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Original Article

Effects of various aging modes on the optical properties of zirconia with different yttria concentrations in coffee and tea

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Abstract *Background/purpose:* The esthetic performance of dental zirconia may be affected by both material composition and environmental exposure. This study aimed to evaluate how different aging conditions-hydrothermal aging and thermal cycling-influenced the optical properties of dental zirconia containing varying yttria concentrations (3Y-TZP, 4Y-TZP, and 5Y-TZP) in coffee and tea.
Materials and methods: A total of 120 zirconia specimens were prepared using three yttria concentrations. Each group was subjected to four artificial aging conditions: storage in coffee or tea at 37 °C for 1 and 6 months (hydrothermal aging), or 10,000 and 50,000 cycles of thermal cycling between 5 °C and 55 °C. Optical parameters (L^*, $a*$, $b*$) and color differences (ΔE_{00}) were measured using a spectrophotometer and calculated using the CIEDE2000 formula. Data were analyzed using ANOVA and Tukey's HSD test ($\alpha = 0.05$).
Results: Zirconia with higher yttria content exhibited more pronounced color changes ($P < 0.001$). Aging in tea resulted in minimal color variation regardless of yttria content or aging mode. In coffee, the ΔE_{00} values of the HT (3Y-TZP), ST (4Y-TZP), and XT (5Y-TZP) groups ranged from 3.5, 7.0 and 8.5, respectively ($P < 0.0001$). In tea, the values ranged from 1.1 for both HT and ST, and from 3.1 for XT ($P < 0.0001$).
Conclusion: Both yttria concentration and aging conditions significantly influenced the color stability of zirconia. Hydrothermal aging had a greater impact than thermal cycling, especially

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in coffee. These findings suggest that material composition and exposure environment should be carefully considered when selecting zirconia for esthetic dental restorations.

Introduction

Zirconia was widely used in the field of dental restorations due to its excellent mechanical strength, biocompatibility, and esthetic properties.[1,2] Clinically, zirconia had become the material of choice for various fixed dental prostheses, including crowns, bridges, and implant abutments.[3–5] With the increasing demand for improved esthetic outcomes in restorative dentistry, manufacturers had modified the yttria content in zirconia to enhance its translucency.[6] Increasing the yttria concentration promoted the formation of the cubic phase, thereby improving light transmittance. However, studies indicated that a higher yttria concentration compromised the mechanical strength.[7] For example, 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) exhibited flexural strength values ranging from 994 to 1024 MPa, whereas 5 mol% yttria-stabilized zirconia (5Y-TZP) showed flexural strength ranging from 668 to 675 MPa.[8] Thus, although translucency improved with increased yttria content, the trade-off was a reduction in flexural strength. Therefore, both dentists and dental technicians needed to consider the functional loading site and esthetic requirements when selecting zirconia materials for clinical applications.

In addition to the intrinsic properties of the material, environmental factors were also considered one of the major influences on the esthetic characteristics of restorations.[9] In the human diet, colored liquids or foods-such as coffee and tea-were commonly consumed. Among them, coffee and tea were the most frequently used agents for evaluating discoloration of dental restorative materials.[10,11] Furthermore, prolonged exposure to these substances could have resulted in changes in the color of restorations.[12] Therefore, the long-term esthetic performance of zirconia might have been compromised by external factors such as dietary staining agents. Rashin Giti et al. reported the effects of sintering temperature on the color stability and translucency of various zirconia systems after immersion in coffee solutions. Their findings indicated that the type of zirconia significantly affected the extent of color change after coffee immersion.[13] However, the human oral environment was highly complex and varied among individuals due to differences in diet and lifestyle habits, which made each case unique. Therefore, it was necessary to simulate different intraoral conditions to better approximate the long-term clinical performance of zirconia materials.

In recent years, various in vitro aging protocols had been developed to simulate the complexity of the oral environment, including hydrothermal aging and thermal cycling.[14,15] These methods aimed to evaluate the mechanical and chemical changes that zirconia restorations underwent during routine exposure to beverages and temperature fluctuations. Among these, thermal cycling (hot and cold cycles) was one of the most commonly employed models for mimicking intraoral conditions.

In 2021, Samah Saker et al. reported on the color stability of polished zirconia immersed in coffee and subjected to 5000 thermal cycles between 5 °C and 55 °C.[16] The color stability and translucency of monolithic zirconia were influenced by the brand of the material, its thickness, and the nature of clinical adjustments. Additionally, the polishing process affected coffee staining on zirconia surfaces, with ΔE values ranging from 1 to 3.7. Al-Zordk et al. observed that although the color changes remained below clinically perceptible thresholds, thermal cycling in coffee did affect the color and translucency of different zirconia systems.[17] Similarly, Alnassar et al. reported that coffee caused significantly more discoloration of monolithic zirconia than other tested substances, including protein shakes, mouthwash, and soft drinks.[18] Despite these findings, long-term aging tests under constant temperature conditions remained limited and required further investigation. Although interest in esthetic ceramics had grown substantially, few studies had directly compared how different aging conditions influenced the optical behavior of zirconia with varying yttria concentrations. In addition, the pursuit of aesthetic outcomes and high-translucency zirconia needed to be balanced with considerations of its long-term performance following extended use.

Therefore, the purpose of this study was to evaluate the differences in optical properties of dental zirconia containing 3 mol%, 4 mol%, and 5 mol% yttria under two aging conditions: hydrothermal aging and thermal cycling. The color coordinates (L∗, a∗, b∗) were measured, and the color differences (ΔE_{00}) were calculated using the CIEDE2000 formula. This study aimed to investigate how yttria concentration and aging mode affected the esthetic durability of zirconia. The findings were expected to provide clinical dentists and dental technicians with a reference for selecting suitable zirconia materials. The hypothesis of this study was that zirconia with different yttria concentrations would exhibit significant color differences under the two aging protocols.

Materials and methods

This study compared three types of dental zirconia containing 3 mol%, 4 mol%, and 5 mol% yttria concentrations (Table 1). All zirconia materials were obtained from the same manufacturer to minimize variability between different brands (VITA, Bad Säckingen, Germany). A low-speed cutter (CL40, Top Tech, Taichung, Taiwan) was used to section the zirconia into specimens measuring $10 \times 10 \times 1.5$ mm^3 at a speed of 150 rpm. Because zirconia

Table 1 The composition and nomenclature of the zirconium oxide samples used in this study.

Code	HT	ST	XT
Name	VITA YZ HT	VITA YZ ST	VITA YZ XT
Color	Pure White		
Manufacturer	VITA, Bad Säkingen, Germany		
Type	3Y-TZP	4Y-TZP	5Y-TZP
Composition	ZrO_2 (90–95 %), Y_2O_3 (4–6 %), HfO_3 (1–3 %), Al_2O_3 (0–1 %) and pigments (0–1 %).	ZrO_2 (88–93 %), Y_2O_3 (6–8 %), HfO_3 (1–3 %), Al_2O_3 (0–1 %) and pigments (0–1 %).	ZrO_2 (86–91 %), Y_2O_3 (8–10 %), HfO_3 (1–3 %), Al_2O_3 (0–1 %) and pigments (0–1 %).
3-Point flexural strength (Mpa)	1200	850	600

3Y-TZP: 3 mol% yttria-stabilized tetragonal zirconia polycrystal.
4Y-TZP: 4 mol% yttria-stabilized tetragonal zirconia polycrystal.
5Y-TZP: 5 mol% yttria-stabilized tetragonal zirconia polycrystal.

shrinks during sintering, each sample was enlarged by approximately 16 % (to 11.6 × 11.6 × 1.74 mm^3) before sintering, following the manufacturer's instructions, to ensure the final dimensions were accurate. After sectioning, the specimens were polished and dimensionally adjusted using silicon carbide papers of varying grits (600, 800, 1200, and 2000).[19] Finally, the thickness (±0.05 mm) was confirmed at five different locations on each sample using Vernier calipers. Following sectioning, the zirconia specimens were sintered in a ceramic furnace (6100MS, VITA) according to the manufacturer's recommended parameters, at temperatures ranging from 1450 °C to 1530 °C for approximately 6 h. The surfaces were then cleaned with deionized water to complete the specimen preparation.

Commercially available sugar-free coffee (UCC BLACK, UCC Ueshima Coffee, Kobe, Japan) and Every Morning Green Tea (Uni-President Enterprises, Tainan, Taiwan) were used as the aging media in this study. Each specimen was immersed in 5 mL of either coffee or tea solution, placed in a 15 mL centrifuge tube, and subjected to different aging conditions. The solution was refreshed every seven days. For the hydrothermal aging condition, centrifuge tubes containing the specimens were stored at 37 °C for one and six months to simulate the intraoral thermal environment and its staining effects on zirconia. In the thermal cycling, specimens were immersed alternately in water baths at 5 °C and 55 °C using a dual-chamber thermal shock machine (TBN-971105, TEN Billion, Tainan, Taiwan).[20] Each temperature was maintained for 30 s, with a 5-s transition interval. The thermal cycling was repeated 10,000 times and 50,000 times to simulate approximately one year and five years of temperature changes caused by food and beverage consumption. In total, this study used three types of zirconia, two types of aging solutions, and four aging conditions. Five specimens were prepared for each condition, resulting in a total of 120 zirconia samples (Fig. 1).

The optical properties of the dental zirconia samples were analyzed using a VITA Easyshade colorimeter (VITA Easyshade Compact, VITA).[21] Each specimen was placed on a standardized black background for color measurement. All samples were measured individually, and the average was calculated. The color coordinates L∗ (lightness), a∗ (red-green), and b∗ (yellow-blue) were recorded. The color difference (ΔE_{00}) from the original zirconia shade was then calculated using the CIEDE2000 formula (1):[22,23]

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{K_C S_C}\right)\left(\frac{\Delta H'}{K_H S_H}\right)\right]^{\frac{1}{2}} \quad \text{formula}(1)$$

The sample size calculation was conducted using G∗ Power software (version 3.1.9.6; Heinrich Heine University, Düsseldorf), which indicated that five specimens per factor combination in the zirconia groups were sufficient to detect the expected differences with a statistical power of 0.80 and a significance level of 0.05. For clinical application analysis, data were collected from three patients. Statistical analyses were performed using JMP 16 software (SAS Institute, Cary, NC, USA). A one-way analysis of variance (ANOVA) followed by Tukey's honest significant difference (HSD) post-hoc test was applied to assess differences between groups, with statistical significance defined at $P < 0.05$.

Results

The initial optical values of the three zirconia materials used in this study are presented in Table 2. The L∗ values ranged from 94.2 ± 0.1 to 100.0 ± 0.1, the a∗ values ranged from 0.6 ± 0.1 to 2.8 ± 0.1, and the b∗ values ranged from 5.7 ± 0.1 to 11.0 ± 0.1.

After undergoing different aging conditions in coffee, the L∗ values of the HT, ST, and XT samples ranged from 96.1 ± 0.1 to 100.0 ± 0.1, 89.5 ± 0.3 to 100.0 ± 0.1, and 84.4 ± 1.0 to 91.7 ± 0.2, respectively ($P < 0.0001$) (Table 3). In tea, the L∗ values of the HT, ST, and XT samples ranged from 99.5 ± 0.2 to 100.0 ± 0.1, 97.6 ± 0.2 to 99.1 ± 0.1, and 92.1 ± 0.5 to 94.9 ± 0.2, respectively ($P < 0.0001$).

Table 4 also shows the a∗ values after coffee aging for the HT, ST, and XT samples, which ranged from 0.5 ± 0.1 to 0.8 ± 0.0, 1.6 ± 0.2 to 2.0 ± 0.0, and 1.5 ± 0.1 to 2.8 ± 0.2, respectively ($P < 0.0001$). In tea, the a∗ values ranged from 0.1 ± 0.1 to 0.9 ± 0.1 for HT, 1.6 ± 0.1 to 1.9 ± 0.1 for ST, and 1.2 ± 0.1 to 2.8 ± 0.1 for XT ($P < 0.0001$).

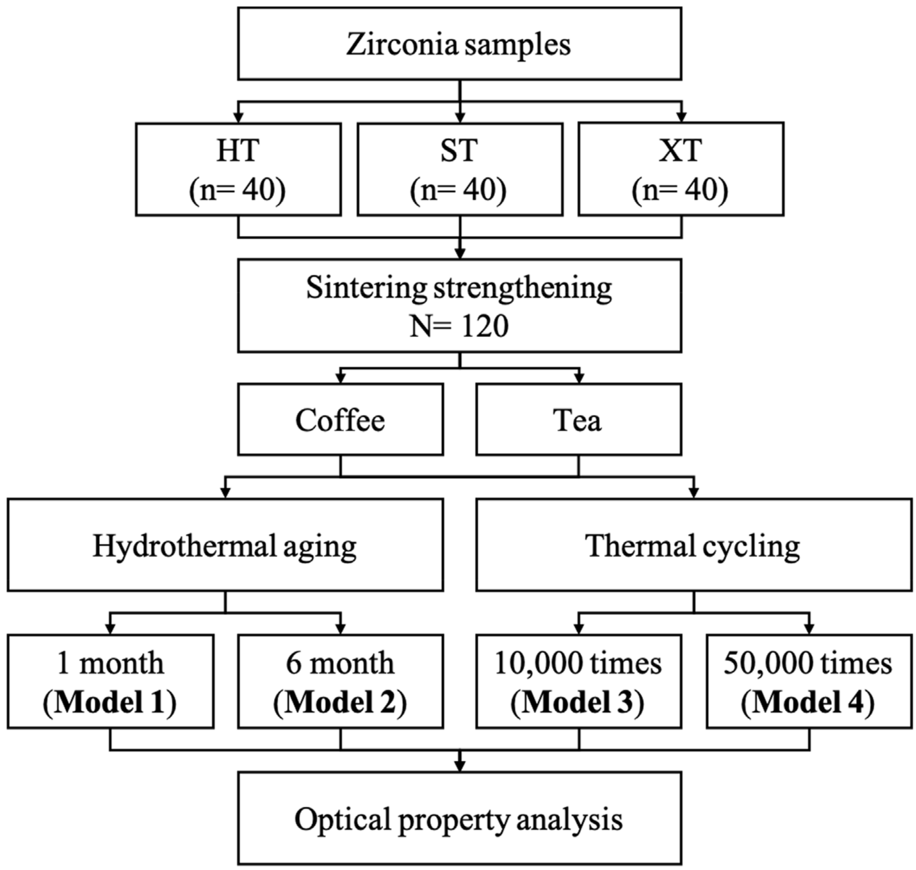

Figure 1 Overview of experimental procedures and sample grouping. HT: VITA YZ HT (3Y-TZP). ST: VITA YZ ST (4Y-TZP). XT: VITA YZ XT (5Y-TZP). Model 1: Hydrothermal aging for 1 month (37 °C). Model 2: Hydrothermal aging for 6 months (37 °C). Model 3: Thermal cycling 10,000 times (5 °C–55 °C). Model 4: Thermal cycling 50,000 times (5 °C–55 °C).

Table 2 The raw optical values of different zirconia samples.

Group	L* Mean (SD)	a* Mean (SD)	b* Mean (SD)
HT	100.0 (±0.1)	0.6 (±0.1)	11.0 (±0.1)
ST	98.9 (±0.1)	1.9 (±0.1)	8.3 (±0.1)
XT	94.2 (±0.1)	2.8 (±0.1)	5.7 (±0.1)

HT: VITA YZ HT (3Y-TZP).
ST: VITA YZ ST (4Y-TZP).
XT: VITA YZ XT (5Y-TZP).

As shown in Table 5, the b* values of the HT, ST, and XT samples after aging in coffee ranged from 10.1 ± 0.1 to 15.2 ± 0.6, 8.3 ± 0.2 to 14.2 ± 0.4, and 5.3 ± 0.5 to 13.2 ± 0.9, respectively ($P < 0.0001$). In tea, the b* values ranged from 11.0 ± 0.1 to 12.3 ± 0.1 for HT, 8.7 ± 0.2 to 9.6 ± 0.2 for ST, and 6.5 ± 0.2 to 10.8 ± 0.2 for XT ($P < 0.0001$).

The color differences (ΔE_{00}) of the HT, ST, and XT groups in coffee ranged from 3.5 ± 0.3, 7.0 ± 0.4, and 8.5 ± 0.5, respectively ($P < 0.0001$) (Fig. 2A). In tea, the ΔE_{00} values ranged from 1.1 ± 0.1 for both HT and ST from 3.1 ± 0.4 for XT ($P < 0.0001$) (Fig. 2B).

Discussion

This study investigated the effects of hydrothermal aging and thermal cycling on the optical properties of dental zirconia with different yttria concentrations (3Y-TZP, 4Y-TZP, and 5Y-TZP). The results indicated that both aging conditions and yttria content significantly affected color changes. Therefore, the null hypothesis was not rejected.

Among the three zirconia materials, the greatest difference in baseline optical values was observed in the b* parameter, suggesting a shift toward a bluish tone with increasing yttria concentration (Table 2).[21] After aging, comparisons of L* values among all groups showed a noticeable decrease under the hydrothermal aging protocol, indicating a reduction in brightness (Table 3).[24] In coffee immersion, the brightness decreased by 3.9 % (HT), 9.5 % (ST), and 10.4 % (XT), respectively. In contrast, tea immersion resulted in minimal brightness changes, ranging from approximately 0.1 %–1.5 %. A similar trend was also observed in the a* values across all samples (Table 4). However, the b* values increased as the yttria content rose to 4 % and 5 % (Table 5), indicating a shift toward a more yellowish appearance after immersion.[25]

Table 3 The L* values of zirconium oxide samples subjected to different aging modes in coffee and tea.

Group		Model 1	Model 2	Model 3	Model 4	*P* value
Coffee mean (SD)	HT	99.5 (±0.2)	96.1 (±0.1)	100.0 (±0.1)	100.0 (±0.1)	<0.0001
	ST	97.2 (±0.2)	89.5 (±0.3)	100.0 (±0.1)	98.4 (±0.4)	<0.0001
	XT	90.9 (±0.2)	84.4 (±1.0)	90.1 (±0.1)	91.7 (±0.2)	<0.0001
Tea Mean (SD)	HT	100.0 (±0.1)	99.5 (±0.2)	100.0 (±0.1)	100.0 (±0.1)	<0.0001
	ST	97.8 (±0.1)	97.6 (±0.2)	99.1 (±0.1)	98.6 (±0.0)	<0.0001
	XT	94.2 (±0.2)	94.1 (±0.1)	94.9 (±0.2)	92.1 (±0.5)	<0.0001
P value		<0.0001	<0.0001	<0.0001	<0.0001	

HT: VITA YZ HT (3Y-TZP).
ST: VITA YZ ST (4Y-TZP).
XT: VITA YZ XT (5Y-TZP).
Model 1: Hydrothermal aging for 1 month (37 °C).
Model 2: Hydrothermal aging for 6 months (37 °C).
Model 3: Thermal cycling 10,000 times (5 °C—55 °C).
Model 4: Thermal cycling 50,000 times (5 °C—55 °C).
SD: Standard deviation.
**P* =Indicates significant difference ($P < 0.05$).

Table 4 The a* values of zirconium oxide samples subjected to different aging modes in coffee and tea.

Group		Model 1	Model 2	Model 3	Model 4	*P* value
Coffee mean (SD)	HT	0.6 (±0.1)	0.7 (±0.1)	0.8 (±0.0)	0.5 (±0.1)	0.6127
	ST	2.0 (±0.0)	1.6 (±0.2)	1.8 (±0.1)	1.7 (±0.1)	0.0722
	XT	2.8 (±0.2)	1.8 (±0.1)	2.2 (±0.1)	1.5 (±0.1)	0.0020
Tea Mean (SD)	HT	0.1 (±0.1)	0.4 (±0.1)	0.9 (±0.1)	0.5 (±0.1)	<0.0001
	ST	1.9 (±0.1)	1.6 (±0.1)	1.8 (±0.1)	1.8 (±0.1)	0.0110
	XT	2.4 (±0.1)	2.5 (±0.1)	2.8 (±0.1)	1.2 (±0.1)	<0.0001
P value		<0.0001	<0.0005	<0.0001	<0.0001	

HT: VITA YZ HT (3Y-TZP).
ST: VITA YZ ST (4Y-TZP).
XT: VITA YZ XT (5Y-TZP).
Model 1: Hydrothermal aging for 1 month (37 °C).
Model 2: Hydrothermal aging for 6 months (37 °C).
Model 3: Thermal cycling 10,000 times (5 °C—55 °C).
Model 4: Thermal cycling 50,000 times (5 °C—55 °C).
SD: Standard deviation.
**P* =Indicates significant difference ($P < 0.05$).

Table 5 The b* values of zirconium oxide samples subjected to different aging modes in coffee and tea.

Group		Model 1	Model 2	Model 3	Model 4	*P* value
Coffee mean (SD)	HT	11.6 (±0.2)	15.2 (±0.6)	10.1 (±0.1)	11.9 (±0.1)	<0.0001
	ST	8.23 (±0.2)	14.2 (±0.4)	8.9 (±0.2)	9.1 (±0.2)	<0.0001
	XT	5.3 (±0.5)	13.2 (±0.9)	8.3 (±0.2)	9.8 (±0.1)	<0.0001
Tea Mean (SD)	HT	12.3 (±0.1)	12.1 (±0.1)	11.0 (±0.1)	11.7 (±0.1)	<0.0001
	ST	9.6 (±0.2)	9.1 (±0.2)	8.7 (±0.1)	8.8 (±0.1)	0.0006
	XT	7.2 (±0.1)	7.1 (±0.1)	6.5 (±0.2)	10.8 (±0.2)	<0.0001
P value		<0.0001	<0.0001	<0.0001	<0.0001	

HT: VITA YZ HT (3Y-TZP).
ST: VITA YZ ST (4Y-TZP).
XT: VITA YZ XT (5Y-TZP).
Model 1: Hydrothermal aging for 1 month (37 °C).
Model 2: Hydrothermal aging for 6 months (37 °C).
Model 3: Thermal cycling 10,000 times (5 °C—55 °C).
Model 4: Thermal cycling 50,000 times (5 °C—55 °C).
SD: Standard deviation.
**P* =Indicates significant difference ($P < 0.05$).

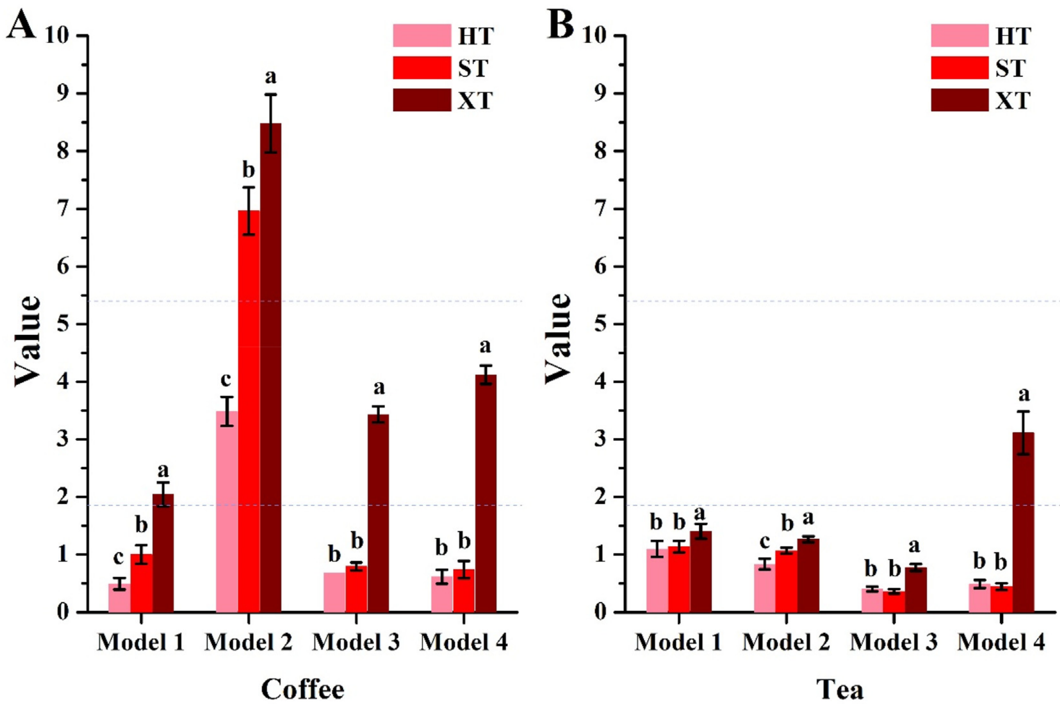

Figure 2 Color difference (ΔE_{00}) of zirconium oxide after various aging modes. (A) In coffee solution. (B) In tea solution. Different lowercase letters indicate significant differences between groups ($P < 0.05$, mean ± SD, n = 10). The dashed line represents values ranging from 2.6 to 5.5. HT: VITA YZ HT (3Y-TZP). ST: VITA YZ ST (4Y-TZP). XT: VITA YZ XT (5Y-TZP). Model 1: Hydrothermal aging for 1 month (37 °C). Model 2: Hydrothermal aging for 6 months (37 °C). Model 3: Thermal cycling 10,000 times (5 °C—55 °C). Model 4: Thermal cycling 50,000 times (5 °C—55 °C).

Tooth color was represented within a three-dimensional color space composed of L∗, a∗, and b∗ coordinates.[26] The color difference between two points was evaluated by calculating the distance between them, expressed as the ΔE_{00} value.[27] In this study, the color difference after aging was assessed based on the original zirconia values as reference (Fig. 2). Among the three types of zirconia, the 3Y-TZP group (HT) exhibited the most stable color behavior under all aging conditions. The L∗ values of the HT group remained consistently high, and its ΔE_{00} values stayed within or close to the clinically acceptable threshold (1.8—5.4).[28] In contrast, the 5Y-TZP group (XT) showed more pronounced color changes. After six months of hydrothermal aging in coffee solution, the ST (6.9 ± 0.4) and XT (8.4 ± 0.5) groups exceeded the clinically acceptable range, whereas the other groups remained within acceptable limits. For tea immersion, the ΔE_{00} values for all zirconia types ranged from 0.4 ± 0.1 to 3.1 ± 0.4, remaining within clinically acceptable levels. This indicated that coffee adhered more strongly to the zirconia surface compared to tea. According to Soyeon Kim et al. tea contains catechins and theaflavins, and the staining observed on tooth surfaces was mainly caused by the adhesion of theaflavins, leading to changes in color.[29] For coffee, the staining effect was not limited to surface adhesion alone. Previous studies suggested that coffee contains tannins and chlorogenic acid, which contribute to discoloration. Moreover, the low pH of coffee could further accelerate the staining process.[30] These factors were likely the main contributors to the pronounced color changes observed in the coffee group, particularly as the hydrothermal aging period increased from one to six months.

The aging protocols revealed that hydrothermal aging had a greater effect on color change than thermal cycling, but only in the coffee group. In contrast, for the tea group, neither the aging protocol nor immersion duration produced significant differences within the same zirconia type. These findings suggested that the staining behavior on zirconia surfaces varied depending on the simulated aging model and the type of staining agent. Although all tested materials exhibited some degree of color change, the extent of discoloration depended on both the material composition and the aging condition.

Previous studies indicated that zirconia underwent low-temperature degradation (LTD) when exposed to humid environments.[31] When stored in aqueous conditions, a portion of the tetragonal grains on the zirconia surface transformed into the monoclinic phase. This phase transformation led to a volume increase, which could result in surface roughening and the formation of microcracks, ultimately compromising the material's mechanical integrity and shortening its service life.[32] It was also found that multiple factors influenced the aging behavior of zirconia, including dopant type, grain size, sintering process, yttria content, aging temperature, aging medium, and applied pressure. Kosmač et al. reported that after exposing biomedical-grade Y-TZP zirconia to artificial saliva at 37 °C for 24 h, its flexural strength decreased from approximately 1000 MPa–900 MPa.[33] These findings suggested that yttria concentration might influence the degree of low-temperature degradation, which in turn could contribute to the observed color differences. Among them, 3Y-TZP demonstrated superior color stability and may be the preferred choice for restorations in esthetically demanding regions. According to the literature, 3Y-TZP crowns with thicknesses of 1.0 mm or 1.5 mm exhibited superior compressive strength and fatigue resistance compared to those made of 5Y-TZP.[34] However, 3Y-TZP showed lower translucency than 5Y-TZP.[35] Therefore, in clinical situations with high occlusal forces or when masking the color of the underlying abutment was necessary, 3Y-TZP was still preferred for crown fabrication. As the demand for higher translucency in zirconia continues to increase, the use of dental stains has been proposed as a strategy to compensate for esthetic limitations.[36] Therefore, the evolution of zirconia materials may expand clinical options and reduce limitations for both dentists and dental technicians.

The limitations of this study included the use of flat specimens instead of clinically shaped restorations, and the possibility that in vitro conditions did not fully replicate intraoral aging. Secondly, only zirconia materials from a single manufacturer were evaluated, which may not fully represent the staining behavior of products from other brands. This study aimed to explore an aging method that closely resembled clinical outcomes. Many previous studies focused on two primary models: hydrothermal aging and thermal cycling. However, which of these approaches better reflected real-life conditions remained open to discussion. In reality, individuals were unlikely to have constant exposure to tea or coffee in their daily diet. Nevertheless, both this study and others extended the duration of exposure to amplify the staining effects of beverages on zirconia. Continuous immersion was used to simulate the long-term use of dental crowns. In addition, the immersion solutions were refreshed every seven days to ensure their effectiveness. Although this approach differed from daily oral conditions, it allowed for a clearer comparison of the staining effects of tea and coffee on zirconia.

Based on the results presented above, the increase in yttria concentration was found to enhance the susceptibility of zirconia surfaces to staining. Compared to tea, coffee produced more pronounced staining effects on zirconia. Hydrothermal aging had a greater impact on staining outcomes than thermal cycling. Therefore, clinicians and dental technicians were encouraged to consider not only the translucency of zirconia but also its color stability when selecting materials for esthetic restorations. Future studies should explore whether wear interactions between zirconia crowns and various foods influenced staining behavior. In addition, a broader range of zirconia products from different manufacturers should be included to provide more comprehensive guidance for clinical material selection.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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