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Colour Stability of Different Zirconia Generations Against Tobacco Smoke and Colouring Beverages: A Comparative Study on Glazing Vs. Polishing

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Abstract

Background.

Long-term aesthetic success of all-ceramic restorations depends heavily on their resistance to surface discoloration under complex intraoral conditions. This study aimed to evaluate the impact of surface finishing methods on the colour stability of leucite-reinforced glass ceramic(LGC) and two generations of monolithic zirconia after chewing simulation and exposure to coffee, black tea, and tobacco smoke.

Methods.

One hundred sixty-two specimens prepared from LGC, 3mol% and 5mol% yttria-stabilized-zirconia(3Y-TZP/5Y-TZP) were divided into glazed and manually polished subgroups(N = 54/material,n = 27/surface treatment).All specimens were first subjected to mechanical wear and thermal aging in a chewing simulator(240.000 cycles,55 N,50–55°C). Specimens were then subdivided(n = 9) and exposed to coffee, black tea(12 days), or tobacco smoke(105 cigarettes) in a custom-made smoke simulator. Colour coordinates(L*a*b*) were measured using a spectrophotometer before and after staining, and overall colour changes(ΔE) were calculated. Data were analyzed using robust three-way ANOVA and Yuen's test with Bonferroni correction test(*alpha* = 0.05).

Results.

All experimental groups exceeded the clinical perceptibility threshold(ΔE > 3.7). Staining agent and surface treatment interactions were statistically significant($P < 0.05$). Overall, coffee induced the highest mean discoloration(ΔE = 5.75 ± 0.26), followed by tobacco smoke(ΔE = 4.91 ± 0.27) and tea(ΔE = 4.68 ± 0.26). For 3Y-TZP, glazed specimens demonstrated significantly higher resistance to coffee discoloration than polished specimens($P < 0.05$). For LGC, glazed specimens exhibited higher staining under tobacco smoke exposure compared to polished specimens.

Conclusions.

Mechanical wear followed by chromogenic exposure significantly alters ceramic colour stability. Coffee poses the highest overall staining risk across tested materials. While glazing provides protection against dietary staining for 3Y-TZP, surface finishing selection should be customized based on material composition and patient-specific habits.

Clinical trial number:

Not applicable

Background

Since expected standards in dentistry continue to rise, the demand for tooth-coloured restorations with superior aesthetic and mechanical properties has also increased. Consequently, various all-ceramic materials have been developed to meet both aesthetic and functional requirements. LGCs are widely used due to their excellent optical properties, adequate bonding capability, ease of fabrication, and pleasing appearance.[1] Compared to veneered ceramic restorations, they are less prone to chipping or delamination. However, despite being one of the most versatile indirect restorative materials, caution is advised when restoring bruxism patients or non-vital teeth due to their relatively low fracture resistance.[2]

Full-ceramic restorations are often preferred for their ability to mimic the optical features of natural dentition.[3] Among these, monolithic zirconia stands out for its superior mechanical performance, attributed to the transformation toughening mechanism.[4] Additionally monolithic zirconia restorations offer distinct benefits, including a streamlined fabrication process that enhances cost and time efficiency, as well as obviating the need for a veneering layer, which effectively prevents chipping. However, a notable drawback lies in their lower esthetic properties compared to other ceramics.[5,6] To overcome this problem, manufacturers have introduced monolithic zirconia with increased yttria content to enhance translucency.[7] This results in materials that attempt to combine the esthetics of conventional ceramics with the strength of zirconia.[8] However, it is known that increasing yttria content of monolithic zirconia to improve translucency may diminish the material's mechanical properties by increasing the cubic phase in the composition.[9,10]

In the oral cavity, dental restorations are exposed to a number of conditions that cause physical and mechanical change of the restorations, such as wear and discoloration. These are critical for the long-term success of restorations. Although the physical and mechanical properties of ceramics have been vastly improved, they are susceptible to discoloration.[11] Extrinsic factors like colouring beverages, mouthwashes, acid solutions, tooth brushing, higher temperatures and humidity are reported to induce the surface degradation of ceramics.[12] The extrinsic discoloration potential depends not only on the environmental exposure but also on the material characteristics, such as surface morphology and composition. Smoother ceramic surfaces are less likely to harbour biofilm, plaque accumulation and extrinsic stains. Therefore, surface finishing methods are critical. Glazing is one of the finishing methods commonly used clinical practice to obtain a smooth surface. However, if the glaze layer is removed during contour adjustments or worn away due to function, surface roughness may increase and the ceramic restorations become generally prone to discoloration.[13,14] Additionally recent studies have shown that a smooth surface can also be obtained by using manual polishing as well as glazing.[15,16]

Despite the increased use of monolithic zirconia in restorative dentistry, especially with higher yttria content to improve aesthetics, their long-term colour stability remains a concern. Given the growing clinical popularity of high-translucent zirconia and the routine exposure to staining challenges, it becomes essential to investigate how surface treatments and staining conditions affect their

discoloration. Understanding these interactions can guide clinical decision-making and material selection. Although various studies have assessed the discoloration resistance of different all-ceramic materials, to the best of the authors' knowledge, no study has compared the discoloration of LGC, 3Y-TZP, and 5Y-TZP zirconia restorations with different surface treatments subjected to staining agents, especially tobacco smoke. Moreover, the combined effects of surface finishing, chewing simulation, and common extrinsic staining sources such as coffee, black tea, and tobacco smoke remain underexplored. Therefore, the present study aimed to evaluate the discoloration of glazed and polished LGC and monolithic zirconia materials (3Y-TZP and 5Y-TZP) after chewing simulation, and immersion in coffee, black tea and subjected to tobacco smoke.

The null hypotheses of this study were as follows:

(1) Surface finishing method would have no effect on the colour stability of the tested ceramics.

(2) The material composition would have no effect on colour stability.

(3) The type of staining agent would have no effect on colour stability.

Material and Methods

Specimen preparation

Three widely used ceramic materials were evaluated in this study: Leucite-reinforced glass ceramic (LGC) (Empress CAD; Ivoclar Vivadent, Ellwangen, Germany), 3Y-TZP (VITA YZ HT; Vita Zahnfabrik, Bad Säckingen, Germany) and 5Y-TZP (VITA YZ XT; Vita Zahnfabrik, Bad Säckingen, Germany). The sample size was calculated via the G*Power version 3.1.9.2 (Kiel University, Kiel, Germany) program and colour change values (ΔE) accepted as the primary outcome. A power calculation was conducted via one-way analysis of variance (ANOVA) test, which was observed in a previous study with $\alpha = 0.05$, $1-\beta(\text{Power}) = 0.95$, and an effect size of 1.9.[17] Thus, 9 specimens (10 mm in diameter; 2 mm in thickness) were required for each study group (n = 9). A total of 162 disc-shaped specimens (10 mm diameter, 2 mm thickness) were prepared and allocated into 18 experimental groups based on material, surface treatment, and chromogenic agent (N = 54 per material) (Table 1).

Table 1
Experimental groups and specimen distribution

Material	Surface Finishing	Coffee (n = 9)	Black tea (n = 9)	Heated tobacco (n = 9)	Total (n)
LGC	Glazed	9	9	9	**27**
	Polished	9	9	9	**27**
3Y-TZP	Glazed	9	9	9	**27**
	Polished	9	9	9	**27**
5Y-TZP	Glazed	9	9	9	**27**
	Polished	9	9	9	**27**
Total		**54**	**54**	**54**	**162**

Regarding surface finishing, specimens from each material group (n = 27) were either manually polished then glazed or manually polished. Polishing procedure was performed by using following burs in sequence: Pre-polisher type VI-H1D/grey, lens VI-H16D/grey and brush VI-DT-H17D/grey; then high-gloss polisher type VI-H1Dmf/cream, lens VI-H16Dmf/cream and brush VI-DT-H17Dmf/cream. Each bur used for 30 seconds under the air cooling. The polishing was interpreted by a single operator to eliminate inter-operator variability.

Glazing was performed using material-specific glaze pastes (IPS Ivocolor®, Ivoclar Vivadent, Schaan, Liechtenstein for LGC; VITA AKZENT®Plus for 3Y-TZP and 5Y-TZP) applied in a uniform thin layer and fired in a dedicated ceramic furnace according to the respective manufacturers' temperature schedules.

Colour measurement and simulated aging procedure

Initial colour values of all specimens were measured by using a reflectance spectrophotometer (VITA Easyshade; Vita Zahnfabrik, Bad Säckingen, Germany) according to the Commission internationale de l'éclairage L*a*b* (CIELAB) system. These baseline colour (T0) measurements were taken against a neutral gray background under standard D65 light condition. To standardize the colour measurement process, a circular-shaped silicone mold with a hole (6 mm in diameter) in the center was prepared. The device was placed into the hole and kept perpendicular to the surfaces of specimens and was calibrated prior to each measurement in accordance with the manufacturer's instructions. After determining the T0 values, all the specimens were subjected to a chewing simulation device (SD Mechatronik Chewing Simulator CS-4.2, Feldkirchen-Westerham, Germany) Each specimen were subjected to 240000 cycles with 55N mastication force, equivalent to one year of aging. A 50–55˚C thermal cycle was applied at the same time.[18]

Staining Protocols

After simulated wear aging, specimens from each subgroup (n = 9) were assigned to one of three chromogenic conditions: coffee, black tea, or tobacco smoke. Non-tested specimen surfaces were protected with a waterproof tape barrier (Scotch, 3M, Maplewood, USA) to limit chromogenic interaction exclusively to the treated testing face.

Coffee solution was prepared with 3.6 g instant coffee (Nescafe Gold; Nestlé, Vevey, Switzerlans) and 300 ml boiling water; black tea solution was prepared by steeping 2 g tea bags (Lipton; Unilever, Glasgow, UK) in 200 mL of boiling water for 5 minutes. Specimens were continuously immersed in 20 mL of the respective solutions in airtight, light-protected containers stored in an incubator at 37°C for 12 days, equivalent to one year of clinical beverage consumption. The solutions were stirred every 8 hours and refreshed daily to maintain homogeneity. Colour measurements were made at a time interval of 12 days (T1) equal to one year in oral cavity.[19] Between solution changes, specimens were rinsed with distilled water and gently blot-dried with lint-free absorbent paper.

Specimens (n = 9 per subgroup) were exposed to tobacco smoke in a custom-made smoke simulator (70 cm^3 capacity), which is designed to simulate the human oral cavity in vitro (Fig. 1). Specimens were fixed to the base of the chamber using non-coloured wax, with their test surfaces positioned at a standardized distance of 1.5 cm from the smoke source.

The smoking cycle was performed using a vacuum-controlled system that applied a negative pressure of 2.7 kPa for 2 seconds to simulate a standardized inhalation puff, filling the chamber with smoke.[20] To simulate the interval between puffs, the cigarette was detached, and the chamber was cleared using negative pressure for 60 seconds. Following the protocol described by Wang et al[21], each cigarette was consumed in a cycle of 6 puffs and 6 intervals, totaling 372 seconds per cigarette. To ensure consistency, the transition between cigarettes was completed in under 20 seconds.

A total of 105 standardized cigarettes (Marlboro Touch Blue, Marlboro, USA) were combusted for each experimental group, simulating a heavy smoking habit of 15 cigarettes daily over a 7-day period. This accelerated smoking protocol was designed to achieve a cumulative tobacco exposure equivalent to approximately one year of clinical aging, ensuring methodological consistency with the 12-day immersion protocols used for the other chromogenic agents in this study.

Following chromogenic exposure, all specimens were thoroughly rinsed under running distilled water for 60 seconds without mechanical brushing to remove non-adherent surface residues, blot-dried, and subjected to final spectrophotometric evaluation (T1). Brushing simulation was intentionally excluded from the staining phase to evaluate the materials' maximum staining susceptibility without the interfering effects of mechanical wear, varying brushing counts and pressures. The colour change was calculated using the CIELab formula[11]:

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$$

The difference ΔL, Δa, Δb values were described as follows: $\Delta L = L_{after} - L_{before}$; $\Delta a = a_{after} - a_{before}$; $\Delta b = b_{after} - b_{before}$. According to the formula, ΔE = colour change; ΔL = lightness difference (L*) such that the greater the L*, the higher the brightness of the sample; Δa = the a* axis difference such that the higher the a*, the redder the sample and the lower the a*, the greener the sample; and Δb = the b* axis difference such that the higher the b*, the yellower the sample and the lower the b*, the bluer the sample.[22] All measurements were performed by the same operator for the standardization.

Statistical analysis

The normality of the data was assessed using the Kolmogorov-Smirnov test, and homogeneity of variances was examined via Levene's test. In traditional analysis of variance (ANOVA), the assumptions of normal distribution and homogeneity of variances across groups are required. However, due to deviations observed in certain groups, these assumptions were not fully met in the present study. Therefore, a robust three-way ANOVA was used to examine how the level of colour change varied in terms of the main and interaction effects of material, procedure, and colouring substances. The analysis was based on 20% trimmed means, and descriptive findings were presented as trimmed mean ± standard error (SE). Pairwise comparisons for significant differences were performed using Yuen's test with Bonferroni correction. For general descriptive statistics of colour change level, mean ± standard deviation (SD) values were reported. A significance level of $P < 0.05$ was adopted for all analyses. All computations and analyses were performed using IBM SPSS 26 (IBM SPSS Statistics for Windows, Version 26.0, IBM Corp.) and R software (R Core Team, R Foundation for Statistical Computing). The robust analysis results were obtained through the WRS2 package in R.

Results

Mean colour change (ΔE) values, standard deviations, trimmed means (0.20 trimming level), and standard errors of all experimental subgroups are summarized in Table 2 and Table 3. Across all evaluated experimental subgroups, mean discoloration values exceeded the clinically acceptable threshold ($\Delta E > 3.7$), indicating that mechanical wear aging followed by chromogenic exposure significantly alters ceramic colour stability regardless of material type or surface finishing (Fig. 2).

Table 3
Pairwise comparison results of colour changes (ΔE) based on material, surface treatment, and staining agent groups.

Material	Staining agent	Surface Finish		Total
		Glazed	Polished	
LGC	**Tea**	4.3 ± 0.52	4.57 ± 0.67	4.43 ± 0.41
	Coffee	5.4 ± 0.55	5.12 ± 0.56	5.28 ± 0.37
	Heated tobacco	6.8 ± 1.13	3.63 ± 0.38	4.71 ± 0.52
	Total	5.22 ± 0.34^{ABC}	4.36 ± 0.33^{A}	4.79 ± 0.23
3Y-TZP	**Tea**	3.42 ± 0.53	6.34 ± 0.74	4.74 ± 0.5
	Coffee	4.73 ± 0.69	8.74 ± 0.64	6.72 ± 0.54
	Heated tobacco	5.23 ± 0.67	3.92 ± 0.83	4.56 ± 0.54
	Total	4.43 ± 0.38^{AB}	6.5 ± 0.56^{C}	5.34 ± 0.35
5Y-TZP	**Tea**	4.19 ± 0.76	5.64 ± 0.59	4.91 ± 0.48
	Coffee	4.76 ± 0.41	6.11 ± 0.39	5.49 ± 0.32
	Heated tobacco	5.64 ± 0.88	5.06 ± 0.51	5.28 ± 0.41
	Total	4.8 ± 0.38^{ABC}	5.64 ± 0.29^{BC}	5.25 ± 0.23
Total	**Tea**	3.9 ± 0.33^{A}	5.45 ± 0.32^{AB}	4.68 ± 0.26^{a}
	Coffee	4.99 ± 0.3^{BC}	6.62 ± 0.37^{BC}	5.75 ± 0.26^{b}
	Heated tobacco	5.75 ± 0.49^{C}	4.21 ± 0.32^{AB}	4.91 ± 0.27^{ab}
	Total	5.06 ± 0.17	5.24 ± 0.33	

Values are expressed as trimmed mean $\pm$ standard error (SE). Different lowercase letters (a, b) within the same column indicates statistically significant differences among main effects of staining agents (P < .05). Different uppercase letters (A–C) indicate statistically significant pairwise interactions between ceramic materials, surface treatments, and staining media (P < .05). All calculated ΔE values exceeded the clinical acceptability threshold (ΔE > 3.7).

Robust three-way ANOVA revealed that while the main effects of ceramic material (Q = 1.442, P = 0.500) and surface treatment (Q = 3.319, P = 0.071) were not statistically significant on their own, the main effect of the chromogenic agent was statistically significant (Q = 12.360, P = 0.003) (Table 2). Furthermore, two-way interaction effects were statistically significant for both Material X Surface Treatment (Q = 16.990, P = 0.001) and Surface Treatment X Chromogenic Agent (Q = 25.814, P = 0.001). The three-way interaction (Material X Surface Treatment X Chromogenic Agent) did not reach statistical significance (Q = 4.431, P = 0.372) (Table 2).

Regarding the main effect of chromogenic exposure, overall coffee immersion induced the most severe colour alteration across all evaluated specimens (5.75 ± 0.26), which was significantly higher than that induced by black tea (4.68 ± 0.26) ($P < 0.05$). Tobacco smoke exposure resulted in an intermediate overall discoloration level (4.91 ± 0.27), which did not differ significantly from tea or coffee as a main effect ($P > 0.05$) (Table 3). Across ceramic types, overall trimmed mean ΔE values were 4.79 ± 0.23 for LGC, 5.34 ± 0.35 for 3Y-TZP, and 5.25 ± 0.23 for 5Y-TZP, with no significant overall material-driven difference ($P = 0.500$) (Table 3).

The significant Material X Surface Treatment interaction ($P = 0.001$) highlighted contrasting behaviour between glass-ceramic and translucent zirconia. For LGC, manually polished specimens maintained a lower overall mean colour shift (4.36 ± 0.33) compared to glazed specimens (5.22 ± 0.34). Conversely, for 3Y-TZP, manual polishing resulted in significantly greater overall colour vulnerability (6.50 ± 0.56) compared to glazing (4.43 ± 0.38) ($P < 0.05$). For 5Y-TZP, overall differences between glazed (4.80 ± 0.38) and manually polished (5.64 ± 0.29) subgroups remained statistically comparable ($P > 0.05$). Similarly, the significant Surface Treatment X Chromogenic Agent interaction ($P = 0.001$) demonstrated that manual polishing generally increased discoloration under tea and coffee immersion, culminating in the highest overall interaction mean under coffee combined with polishing (6.62 ± 0.37), whereas glazed surfaces accumulated greater discoloration under tobacco smoke exposure (5.75 ± 0.49) than polished surfaces (4.21 ± 0.32).

Although the three-way interaction ($P = 0.372$) and the two-way Material X Staining Agent interaction ($P = 0.109$) were statistically non-significant, notable numerical trends were observed within specific subgroups that warrant clinical consideration. Under tobacco smoke exposure, glazed LGC specimens exhibited a numerically higher mean discoloration (ΔE = 6.80 ± 1.13) compared to manually polished LGC specimens (ΔE = 3.63 ± 0.38), displaying an almost twofold increase in stain retention on glazed glass-ceramic surfaces despite lacking pairwise statistical significance. Furthermore, manually polished 3Y-TZP exposed to coffee demonstrated a substantially higher numerical colour shift (ΔE = 8.74 ± 0.64) compared to glazed 3Y-TZP (ΔE = 4.73 ± 0.69), representing the highest absolute discoloration value observed across all experimental conditions. In contrast, surface treatment variations in 5Y-TZP did not produce distinct numerical or statistical variations across media, maintaining relatively stable discoloration patterns between glazed (4.80 ± 0.38) and polished (5.64 ± 0.29) subgroups.

Discussion

The present study evaluated the chromatic stability of glazed and manually polished LGC, 3Y-TZP and 5Y-TZP materials exposed to traditional chromogenic beverages or tobacco smoke following aging simulation. The results demonstrated that while the main effects of ceramic material ($Q = 1.442$, $P = 0.298$) and surface finishing ($Q = 3.319$, $P = 0.273$) were not statistically significant on their own, the main effect of the chromogenic agent was statistically significant ($Q = 12.360$, $P = 0.003$). Furthermore, significant two-way interactions were identified for Material X Surface Treatment ($Q = 16.990$, $P = 0.001$) and Surface Treatment X Chromogenic Agent ($Q = 25.814$, $P = 0.001$). Based on these findings:

The first null hypothesis, that surface finishing method would have no effect on the colour stability, was partially rejected, as polished 3Y-TZP exhibited significantly higher overall discoloration (ΔE = 6.5 ± 0.56) than 3Y-TZP (ΔE = 4.43 ± 0.38), particularly under coffee immersion (ΔE = 8.74 ± 0.64), whereas no statistically significant differences were found between polished and glazed 5Y-TZP or LGC groups.

The second null hypothesis, that material composition would have no effect on the colour, was rejected. Although material composition alone did not yield significant differences, it significantly modulated discoloration when interacting with specific surface treatments and staining agents ($P = 0.001$).

Finally, the third null hypothesis was partially rejected, as coffee immersion induced significantly higher overall discoloration (ΔE = 5.75 ± 0.26) than black tea (ΔE = 4.68 ± 0.26) ($P < 0.05$) and tobacco smoke (ΔE = 4.91 ± 0.27). Importantly, all evaluated experimental subgroups exhibited colour shifts exceeding the clinical acceptability threshold (ΔE > 3.7), confirming that both immersion in chromogenic agents and exposure to tobacco smoke pose a substantial risk to long-term aesthetic success.[1,5,23]

Regarding the main effect of chromogenic exposure, coffee consistently demonstrated the highest staining potential across all tested ceramic substrates ($P < 0.05$), reaching a peak in polished 3Y-TZP (ΔE = 8.74 ± 0.64). This aggressive discoloration aligns with the findings of Haralur et al.[17], who identified coffee as the most aggressive staining agent among traditional beverages. This can be explained by the presence of low molecular weight yellow pigments in coffee, which exhibit a high affinity for surface-modified ceramics after thermal aging, coupled with its relatively lower pH, which may promote superficial degradation.[24] In contrast, black tea yielded the lowest overall discoloration (ΔE = 4.68 ± 0.26). This discrepancy can be attributed to the different molecular sizes and polarities of the colorants; tea's larger tannic acid molecules primarily adsorb onto the outer surface, whereas coffee's smaller chromogenic molecules penetrate more deeply into micro-porosities created by thermal stress and mechanical finishing protocols.[25] Tobacco smoke resulted in an intermediate overall discoloration level (ΔE = 4.91 ± 0.27). Unlike aqueous solutions that rely on liquid absorption, tobacco smoke imparts staining via airborne deposition of sticky tar, polycyclic aromatic hydrocarbons, and combustion byproducts.[23,25] Consequently, the synergistic effect of thermal aging and the high pigment density of coffee appear to represent the most challenging scenario for the long-term colour stability of both LGC and zirconia restorations.

In the present study, all specimens were subjected to thermal cycling prior to immersion or smoke exposure to simulate the dynamic intraoral temperature changes over a one-year service period. Thermal cycling is well known to induce repetitive thermal expansion and contraction stresses that can gradually deteriorate the superficial matrix and surface quality of monolithic ceramics, making them inherently more vulnerable to extrinsic staining agents.[1,17] These thermal stresses induce micro-structural alterations, micro-fissures, and surface degradation that significantly lower the surface energy barrier, thereby facilitating the deep penetration and entrapment of staining chromogens during subsequent immersion or smoke exposure protocols.[1,17]

There are reports indicating that both material composition and surface finishing significantly influence the optical stability of dental ceramics.[14–17,26] Producing a smooth surface on a restoration either by polishing or glazing is one way to prolong intraoral service of a prosthesis, and reduce its plaque accumulation.[26,27] Although glazed surfaces have been associated with smoother topographies, clinical and laboratory studies show that glaze layers may wear or micro-fracture over time, potentially altering surface energy and stain susceptibility.[28,29] In contrast, well-polished zirconia surfaces, when finished with appropriate protocols, can maintain colour stability over extended periods.[26,29] In the present study, the significant interaction between material composition and surface treatment ($P = 0.001$) underscored structural differences between glass-rich and polycrystalline systems. Glazed 3Y-TZP exhibited statistically lower colour change than polished 3Y-TZP, which is in alignment with previous literature[10] and can be explained by its tetragonal-dominant microstructure and lower translucency, which can accentuate pigment retention when unsealed by glaze.[30] Conversely, for LGC, manually polished specimens exhibited lower overall discoloration ($\Delta E = 4.36 \pm 0.33$) than glazed specimens ($\Delta E = 5.22 \pm 0.34$), contrasting with studies on feldspathic ceramics where glazing yielded lower colour change than polishing.[31] This suggests that meticulous mechanical polishing of leucite-reinforced glass-ceramics removes the vitreous surface glaze that might otherwise undergo micro-corrosion or trap airborne particulates.

The significant Surface Treatment X Chromogenic Agent interaction ($P = 0.001$) revealed distinct deposition dynamics under tobacco smoke exposure compared to liquid immersion. Under liquid immersion (tea and coffee), mechanical polishing generally increased discoloration compared to glazing, consistent with reports by researchers demonstrating that glazed ceramics show statistically higher colour stability than mechanically polished ceramics after immersion staining.[30] This increase in staining can be explained by micro-grooves generated during manual polishing, which act as reservoirs for chromogenic liquid molecules.[10,32] In direct contrast, under tobacco smoke exposure, glazed LGC specimens accumulated a substantially higher mean discoloration ($\Delta E = 6.80 \pm 1.13$) compared to smoke-exposed polished 3Y-TZP ($\Delta E = 3.92 \pm 0.83$) and 5Y-TZP ($\Delta E = 5.06 \pm 0.51$) specimens. This finding indicates that the glass-rich matrix and silicate-based glaze layer of LGC are more prone to the physical entrapping of sticky tobacco combustion byproducts than the dense, polycrystalline structure of monolithic zirconia, supporting the findings of a previous study [24], regarding how CAD/CAM materials interact with cigarette smoke.

When evaluating cubic-containing monolithic zirconia, an interesting "translucency-stability paradox" was observed between 3Y-TZP and 5Y-TZP.[10] Monolithic zirconia manufacturers increase the yttria content (to 5 mol%) to stabilize the cubic phase and improve translucency.[5,33] However, while higher yttria content stabilizes the cubic phase and theoretically increases resistance to spontaneous phase transformation (Low Temperature Degradation - LTD), 5Y-TZP specimens in this study showed higher discoloration values in certain subgroups than 3Y-TZP. This paradox can be attributed to the larger grain size inherently present in cubic 5Y-TZP microstructures.[10] During simulated thermal aging, these larger

grains are more susceptible to micro-pitting, creating microscopic reservoirs for extrinsic stains.[10,32,34] Furthermore, the increased light transmission of 5Y-TZP makes surface-bound pigment deposition visually and spectrophotometrically more apparent, exacerbating the calculated ΔE values.[1,34]

Specific non-significant numerical trends observed in this study provide valuable clinical insights that warrant consideration despite lacking pairwise statistical significance ($P > 0.05$). Most notably, under tobacco smoke exposure, glazed LGC specimens exhibited a mean colour shift nearly twice as high (ΔE = 6.80 ± 1.13) as manually polished LGC specimens (ΔE = 3.63 ± 0.38). From a clinical perspective, these results indicate that for patients with high tobacco smoke exposure, 3Y-TZP restorations or meticulously polished LGC surfaces without over-glazing may offer superior aesthetic longevity compared to glazed glass-ceramic restorations.[24] Conversely, for patients with high coffee consumption receiving 3Y-TZP restorations, applying a surface glaze appears paramount, as polished 3Y-TZP subjected to coffee exhibited the highest absolute discoloration in the entire study (ΔE = 8.74 ± 0.64).[1,17]

Despite the comprehensive nature and clinical relevance of the present study, several methodological limitations should be acknowledged. First, as an in-vitro investigation, the complex dynamic conditions of the oral cavity, including the buffering and cleansing capacity of natural saliva, acquired pellicle formation, and frequent pH fluctuations induced by dietary habits, could not be fully replicated.[1,17] Furthermore, while thermal cycling effectively simulated physical aging stresses over a one-year intraoral service period, it cannot entirely capture the biochemical degradation resulting from these continuous intraoral chemical variations.[10]

A key methodological consideration of this protocol was that specimens were continuously immersed in chromogenic solutions or exposed to tobacco smoke and subsequently rinsed solely with distilled water, omitting simulated mechanical toothbrushing.[23] While daily toothbrushing represents a fundamental intraoral hygiene measure, the decision to exclude brushing was methodologically deliberate. Standardizing mechanical toothbrushing introduces multiple confounding parameters, including toothbrush bristle stiffness, toothpaste abrasivity, and variable brushing pressure, all of which can mechanically alter ceramic surface roughness and either mask or artificially accentuate pure chemical staining dynamics.[26] By omitting toothbrushing, this experimental protocol isolated the true chromatic stability of glazed and polished ceramics following thermal aging.[1,24]

In this study, colour changes were evaluated using the classical CIELAB (ΔE) formula to allow direct comparison with existing literature. However, the absence of CIEDE2000 calculations and quantitative surface roughness analysis (e.g., profilometry or SEM) represent limitations of this study.

Finally, while certain observational trends provided valuable clinical insights despite lacking pairwise statistical significance ($P > 0.05$), the statistical power to detect smaller effect sizes may have been constrained by the defined sample size. Consequently, these observed patterns might exhibit variability across different ceramic formulations, shades, or manufacturer-specific sintering protocols.[5,34] Acknowledging these inherent variables is essential for a balanced interpretation of the present results

and serves as a valuable framework for guiding future clinical research incorporating dynamic intraoral aging and mechanical hygiene protocols.

Conclusion

Within the limitations of this study, it can be concluded that while material type and finishing method alone did not determine colour stability, their interaction with specific staining agents is critical. Coffee remains the most detrimental agent for all materials, particularly for polished 3Y-TZP. For patients with high tobacco or coffee consumption, glazed zirconia restorations appear to provide better long-term aesthetic reliability.

Abbreviations

LGC
Leucite–reinforced glass ceramic
Y
TZP–Yttria stabilized tetragonal zirconia

Declarations

Ethics approval and consent to participate – Not applicable

Consent for publication - Not applicable

Availability of data and materials – The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests - The authors declare that they have no competing interests

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Author contributions – All authors contributed to the study conception and methodology. Material preparation, investigation, data curation, formal analysis and writing-original draft were performed by MKAA. Supervision, funding acquisition, resources and writing-review & editing were performed by AKB. All authors read and approved the final manuscript.

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Figures

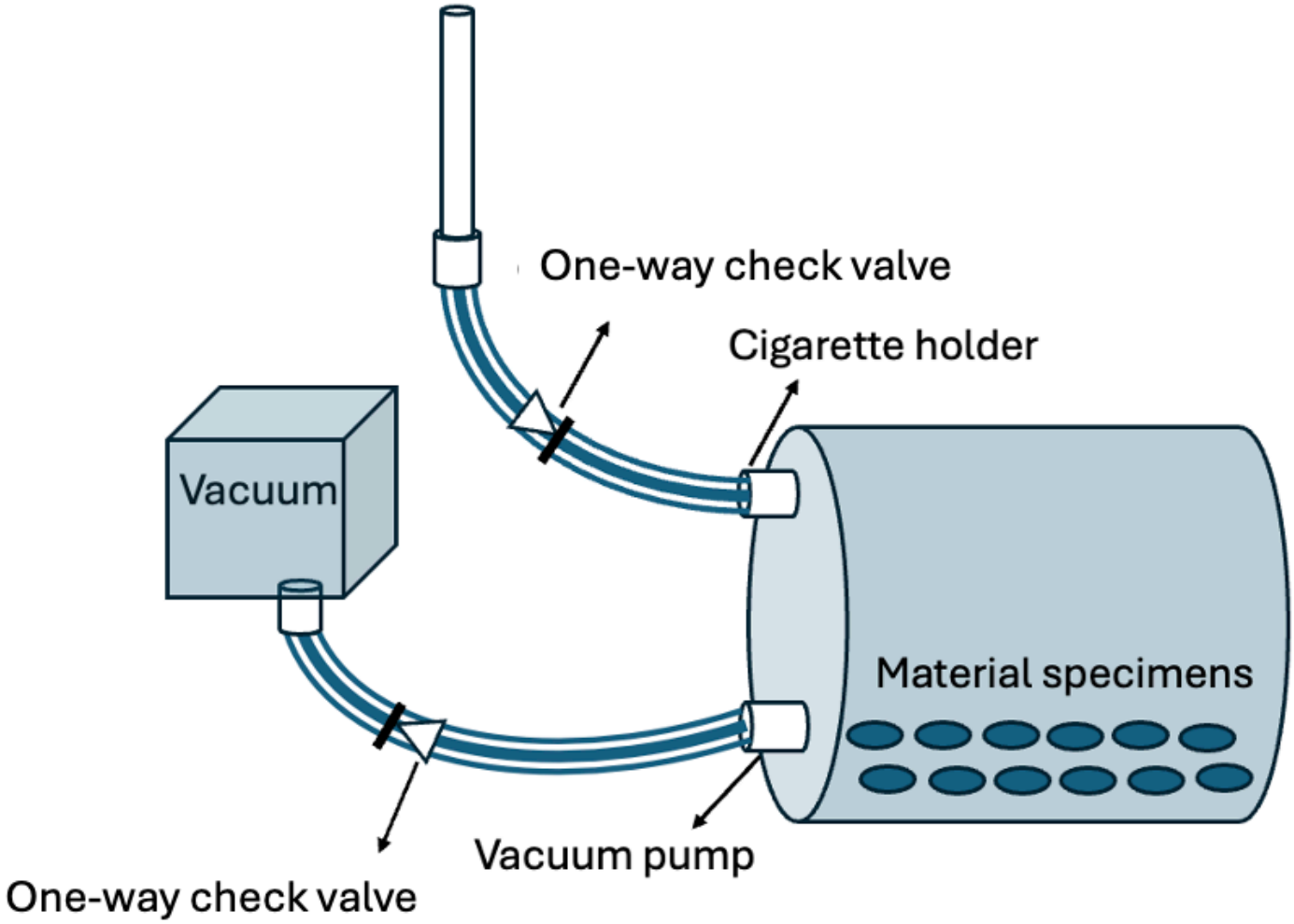

Figure 1

Schematic illustration of the custom-made smoking apparatus

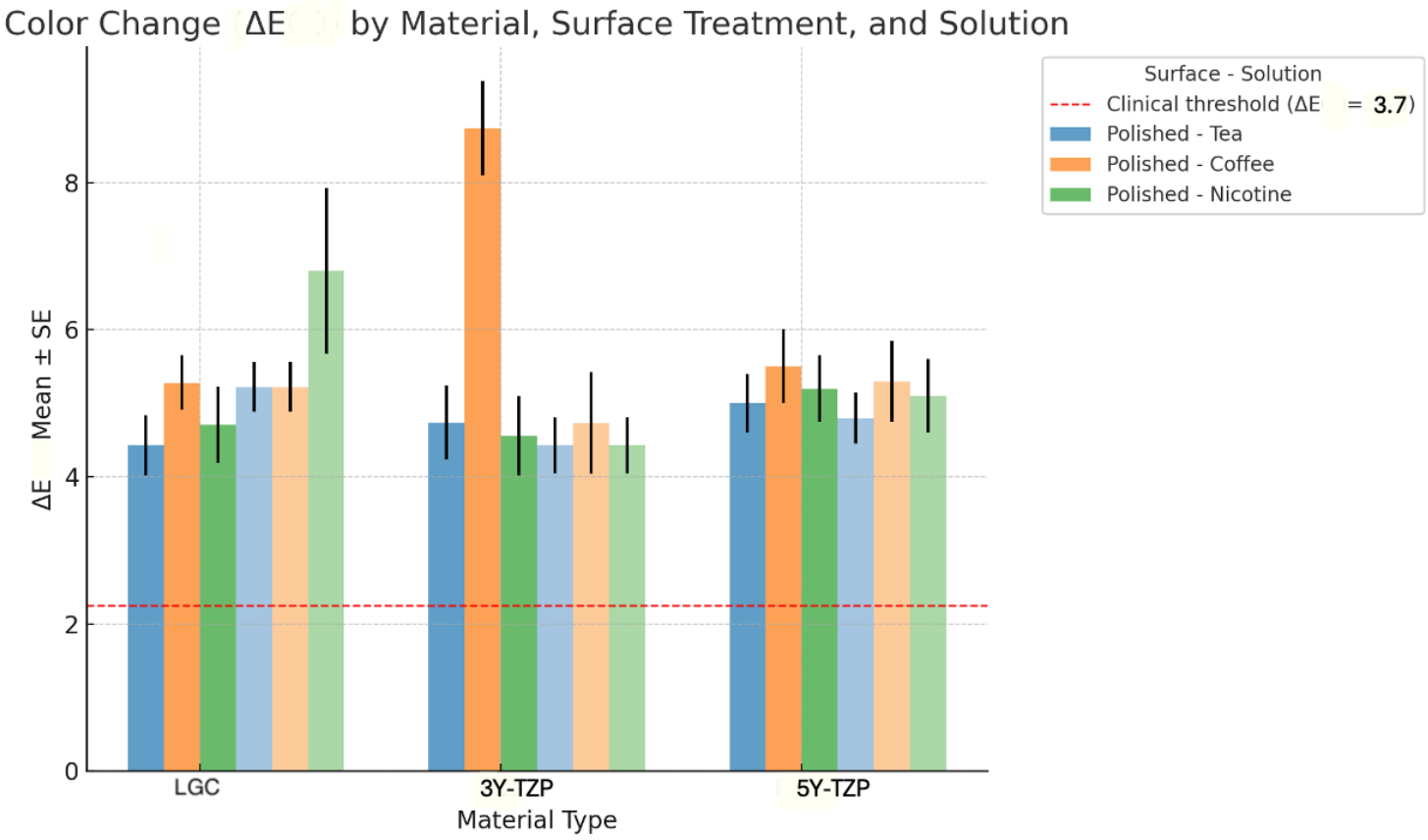

Figure 2

Colour change (ΔE) values across different materials and surface finishing methods after exposure to staining agents. The dashed horizontal line represents the clinical acceptability threshold (ΔE=3.7)