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Influence of Thermocyling on Strength and Optical Stability of Zirconia Brackets

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Deaprtment of Dentistry

The Graduate School, Yonsei University

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Influence of Thermocyling on Strength and Optical Stability of Zirconia Brackets

Directed by Professor Kee-Joon Lee

A Doctoral Dissertation

Submitted to the Department of Dentistry

And the Graduate School of Yonsei University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy of Dental Science

Giap Hai Van

December 2023

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ABBREVIATIONS

Yttria-stabilized zirconia	YSZ
3 mol% yttria-stabilized tetragonal zirconia	3Y-YSZ
4 mol% yttria-stabilized tetragonal zirconia	4Y-YSZ
5 mol% yttria-stabilized tetragonal zirconia	5Y-YSZ
Intraclass correlation coefficient	ICC

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ABSTRACT

Influence of Thermocycling on Strength and Optical Stability of Zirconia Brackets

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(Directed by Professor Lee Kee-Joon, D.D.S., M.S.D, Ph.D.)

Recent advancements in the composition, structure, and fabrication techniques of zirconia material have fueled an increasing interest in employing zirconia in the manufacture of orthodontic brackets, surpassing the constraints of conventional alumina ceramic brackets. However, the performance of orthodontic appliances fabricated by these novel zirconia variants remained unclear. This *in vitro* study evaluated the performance of zirconia brackets with varying yttria proportions in the manufacture of advanced orthodontic brackets. The fracture strength and optical properties of these zirconia brackets were investigated while considering the impact of aging, as they serve as intraoral fixed appliances. These properties were compared with those of commercial polycrystalline alumina brackets.

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Three experimental groups of zirconia brackets were fabricated using yttria-stabilized zirconia (YSZ) materials with different yttria proportions—3 mol% yttria (3Y-YSZ), 4 mol% yttria (4Y-YSZ), and 5 mol% yttria (5Y-YSZ) (Tosoh Ceramic, Japan). The control group consisted of a commercial polycrystalline alumina ceramic bracket (3M™ Clarity™ Advanced, MBT 0.022-inch slot). An artificial aging process was implemented through 20,000 cycles of thermocycling, simulating two years of clinical use within the oral cavity, aligning with the recognized average duration of orthodontic treatment. Fracture strength of bracket tie wings was examined through tensile tests conducted before and after thermocycling. Baseline optical properties, including color and translucency, were assessed, and optical stability was tested after thermocycling and immersion for seven days in various coloring agents.

In this study, artificial aging appeared to have an insignificant effect on the fracture strength of the brackets. Among the groups, the 3Y-YSZ group presented the highest fracture strength of the bracket tie wing, followed by the control group ($p<0.05$). No significant difference in the fracture strength of the bracket tie wing was observed between the 4Y-YSZ and 5Y-YSZ groups. Despite exceeding other experimental groups in translucency, the 5Y-YSZ group remained inferior to the control group ($p < 0.05$). Overall, the zirconia brackets demonstrated favorable optical stability.

Within the limitations of this study, zirconia brackets containing 3 to 5 mol% YSZ exhibited favorable stability in terms of fracture strength and optical characteristics.

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Notably, owing to its advantageous fracture strength resistance, the 3Y-YSZ variant showed remarkable potential as an advanced material for fabricating orthodontic brackets.

Keywords: Orthodontic ceramic bracket, Yttria-stabilized zirconia, Zirconia bracket, Thermocycling.

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Influence of Thermocycling on Strength and Optical Stability of Zirconia Brackets

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I. INTRODUCTION

Ceramic brackets emerged in the 1980s as a viable solution for orthodontic appliances, catering to the increasing demand for enhanced esthetics while maintaining clinical performance (Kusy, 2002). These brackets predominantly employ alumina, either in polycrystalline or monocrystalline form, depending on the manufacturing process. Despite offering aesthetic benefits, ceramic brackets present certain drawbacks, such as elevated friction resistance (FR) and diminished fracture toughness as compared to stainless-steel brackets (Cacciafesta et al., 2003; Johnson et al., 2005). These limitations often lead to challenges for orthodontists, including bracket wing fractures during clinical procedures.

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Such incidents can compromise enamel integrity and result in supplementary costs due to bracket replacement (Johnson et al., 2005). To address these limitations, various innovative approaches have been proposed to develop advanced orthodontic brackets, with zirconia emerging as a promising material for enhancing mechanical properties owing to its remarkable toughness (Namura et al., 2022; Polychronis et al., 2023).

Zirconia brackets have been the subject of orthodontic research since the 1990s (Springate et al., 1991). However, during this period, they did not demonstrate substantial improvements over alumina brackets in aspects such as frictional characteristics and aesthetic performance (Keith et al., 1994). Recent advancements in zirconia materials have led to the development of several variants, influenced by factors such as powder selection, sintering additives, heat treatment, and other processing considerations (Kontonasaki et al., 2019). Pure zirconia is composed of three main phases: monoclinic (m) at room temperature, tetragonal above 1,170 °C, and cubic above 2,370 °C (Zhang et al., 2018). While the monoclinic phase itself lacks remarkable mechanical attributes, the incorporation of dopants into the starting powder can augment strength and fracture toughness. This is achieved by partially stabilizing the tetragonal phase within the microstructure at ambient temperature (Zhang et al., 2018). Among the various dopants, yttria (Y_2O_3) stands out for its efficacy in providing a synergistic blend of robust strength and toughness, facilitating the stabilization of the tetragonal or cubic phase at room temperature (Kelly et al., 2008; Denry et al., 2008). Furthermore, yttria-stabilized zirconia (YSZ) allows for efficient

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production through computer-assisted design and fabrication (CAD/CAM) technologies. This ensures the reproduction of intricate details and lowered manufacturing costs, all while maintaining superior physical characteristics. As a result, 3 mol% yttria-stabilized tetragonal zirconia (3Y-YSZ) polycrystals have gained popularity in dental ceramics, particularly for prosthetic restorations. Recently, high-translucency partially stabilized zirconia with greater quantities of the non-birefringent cubic phase—achieved by utilizing higher yttria contents such as 4 mol% (4Y-YSZ) or 5 mol% (5Y-YSZ)—has been engineered. These innovations have notably broadened their clinical applications in terms of aesthetics (Han et al., 2017). Consequently, zirconia's emerging prominence in research and the creation of orthodontic brackets has become evident (Namura et al., 2022; Polychronis et al., 2023; Maki et al., 2016; Panayi et al., 2022; Zang et al., 2023). However, existing literature has reported a direct correlation between yttria concentration, translucency, and mechanical strength in zirconia restorations. While an increase in yttria concentration can stabilize the cubic phase, resulting in greater translucency, it may concurrently diminish the mechanical strength (Tong et al., 2016; Pekkan et al., 2020). Therefore, to achieve a balance between mechanical properties and aesthetic demands in clinical applications, it becomes imperative to explore the performance and appropriateness of zirconia brackets with different yttria concentrations. To the best of our knowledge, the information available on this subject is scarce.

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In fixed orthodontic treatment, the average duration is widely recognized to be approximately 24.9 months (Abbing et al., 2020). Given that orthodontic brackets are exposed to harsh oral conditions, maintaining the aesthetic advantages of ceramic brackets is of paramount importance. However, while aesthetics represent the primary advantage of ceramic brackets over metal ones, some studies have demonstrated that commercially available alumina ceramic brackets exhibit long-term instability (Guignone et al., 2015). The optical stability of zirconia brackets remains an unresolved question. Furthermore, in YSZ materials, there can be a significant reduction in mechanical properties due to low-temperature degradation resulting from the tetragonal-to-monoclinic transformation when the tetragonal phase is exposed to aqueous environments. Hence, evaluating the aging resistance in the strength of zirconia brackets becomes imperative (Uwanyuze et al., 2021).

This *in vitro* study aimed to contribute to the existing knowledge base regarding the utilization of YSZ materials in the fabrication of advanced orthodontic brackets. Specifically, the influence of aging on the strength and optical stability of zirconia brackets with different yttria concentrations were investigated, while comparing with those of commercial polycrystalline brackets. The hypothesis was that there was no significant difference in the fracture strength and optical properties of zirconia brackets containing 3 to 5 mol% yttria proportions before and after artificial aging.

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II. MATERIAL AND METHODS

1. Design and manufacture of zirconia brackets

The experimental groups were fabricated utilizing three distinct zirconia powders: 3Y-YSZ (Zpex; Tosoh Ceramic, Japan), 4Y-YSZ (Zpex4; Tosoh Ceramic, Japan), and 5Y-YSZ (ZpexSmile; Tosoh Ceramic, Japan). According to the manufacturing specifications, all these powders are highly translucent zirconia grades, containing less than 0.1 wt% alumina, with the primary distinction being the yttria content (Fonseca et al., 2019).

All brackets were meticulously fabricated for the maxillary right central incisors, based on the morphology of an existing polycrystalline alumina ceramic bracket product (3M™ Clarity™ Advanced, MBT 0.022-inch slot) used as the control group. Figure 1 delineates the ceramic injection molding method employed for the production of the zirconia brackets. During this procedure, the mold was digitally conceptualized through three-dimensional (3D) software (Creo 5.0, PTC, USA)—referred to as *the digital reference design*—based on a 3D scanned image of the control group's morphology (micro-computed tomography scanner, SkyScan 1173, Bruker, USA). This design process took into consideration the linear shrinkage associated with zirconia materials.

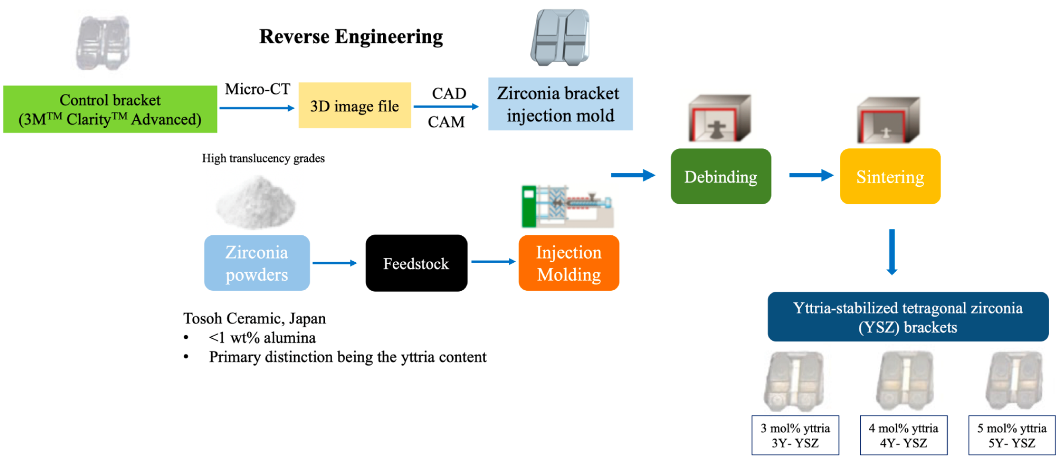

Figure 1. Schematic diagram illustrating the ceramic injection molding method utilized for the production of zirconia specimens

2. Artificial aging

An artificial aging was implemented through 20,000 cycles of thermocycling, each with a 30s-dwell time in distilled water at temperatures of 5 °C and 55 °C (Thermal cyclic tester model No RB 508, R&B Inc., Korea) (Figure 2). This process aimed to emulate two years of clinical utilization within the oral cavity, in accordance with the recognized average duration of orthodontic treatment (Gale et al., 1999).

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Figure 2. Thermocycling testing apparatus.

3. Measurements

3.1 Fracture strength of bracket tie wings

Fracture strength of all bracket groups was recorded before and after thermocycling. Consequently, each group's sample of twenty brackets was subjected to a fracture strength test.

Brackets were bonded to acrylic molds (Acrylic polycoat FRP resin LST-240, Aekyung, Korea) which were fixed firmly with the lower tensile grip within a universal testing machine (Intron 3366; Instron Corp., USA) (Figure 3). Transbond™ XT Light Cure

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Adhesive Primer (3M) was applied to both the acrylic mold and bracket base using a brush. A composite resin (Transbond^{TM} XT Light Cure Adhesive Paste – 3M) was used to bond brackets to acrylic molds, followed by 20 seconds of light polymerized. To enhance the stabilization, 0.010-inch steel ligature tie wire (TP Orthodontics, Inc., USA) was tied around, then the composite resin was added over the bracket surface and flowed onto the acrylic mold so that no composite resin flowed under the tested tie wing. The composite resin was light polymerized from 5 directions (mesial, distal, gingival, incisal, and facial) for 40 seconds each.

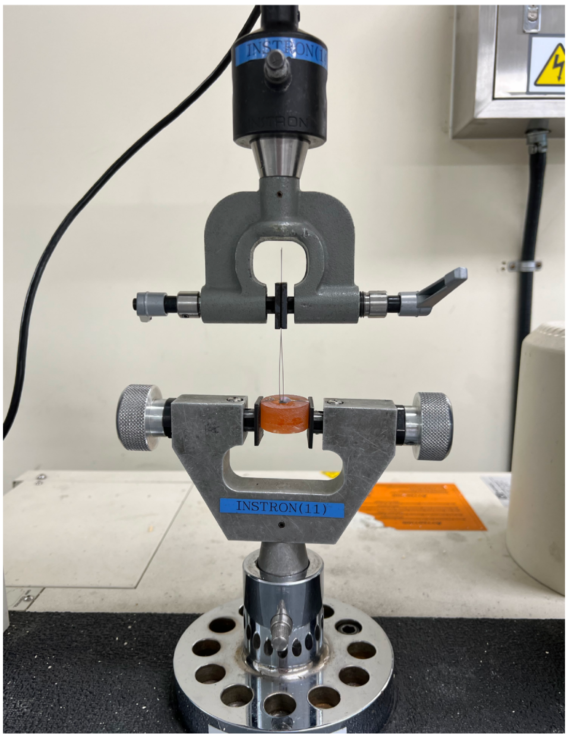

Figure 3. Mechanical testing apparatus.

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A 0.016-inch stainless steel wire (Ormco) was looped under the distoincisal tie wing and affixed to the upper tensile grip (Figures 3 and 4). The distoincisal tie wing was tested to failure at a crosshead speed of 10 mm/min. The fracture strength of bracket tie wings (MPa) was calculated by dividing the tensile load at failure (N) by the area of contact between the wire and tie wing (mm^2) (Johnson et al., 2005). The area of contact was calculated by using a 3D Inspection Microscope (Hirox KH-1000 Inc., USA) at a magnification of 50x.

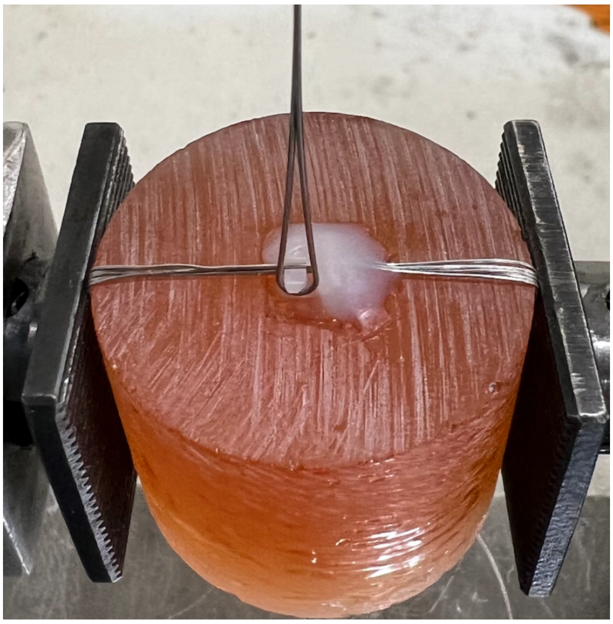

Figure 4. Illustration of tensile testing for bracket wing fracture.

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3.2 Optical properties and optical stability

The color and translucency properties of the brackets were scrutinized using both reflection and transmission methodologies with a spectrophotometer (CM-5, Konica Minolta, Japan), employing a D65 light source (Figure 5). Calibration of the spectrophotometer was diligently executed according to the manufacturer's directives before initiating the measurements.

Figure 5. Optical testing apparatus.

The stability of the optical characteristics of the brackets was examined through a process of artificial aging and exposure to a seven-day period in coloring substances found in commonplace beverages, including coffee (Maxim Arabica 100, South Korea), red wine (Bourgogne Hautes-Côtes de Nuits Les Dames de Vergy 2018, France), coke (Coca-Cola Zero, South Korea), and black tea (Starbucks Teavana Earl Grey Black Tea, South Korea) (Haralur et al., 2019) (Figure 6).

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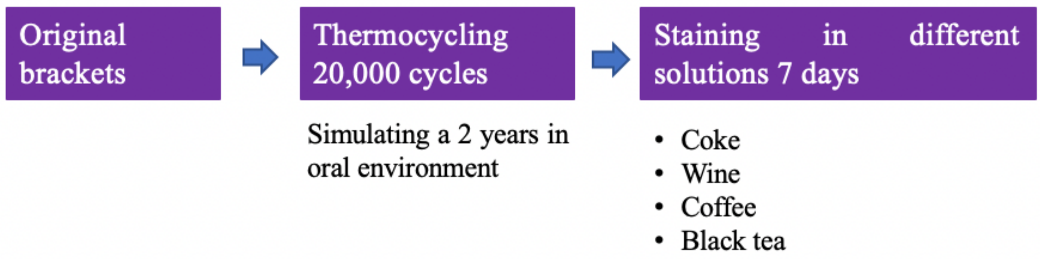

Figure 6. Schematic diagram illustrating the optical stability testing process.

Baseline color and translucency were documented to investigate alterations following thermocycling and immersion in coloring agents. Measurements were obtained from randomly selected brackets (10 from each group), subsequent to cleansing with distilled water to remove any residual dye waste.

Direct transmission analysis was conducted three times within the 400–700 nm wavelength range (visible light spectrum). Each specimen was shielded with an opaque black cardboard mask, featuring a central window for measurement, and the mean value was subsequently determined (Lopes et al., 2012).

Reflection analysis adhered to the Commission Internationale de l'Eclairage (CIE) L* a* b* (LAB) color scale, where L* represents brightness (from black to white), a* denotes the color value from green to red, and b* signifies the color value from yellow to blue. Five assessments were recorded with a measuring aperture diameter of 3 mm at the labial surface center of the bracket and averaged to ascertain the value for each specimen. Color alterations before and after testing were computed using the equation:

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$$\Delta E_{ab}^{*} = [(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}]^{1/2}$$ (Lee, 2008; Lee, 2007).

4. Statistical analysis

The measurement repeatability and intra-observer variability were evaluated by computing the intraclass correlation coefficient between two assessments taken at 2-week intervals by a single inspector. The ensuing intraclass correlation coefficient (ICC) between the measurement pairs denoted high reliability (ICC > 0.97).

To verify the data distribution's normality, the Shapiro-Wilk test was administered. A one-sample T-test analysis was utilized to examine intragroup disparities in trueness. One-way ANOVA and post-hoc Tukey's multiple comparison tests were employed to analyze the intergroup variations in fracture strength, and optical parameters. A pair T-test analysis was performed to investigate the intragroup difference before and after testing. All statistical evaluations were conducted with SPSS 24.0 Statistical Software (SPSS, Armonk, NY, USA), applying a significance threshold of 0.05.

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III. RESULTS

1. Fracture strength of bracket tie wings

Table 1. Fracture strength of bracket tie wings in the experimental and control groups

Group	Fracture strength				Sig. †
	Before thermocycling	P§	After thermocycling	P§	
Control	132.68 ± 7.13[a]	0.000	131.97 ± 6.38[a]	0.000	0.822
3Y-YSZ	141.51 ± 5.30[b]		142.92 ± 4.12[b]		0.495
4Y-YSZ	75.3 ± 7.36[c]		72.59 ± 7.79[c]		0.654
5Y-YSZ	67.18 ± 8.29[c]		66.00 ± 5.70[c]		0.192

Data are presented as mean ± standard deviation (MPa).

† Intra-group comparisons before and after thermocycling were performed using a paired T-test.

§ Inter-group comparisons were performed using one-way ANOVA. The same upper superscript letters indicate no significant differences between groups (Tukey's multiple comparison test).

The fracture strength of each bracket group was examined through tensile tests. Among them, the 3Y-YSZ group presented the highest fracture strength of the bracket tie wing, followed by the control group ($p<0.05$). No significant difference in the fracture strength of the bracket tie wing was observed between the 4Y-YSZ and 5Y-YSZ groups. (Table 1).

No significant difference in the fracture strength of bracket tie wings were observed before and after 20,000 thermocycles in all brackets groups.

2. Optical properties and optical stability

Prior to testing, the control group demonstrated the highest direct light transmission, succeeded by the 5Y-YSZ group. There was no significant variation in percentage transmittance between the 3Y-YSZ and 4Y-YSZ groups (Table 2).

Table 2. Percentage of transmittance of experimental and control groups before and after thermocycling

t%	Before thermocycling	After thermocycling	Sig. †
Control	64.35 ± 5.99^{a}	64.27 ± 2.18^{d}	0.976
3Y-YSZ	30.26 ± 1.27^{b}	31.69 ± 0.83^{e}	0.060
4Y-YSZ	29.34 ± 2.27^{b}	30.57 ± 1.98^{e}	0.416
5Y-YSZ	44.74 ± 1.91^{c}	43.49 ± 2.52^{f}	0.463
P§	a>c>b	d>f>e	

Data are shown as mean ± standard deviation.

† Intrgaroup comparisons before and after thermocycling were tested by by pair T-test in each group.

§ Intergroup comparisons were tested by One-way ANOVA. The same upper superscript letters indicate no significant differences between groups (Tukey's multiple comparison test).

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Post-thermocycling and immersion in different staining solutions, all groups exhibited a reduction in transmittance percentage, with the 5Y-YSZ group manifesting pronounced alterations following a 7-day immersion in tea, coffee, and red wine solutions (Table 3).

Table 3. Percentage of transmittance of experimental and control groups after immersion in different staining solutions

t%	**Coke**	**Sig. †**	**Wine**	**Sig. †**	**Coffee**	**Sig. †**	**Tea**	**Sig. †**
Control	59.24 ± 1.73^{a}	N.S.	60.31 ± 1.87^{d}	N.S.	56.54 ± 2.03^{g}	N.S.	59.43 ± 3.26^{k}	N.S.
3Y-YSZ	30.99 ± 0.60^{b}	N.S.	26.86 ± 0.83^{e}	N.S.	28.59 ± 0.79^{h}	N.S.	27.75 ± 1.34^{l}	N.S.
4Y-YSZ	30.10 ± 1.12^{b}	N.S.	29.17 ± 1.91^{e}	N.S.	27.85 ± 1.41^{h}	N.S.	24.82 ± 0.98^{l}	N.S.
5Y-YSZ	42.29 ± 2.52^{c}	N.S.	40.74 ± 1.34^{f}	Sig.	39.20 ± 1.15^{i}	Sig.	39.35 ± 1.89^{m}	Sig.
P§	a>c>b		d>f>e		g>i>h		k>m>l	

Data are shown as mean ± standard deviation.

† Changes in the transmittance percentage before thermocycling and after immersion in each testing solution were compared by pair T-test in each group.

§ Intergroup comparisons were tested by One-way ANOVA. The same upper superscript letters indicate no significant differences between groups (Tukey's multiple comparison test).

N.S. = not significant Sig. = significant

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Table 4. Changes in reflected color (ΔE^*_{ab}) and color parameters of the experimental and control groups

Group	ΔE^*_{ab}	p	ΔL^*	p	Δa^*	p	Δb^*	p
Thermal cycling								
Control	0.39 ± 0.14	0.794	-0.15 ± 0.36	0.737	-0.05 ± 0.06	0.962	0.11 ± 0.19	0. 558
3Y-YSZ	0.54 ± 0.25		-0.14 ± 0.61		-0.04 ± 0.06		0.12 ± 0.11	
4Y-YSZ	0.50 ± 0.37		-0.34 ± 0.49		-0.03 ± 0.06		0.19 ± 0.13	
5Y-YSZ	0.53 ± 0.21		-0.39 ± 0.18		-0.03 ± 0.06		0.27 ± 0.29	

Coke								
Control	1.25 ± 0.75		0.93 ± 1.03		-0.02 ± 0.09[a]		0.49 ± 0.25	
3Y-YSZ	0.92 ± 0.30	0.246	-0.24 ± 0.83	0.060	0.16 ± 0.06[b]	0.002	0.53 ± 0.04	0.095
4Y-YSZ	1.08 ± 0.43		-0.25 ± 0.83		0.11 ± 0.04[b]		.80 ± 0.25	
5Y-YSZ	0.62 ± 0.33		-0.40 ± 0.27		0.10 ± 0.04[b]		0.41 ± 0.31	
Wine								
Control	1.15 ± 0.51		-0.86 ± 0.78		0.12 ± 0.07[c]		0.50 ± 0.21	
3Y-YSZ	1.22 ± 0.28	0.126	-0.88 ± 0.30	0.202	0.40 ± 0.08[d]	0.000	0.72 ± 0.13	0.588
4Y-YSZ	1.65 ± 0.66		-1.31 ± 0.77		0.50 ± 0.13[d]		0.70 ± 0.41	

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5Y-YSZ	1.75 ± 0.23		-1.55 ± 0.20		0.50 ± 0.05^{d}		0.62 ± 0.25	
Coffee								
Control	2.22 ± 0.56		-1.11 ± 0.91		0.11 ± 0.07^{e}		1.80 ± 0.17	
3Y-YSZ	2.64 ± 0.74	0.214	-1.65 ± 0.90	0.225	0.35 ± 0.08^{f}	0.000	1.95 ± 0.28	0.089
4Y-YSZ	2.32 ± 0.45		-1.62 ± 0.58		0.43 ± 0.14^{f}		1.55 ± 0.20	
5Y-YSZ	2.96 ± 0.55		-2.12 ± 0.38		0.48 ± 0.08^{f}		2.01 ± 0.42	

Tea								
Control	2.75 ± 0.56		-1.84 ± 0.70		0.27 ± 0.05[g]		1.99 ± 0.18	
3Y-YSZ	3.27 ± 0.71	0.319	-2.55 ± 0.86	0.289	0.62 ± 0.08[h]	0.000	1.88 ± 0.18	0.549
4Y-YSZ	3.36 ± 0.79		-2.42 ± 0.98		0.73 ± 0.14[h]		2.14 ± 0.21	
5Y-YSZ	3.46 ± 0.38		-2.74 ± 0.22		0.66 ± 0.07[h]		1.98 ± 0.44	

Data are shown as mean ± standard deviation.

Intergroup comparisons were performed using one-way ANOVA. The same upper superscript letters indicate no significant differences between groups (Tukey's multiple comparison test).

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Significant color changes occurred in all bracket groups, reaching up to 2.75 units in the control group and 3.46 units in the experimental groups, predominantly in coffee and tea solutions. However, no marked intergroup differences in the degree of color change (ΔE^*_{ab}) were detected under the experimental conditions (Table 4).

Figure 7. Changes in the appearance of the experimental and control bracket groups over time

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IV. DISCUSSION

Recent advancements in the composition, structure, and fabrication techniques of zirconia material have substantially enhanced its mechanical properties and aesthetic features, particularly within dental prosthodontics (Kontonasaki et al., 2019). This evolution has fueled an increasing interest in employing zirconia in the manufacture of orthodontic brackets, surpassing the constraints of conventional alumina ceramic brackets (Namura et al., 2022; Polychronis et al., 2023; Maki et al., 2016; Panayi et al., 2022; Zang et al., 2023). However, the performance of orthodontic appliances fabricated by these novel zirconia variants remained unclear. This study serves as a pioneering effort to bridge this gap by offering crucial insights into the performance of zirconia brackets, while considering the impact of aging. The in vitro study spans an exploration of varying yttria proportions and their implications for developing advanced orthodontic brackets. The findings emphasize significant variations in the fracture strength and optical properties of the brackets, depending on the yttria proportions. The null hypothesis was therefore rejected.

In orthodontic treatment, fracture strength is a vital mechanical property that holds relevance to the clinical functionality of ceramic brackets. The manufacturing process is instrumental in defining the ceramics' strength; hence, it is advised to test actual ceramic brackets rather than bulk bracket materials (Johnson et al., 2005). All bracket groups in the present study were true-twin brackets, fabricated through the injection molding process, and maintained uniformity in size and shape to regulate the factors that could influence the brackets' fracture strength (Johnson et al., 2005). In this investigation, the simulation of a 2-year in an oral environment played an insignificant effect on the fracture strength of all brackets. Among groups, the 3Y-YSZ group presented statistically the highest mean maximum tie-wing fracture strength (Table 1). This outcome can be attributed to the distinctive transformation toughening characteristic of zirconia material, where stress induces a phase shift from the tetragonal to monoclinic phase at the crack tip. This transformation, accompanied by a resultant increase in volume, modifies crack propagation and thereby augments the material's fracture resistance (Polychronis et al., 2023; Guazzato et al., 2004). However, zirconia stabilized with an elevated yttria content leads to an increase in cubic content, thus resulting in reduced fracture toughness (Polychronis et al., 2023; Tong et al., 2016; Pekkan et al., 2020; Zhang et al., 2016). Unlike zirconia, alumina brackets lack these protective mechanisms (Polychronis et al., 2023). Consequently, the utilization of 3Y-YSZ brackets in orthodontic treatment might prove advantageous because of the diminished incidence of wing fracture.

The aesthetic appeal of orthodontic fixed appliances has long been a concern for patients. To get a good aesthetic appearance, the bracket should match the underlying tooth color and/or possess high translucency (Lopes et al., 2012). In the current study, the 5Y-YSZ group displayed a significantly enhanced translucency compared to the 3Y-YSZ and

4Y-YSZ groups, yet all experimental groups were less translucent than the control group (Table 2) (Cho et al., 2020). Therefore, to achieve a visually imperceptible appearance, options such as coloring the brackets to achieve desirable color-matching with patients' teeth and/or enhancing the translucency of the zirconia bracket can be considered. Nevertheless, to maintain an aesthetic appearance, good optical stability is required (Lopes et al., 2012; Lee, 2008). In this study, changes in transmittance percentage were detected across all groups, with substantial differences noted in the 5Y-YSZ group following a seven-day immersion in tea, coffee, and red wine solutions (Table 3). Likewise, significant alterations in the coloration of all bracket groups were observed, but without noticeable differences between the groups in the degree of color change (ΔE_{ab}^{*}) (Table 4). These findings indicate that the yttria proportion influences the translucency of the YSZ material, but not its resistance to staining or discoloration (Lee, 2007; Nascimento Oliveira et al., 2022). Even though substantial variations in optical properties were registered, acceptable color stability was confirmed in both control and experimental groups according to a threshold of 3.7 ΔE_{ab}^{*} units for clinically perceptible color change (Table 4 and Figure 7).

This study revealed that among the zirconia bracket categories, the 3Y-YSZ brackets presented enhanced surface integrity in response to fracture loads, even after simulating a 2-year exposure to an oral environment. Such attributes offer advantages in optimizing orthodontic treatment by reducing the incidence of bracket wing fracture during active treatment. While the color stability of zirconia brackets was verified and the translucency of YSZ significantly augmented by raising the yttria proportion in the 5Y-YSZ bracket, further advancements in translucency or color-matching strategies may be required to satisfy patient preferences without compromising the exceptional physical and mechanical characteristics of the zirconia material (Panayi, 2022; Tabtabaian, 2018). Moreover, it must be noted that the results obtained in this study may not wholly represent the clinical scenario, owing to limitations inherent in laboratory conditions, despite measures taken to control for confounding variables (Lopes et al., 2012). Additional clinical investigations are warranted to investigate the effects of these material properties in daily orthodontic practice.

V. CONCLUSION

This study revealed key findings regarding the properties and performance of zirconia brackets.

- The artificial aging played an insignificant effect on the fracture strength of all bracket groups. Notably, the 3Y-YSZ bracket group manifested enhanced fracture resistance compared to other bracket groups.
- The zirconia brackets showcased pleasing color stability with clinically inconspicuous color alterations. Despite marked improvement in the translucency of the 5Y-YSZ group relative to the 3Y-YSZ and 4Y-YSZ groups, the experimental groups were found to be less translucent than the control group.

These insights contribute to the understanding of the potential advantages and limitations of zirconia brackets regarding their yttria proportion, informing their application in orthodontic treatment.

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국문 요약

Thermocycling 에 따른 Zirconia Brackets 의 강도 및 광학적 안정성

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임상 교정 영역에서 심미적 브라켓의 주 재료인 알루미나 세라믹(alumina ceramic)의 물리적 단점을 개선하기 위해 지르코니아(zirconia)에 대한 관심이 높아지고 있다. 그러나 지르코니아를 상용화된 브라켓의 형태로 제작했을 때의 강성이나 심미성에 대해서 연구가 미미한 상태이다. 본 연구는 다양한 이트리아(yttria) 비율로 제작한 교정용 지르코니아 브라켓의 물성과 색조 안정성을 평가하고자 하였다. 이러한 특성을 상용 다결정 알루미나 브라켓의 특성과 비교했다.

서로 다른 이트리아 비율(3 mol%, 4 mol% 및 5 mol%)을 갖는 이트리아 안정화 지르코니아 (yttria-stabilized zirconia, YSZ)를 이용하여, 다결정 알루미나 세라믹

브라켓을 대조군으로 역공학을 통해 세 가지 브라켓을 동일 형태로 제작하였다. 브라켓 윙의 파절강도는 열순환 전후의 인장시험을 통해 측정하였다. 구강내 약 2 년간의 노화를 재현하기 위해 20,000 주기의 열 순환 처리를 시행하였고 색상 및 투명도를 포함한 기본 광학 특성을 평가하고 열순환 및 다양한 착색제에 7 일 동안 담근 후 광학 안정성을 측정하였다.

파절강도에 있어서 열순환 전후의 유의한 차이는 관찰되지 않았다. 파절강도는 3Y-YSZ 그룹이 가장 높았고, 대조군이 그 뒤를 이었다($p<0.05$). 투명도에서는 5Y-YSZ 군은 실험군 중 유의하게 우수하였으나 대조군에 비해 유의하게 낮았다($p<0.05$).

본 연구의 한계 내에서 YSZ 를 3~5 mol% 함유한 지르코니아 브라켓은 파절강도와 광학적 특성 면에서 전반적으로 양호한 성능을 보였으며 특히 3Y-YSZ 의 물리적 특성은 교정용 브라켓 제작을 위한 재료로 적합할 것으로 사료된다.

핵심 문구: 교정용 브라켓, 알루미나 세라믹, 이트리아, 지르코니아, 열순환 처리