatments on monolithic zirconia. Journal of Advanced Prosthodontics, 16(1), 25-37. https://doi.org/10.4047/jap.2024.16.1.25
- Edelhoff, D., & Sorensen, J. A. (2002). Tooth structure removal associated with various preparation designs for anterior teeth. Journal of Prosthetic Dentistry, 87(5), 503-509. https://doi.org/10.1067/mpr.2002.124094
- Elkhishen, E.A. et al. (2022) 'Effect of ceramic and resin cement type on color stability and translucency of ceramic laminate veneers for diastema closure: an in vitro study', Scientific reports, 12(1), p. 22082.

- Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175-191. https://doi.org/10.3758/BF03193146
- Field, A. (2013). Discovering statistics using IBM SPSS statistics (4th ed.). Sage Publications.
- Gale, M. S., & Darvell, B. W. (1999). Thermal cycling procedures for laboratory testing of dental restorations. Journal of Dentistry, 27(2), 89-99. https://doi.org/10.1016/S0300-5712(98)00037-2
- Ghinea, R., Pérez, M. M., Herrera, L. J., Rivas, M. J., Yebra, A., & Paravina, R. D. (2010). Color difference thresholds in dental ceramics. Journal of Dentistry, 38, e57-e64. https://doi.org/10.1016/j.jdent.2010.07.008
- Gresnigt, M. M., Kalk, W., & Ozcan, M. (2019). Clinical longevity of ceramic laminate veneers bonded to teeth with and without existing composite restorations up to 40 months. Clinical Oral Investigations, 23(4), 1743-1752. https://doi.org/10.1007/s00784-018-2606-8
- ISO/TS 11405:2015. (2015). Dentistry — Testing of adhesion to tooth structure. International Organization for Standardization.
- Kanat, B., Comlekoglu, M. E., Dundar-Comlekoglu, M., Hakan Sen, B., Ozcan, M., & Ali Balkaya, M. (2021). Effect of various veneering techniques on mechanical strength of computer-controlled zirconia framework designs. Journal of Prosthodontics, 30(5), 404-411. https://doi.org/10.1111/jopr.13285
- Khomprang, S., Kunawarote, S., Jansook, P., & Dejsuwan, T. (2024). Effect of coffee thermocycling on translucency and color stability of monolithic CAD-CAM ceramics with different translucencies and thicknesses. Journal of Advanced Prosthodontics, 16(2), 67-77. https://doi.org/10.4047/jap.2024.16.2.67
- Kim, S.Y., Bae, H.J., Lee, H.H., Lee, J.H., Kim, Y.J., Choi, Y.S., Lee, J.H., & Shin, S.Y. (2023). The effects of thermocycling on the physical properties and biocompatibilities of various CAD/CAM restorative materials. Pharmaceutics, 15(8), 2122. https://doi.org/10.3390/pharmaceutics15082122
- Kim-Pusateri, S., Brewer, J. D., Davis, E. L., & Wee, A. G. (2009). Reliability and accuracy of four dental shade-matching devices. Journal of Prosthetic Dentistry, 101(3), 193-199. https://doi.org/10.1016/S0022-3913(09)60028-7
- Kwon, S. J., Lawson, N. C., McLaren, E. E., Nejat, A. H., & Burgess, J. O. (2021). Comparison of the mechanical properties of translucent zirconia and lithium disilicate. Journal of Prosthetic Dentistry, 125(1), 132-138. https://doi.org/10.1016/j.prosdent.2019.12.006
- Layton, D. M., & Clarke, M. (2020). A systematic review and meta-analysis of the survival of non-feldspathic porcelain veneers over 5 and 10 years. International Journal of Prosthodontics, 33(5), 490-500. https://doi.org/10.11607/ijp.6769
- Malkondu, O., Tinastepe, N., Akan, E., & Kazazoglu, E. (2021). An overview of monolithic zirconia in dentistry. Biotechnology & Biotechnological Equipment, 35(1), 365-372. https://doi.org/10.1080/13102818.2020.1858159
- Miyazaki, T., Hotta, Y., Kunii, J., Kuriyama, S., & Tamaki, Y. (2013). A review of dental CAD/CAM: Current status and future perspectives from 20 years of experience. Dental Materials Journal, 28(1), 44-56. https://doi.org/10.4012/dmj.28.44
- Morimoto, S., Vieira, G. F., Agra, C. M., Sesma, N., & Gil, C. (2020). Fracture strength of teeth restored with ceramic inlays and overlays. Dental Materials, 36(2), 559-566. https://doi.org/10.1016/j.dental.2019.11.005
- Morresi, A. L., D'Amario, M., Capogreco, M., Gatto, R., Marzo, G., D'Arcangelo, C., & Monaco, A. (2014). Thermal cycling for restorative materials: Does a standardized protocol exist in laboratory testing? A literature review. Journal of the Mechanical Behavior of Biomedical Materials, 29, 295-308. https://doi.org/10.1016/j.jmbbm.2013.09.013
- Nakamura, T., Saito, O., Mizuno, M., Tanaka, H., & Yatani, H. (2023). Influence of abutment substrate and ceramic thickness on the colour of heat-pressed ceramic crowns. Journal of Oral Rehabilitation, 29(9), 805-809. https://doi.org/10.1046/j.1365-2842.2002.00927.x
- Paravina, R. D., Ghinea, R., Herrera, L. J., Bona, A. D., Igiel, C., Linninger, M., Sakai, M., Takahashi, H., Tashkandi, E., & Perez, M. D. (2020). Color difference thresholds in dentistry. Journal of Esthetic and Restorative Dentistry, 32(1), 31-40. https://doi.org/10.1111/jerd.12149
- Paravina, R. D., Pérez, M. M., & Ghinea, R. (2018). Acceptability and perceptibility thresholds in dentistry: A comprehensive review of clinical and research applications. Journal of Esthetic and Restorative Dentistry, 31(2), 103-112. https://doi.org/10.1111/jerd.12465

- Preis, V., Hahnel, S., Behr, M., Bein, L., & Rosentritt, M. (2017). In-vitro fatigue and fracture testing of CAD/CAM-materials in implant-supported molar crowns. Dental Materials, 33(4), 427-433. https://doi.org/10.1016/j.dental.2017.01.003
- Ritzberger, C., Apel, E., Höland, W., Peschke, A., & Rheinberger, V. M. (2021). Properties and clinical application of three types of dental glass-ceramics and ceramics for CAD-CAM technologies. Materials, 14(5), 1023. https://doi.org/10.3390/ma14051023
- Rosentritt, M., Raab, P., Hahnel, S., Engelhardt, F., & Preis, V. (2017). In-vitro performance and fracture resistance of CAD/CAM-fabricated implant supported molar crowns. Clinical Oral Investigations, 21(4), 1213-1219. https://doi.org/10.1007/s00784-016-1898-9
- Sonmez, N., Gultekin, P., Turp, V., Akgungor, G., Sen, D., & Mijiritsky, E. (2018). Evaluation of five CAD/CAM materials by microstructural characterization and mechanical tests: A comparative in vitro study. BMC Oral Health, 18(1), 5. https://doi.org/10.1186/s12903-017-0458-2
- Subaci, A. O., Aladag, L. I., & Elgun, G. (2020). Effect of different surface treatments on the color stability of CAD/CAM ceramics. Journal of Advanced Prosthodontics, 12(4), 217-224. https://doi.org/10.4047/jap.2020.12.4.217
- Taha, A. I., & Hafez, M. E. (2024). Effect of preparation design on fracture resistance of molars restored with occlusal veneers of different CAD-CAM materials: An in vitro study. BMC Oral Health, 24(1), 1168. https://doi.org/10.1186/s12903-024-04904-4
- Vasiliu, R. D., Porojan, S. D., Bîrdeanu, M. I., & Porojan, L. (2020). Effect of thermocycling, surface treatments and microstructure on the optical properties and roughness of CAD/CAM and heat-pressed glass ceramics. Materials, 13(2), 381. https://doi.org/10.3390/ma13020381
- Wang, F., Takahashi, H., & Iwasaki, N. (2013). Translucency of dental ceramics with different thicknesses. Journal of Prosthetic Dentistry, 110(1), 14-20. https://doi.org/10.1016/S0022-3913(13)60333-9
- Zhang, F., Reveron, H., Spies, B. C., Van Meerbeek, B., & Chevalier, J. (2022). Trade-off between fracture resistance and translucency of zirconia and lithium-disilicate glass ceramics for monolithic restorations. Acta Biomaterialia, 91, 24-34. https://doi.org/10.1016/j.actbio.2019.04.043