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# Simulation of oral environmental conditions through artificial aging of teeth for the assessment of enamel discoloration in orthodontics

Celal Irgın[1*]

## Abstract

**Background** The clinical performance of dental materials can be predicted via artificial aging approaches. The bracket bonding procedure may cause irreversible alterations to the enamel surface. The aim of this study was to introduce a novel artificial aging protocol and evaluate its effect on the discoloration of both bracket-bonded and unbonded teeth while also comparing the effects of four orthodontic adhesives on enamel color and whiteness.

**Methods** One hundred permanent lower incisors from humans were randomly divided into five groups, each including 20 specimens. The lower incisor metal brackets were bonded to the teeth via four different orthodontic adhesives (Transbond XT, Kurasper F, Bisco ORTHO, and Light Bond), and a control group was established. To simulate the cumulative effects of aging on the oral cavity, all the samples were subjected to mechanical cyclic loading (50,000 cycles), hydrothermal cycling (10,000 cycles), or exposure to stained beverages (25 days). A colorimeter device was used to measure the color of the teeth before and after testing. Statistical differences were calculated via one-way analysis of variance (ANOVA) and Tukey's test.

**Results** The combined aging protocol resulted in statistically significant and clinically unacceptable differences in tooth color alterations and whiteness index values across all groups ($p < 0.05$). The control group presented the least significant discoloration, whereas the bracket-bonded groups presented greater discoloration. Furthermore, there were statistically significant differences among the bracket-bonded groups ($p < 0.05$).

**Conclusions** The combined artificial aging protocol can be employed to simulate the macroenvironmental conditions of the oral cavity in laboratory investigations. The composition of the orthodontic adhesive also influences the severity of tooth discoloration.

**Keywords** Artificial aging, Tooth color, Discoloration, Orthodontic adhesive

*Correspondence:
Celal Irgın
cirgin@hotmail.com; celal.irgin@erciyes.edu.tr
[1]Department of Orthodontics, Faculty of Dentistry, Erciyes University, Kayseri, Melikgazi 38039, Türkiye

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## Background

Dental appearance, which is related to oral aesthetics and facial and smile attractiveness, is an important source of motivation for patients seeking orthodontic treatment [1, 2]. A smile reveals the maxillary and mandibular anterior teeth. Thus, essential components of microaesthetics and an individual's tooth color become noticeable [3, 4]. An individual tooth color, which is perceived according to the way light is scattered and absorbed on the surface and internal structures of the tooth, is determined by the interaction of the intrinsic color of the tooth and the presence of external stains on the enamel surface [5]. Although fixed appliances or attachments are temporarily bonded to teeth for a certain period of orthodontic treatment, permanent damage to the enamel is inevitable due to some procedures performed [6]. The popular acid-etching procedure [7–9], in which 10–20 μm prismatic mineral units are irreversibly removed superficially from the enamel surface [10], the formation of adhesive resin tags [9–11] that reach a relative depth of 50 μm from the enamel surface [8, 12], the bracket removal procedure [9, 13], the retention of resin tags in the enamel after debonding [10, 14, 15], and the cleaning and polishing of the enamel surface [6, 10, 14] have been indicated in the literature as procedures that cause structural enamel changes. These procedures may result in the loss of enamel tissue at the tooth surface and the formation of decalcification, microcracks, scratches, abrasions and surface roughness. Additionally, dental aesthetic concerns such as tooth discoloration may be observed [8–13, 15].

The presence of orthodontic adhesive tags in the enamel may indirectly affect tooth color; therefore, the clinical importance of considering the color stability of orthodontic adhesives has also been emphasized [11, 12]. The discoloration of adhesive materials is considered to be a multifactorial process and is influenced by many internal and external factors [9, 16, 17] as well as exposure to degradation processes [18, 19]. The internal factors are related to the resin matrix itself, the content and size of the filling particles, and the degree of polymerization capacity and humidity, whereas the external factors include the consumption of pigmented foods and beverages, the use of colored mouthwashes, smoking, poor oral hygiene and microbial plaque [16, 17].

The oral cavity is an intricate and multifaceted environment, presenting numerous challenges. The chemical structure, physical properties and aesthetic appearance of adhesive materials are strongly influenced by intraoral conditions and change over time, ultimately resulting in the clinical performance of the adhesive material [19, 20]. To evaluate the clinical performance and lifetime of adhesive materials, standardized procedures that simulate the degradation processes occurring in the oral cavity are needed in experimental studies [20]. Artificial aging methods, including a variety of static liquid storage methods (such as water, artificial saliva, ethanol, beverages or food dyes) and dynamic tests (thermocycling and mechanical loading), are employed alone or in combination for this purpose [18–22]. Moreover, these tests, particularly those of a dynamic nature, are used to gain insight into the fatigue and wear processes that lead to deterioration and failure of human enamel or teeth in the oral cavity [23]. Owing to the complexity of the oral cavity, more complete aging protocols are needed, and dynamic testing is extremely valuable for predicting the clinical performance of dental materials, as it better mimics clinical conditions [18]. In other words, in vitro tests should be as representative as possible of the in vivo situation [23]. Mechanical cyclic loading, defined as fatigue, may produce microscopic flaws in a structure that grows slowly over many cycles of stress, but one single load application causes no apparent damage. Fatigue is especially problematic when a structure or material is subjected to prolonged and accumulated loading stresses during lengthy treatment [19, 22, 23]. However, mechanical cyclic loading tests have not been evaluated for any predictions of the in vitro tooth color performance of light-cured orthodontic adhesive systems.

Tooth color alterations might also be an important property in choosing an appropriate adhesive material for use in areas where the aesthetic appearance is valuable [11, 24]. A combined artificial aging method, which can be defined as the sequential application of aging tests, can be used to assess tooth discoloration and the long-term color survival of dental materials. The combined use of mechanical loading, thermocycling and colorant beverages may create an additive or an adverse effect on the color of the teeth according to laboratory research, and this approach can be considered a potential method for mimicking oral conditions. This experimental study aimed to compare the cumulative effects of combined artificial aging protocols, including mechanical cyclic loading, thermocycling and beverage staining, on the discoloration of teeth by using four different orthodontic adhesive systems for bracket bonding. The null hypothesis was that there would be no difference between the color alterations of the teeth when the teeth were subjected to the combined artificial aging procedures and when different orthodontic adhesive systems were used.

## Methods

Ethical approval for this experimental study was obtained from the Erciyes University Clinical Research Ethics Committee (Decision no: 2024/146). According to the results of the power analysis with 95% confidence (1-α) and 90% test power (1-β), d=0.45 effect size [8], a total

of 100 teeth were included in the study, with 20 teeth in each group.

### Specimen preparation

The sample group included 100 human permanent lower incisors extracted for orthodontic reasons or periodontal diseases without any caries, discoloration, or abnormality on the surfaces when examined under daylight. Chemically cured acrylic resin was placed into plastic molds, and each tooth was embedded in acrylic perpendicular to the base of the molds. The samples were stored in distilled water at room temperature, except during color measurements, bracket bonding, and testing procedures. Before the bracket bonding and aging procedures, the labial surfaces of the teeth were polished with fluoride-free pumice, rinsed with water, and dried with oil and moisture-free compressed air. The samples were assigned code numbers for identification and randomization.

**Table 1** Orthodontic adhesive systems used for artificial aging

| Materials | Curing Time | Material Type | Primer | Manufacturer |
|---|---|---|---|---|
| Transbond XT (Light Cure) | 20 Second | Bis-GMA (5%-10%), Bis-EMA (10%-20%), TEG-DMA(5%-10%), silane-treated quartz (70%-80%), silane-treated silica (2%) | Transbond XT Primer | 3M Unitek Ortho Prod, Monro, USA (patch code: 9892867) |
| Kurasper F (Light Cure) | 40 Second | Bis-GMA (5%-25%), TEG-DMA (6%), Silanated barium glass filler, Colloidal silica, dl-Camphorquinone, Catalysts, Accelerators | F Bond | Kuraray Europe GmbH, Frankfurt, Germany (patch code:0135092) |
| Bisco ORTHO (Light Cured) | 20 Second | Bis-GMA (15%-40%), TEG-DMA (5%-15%), fused silica (30%-60%) | One-Step | Bisco, Inc, Scham, IL, USA (patch code: 0004589) |
| Light Bond (Light Cure) | 40 Second | UDMA (15%-19%), Bis-GMA (3%-7%), Silica-crystalline, Fused silica, Amorphous Silica, Sodium Fluoride | Light Bond Sealant Resin | Reliance Orthodontic Products, Itasca, IL, USA (patch code: 23111408) |

37% Phosphoric acid was applied for 30 seconds; Light curing time was carried out with the manufacturer's instructions. Bis-GMA, Bisphenol A Diglycidylmethacrylate. Bis-EMA, Bisphenol A Bis (2-Hydroxethyl Ether) Dimethacrylate. TEG-DMA, Triethylene Glycoldimethacrylate-Decamethylenm Dimethacrylate. UDMA, urethane dimethacrylate

The samples were randomly divided into 5 groups of 20 teeth each ($n=20$). The lower incisor metal brackets (Equilibrium 2, Dentaurum, Germany) were bonded with 4 different orthodontic adhesive systems to the teeth, and the last group served as the control group, with no surface conditioning or bonding. The orthodontic adhesive systems investigated for color and whiteness changes in teeth were obtained from Transbond XT, Kurasper F, Bisco ORTHO, and Light Bond and are listed in Table 1. Acid etching of all the samples was performed via 37% phosphoric acid gel (Gel Etch®, 3M Unitek) for 30 s, after which the tooth was rinsed with a water/spray combination for 30 s and subsequently dried until a characteristic frosty, white conditioned area was observed. The primer of each orthodontic adhesive provided by the manufacturer in the adhesive kit was applied to the conditioned enamel area in a thin layer for 3 to 5 s via an applicator brush. To ensure an even distribution of the primer on the enamel surface, a blast of air free of oil and moisture was used for 1 to 2 seconds. After the tooth was primed, bracket bonding was started immediately. Orthodontic adhesive was applied as a uniform layer on the metal bracket base, and then the bracket was positioned on the middle third of the labial surface of the incisors with minimal pressure. The overflow of excess adhesive from the bracket base was removed prior to the light-curing process. The samples were subjected to curing via a light-emitting device (Elipar™ S10, 3M ESPE) with an irradiance of 1200 mW/cm$^2$. For optimal light curing, irradiance was applied by positioning the light guide tip of the device so that it contacted all the edges of the bracket base at a 45° angle. The bracket base was subjected to irradiation for equally distributed periods of time. The total irradiance duration for the treatment groups was 20 s for Transbond XT and Bisco ORTHO and 40 s for Kurasper F and Light Bond (Table 1).

### Aging processes

All the samples were subjected to three different tests in succession—cyclic mechanical loading, thermal cycling, and exposure—to stain beverages to more accurately simulate the macroconditions within the oral cavity. Initially, a chewing simulator test device (CS-4.8, SD Mechatronik GmbH, Feldkirchen, Germany) was employed to mimic the vertical occlusal loading that mandibular anterior teeth experience while biting. The samples were mounted in the chewing simulator with the incisal edge of the tooth perpendicular to the stainless-steel upper rod (5 mm in diameter). A mechanical load pulse was applied to the center of the incisal edges of the teeth 50,000 times at a frequency of 0.5 Hz, ranging from 25 to 50 Newtons, and distilled water was used as the testing medium. The parameters for mechanical cyclic loading were determined based on results from a previous

meta-analysis [19], considering that incisors experience vertical forces with less frequency and magnitude than posterior teeth do during mastication. This analytical strategy was chosen because the majority of publications in that review focused on the posterior teeth. Second, all the samples were thermocycled between 5 °C and 55 °C via an electronic thermocycling machine (FT 400, Julabo GmbH, Seelbach, Germany) in water tanks with a dwell time of 30 s and a transition time of 30 s in each tank. The thermal cycling parameters were adjusted in accordance with the ISO 11,405 standard and were based on 10,000 thermal cycles, reflecting the temperature fluctuations experienced in the oral cavity over one year, as reported in the literature [25, 26]. Given the growing interest in studying the effects of various beverages on the color stability of dental adhesives [17] and the wide range of dietary preferences among individuals, all the samples were ultimately exposed to five different beverage stains: black tea, coffee, milk, cherry juice, and cola (Table 2). Each staining solution was renewed every day for five days, and the samples were completely immersed in a vertical orientation. After 24 h of immersion in the beverages, the samples were gently rinsed with distilled water for 5 min and dried with tissue paper. The preparation of black tea involved the addition of 2–2.5 g to every 125 ml of boiled water in a porcelain teapot. The tea was permitted to brew for 10–15 min. Coffee was prepared by adding 2 g of coffee to 200 ml of boiling water and allowing it to reach the standard drinking temperature of 70 °C. The preparation of black tea and coffee was carried out in accordance with the manufacturers' instructions. Ready-to-drink milk, cherry juice, and cola were purchased. Upon completion of the staining procedures, the samples were placed in individual containers with distilled water and stored at ambient temperature to prevent contamination and dehydration.

After all of the aging processes were completed, the brackets were removed via a debonding plier, and the adhesive residues were cleaned with a low-speed carbide bur set on a water-cooled counter angle. The enamel surface was polished using Sof-Lex finishing disks (3 M Dental, St. Paul, Minnesota) for the final color measurements.

### Colorimetric evaluation

A colorimetry device (Vita Easyshade Compact, Vita Zahnfabrik, Germany) was used to determine the color parameters of all teeth at baseline and after combined artificial aging. To ensure standardization, in vitro spectrophotometric color measurements were taken in the same examination room facing north during the same hours of the day. The light sensor tip of the device was positioned perpendicularly to the tooth's axis on the middle third of the labial surface. The color measurement was repeated three times for each tooth in both stages. The color parameters obtained for each stage were averaged. The color difference ($\Delta E_{00}$) before and after combined artificial aging was computed via the CIEDE2000 color system [27]. The formula for the calculation of $\Delta E_{00}$ is presented below and is based on the differences in lightness ($\Delta L'$), saturation ($\Delta C'$), and hue ($\Delta H'$), with correction using weighing coefficients ($S_L$, $S_C$, and $S_H$), constants called parametric coefficients ($k_L$, $k_C$ and $k_H$) and a rotation factor ($R_T$). The parametric factors of the CIEDE2000 color difference formula were set to 1. $\Delta E_{00}$ was computed via an Excel spreadsheet implementation of the formula provided by Sharma et al. [28]. The $\Delta E_{00}$ values of the groups were compared against the perceptibility ($\Delta E_{00}=0.8$) and acceptability ($\Delta E_{00}=1.8$) thresholds established in the relevant literature [29], and the results were then interpreted clinically in accordance with these threshold values.

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

The whiteness index for dentistry ($WI_D$) was computed utilizing the values of three CIELAB chromatic coordinates (L*, a*, and b*) for each group, following the specified formula: $WI_D=0.511\ L^*-2.324a^*-1.100b^*$. A high $WI_D$ index value indicates a greater degree of whiteness in the sample, whereas a low (or negative) value indicates a lesser degree of whiteness [30]. The difference between the $WI_D$ values obtained at baseline ($WI_{D1}$) and after cumulative artificial aging ($WI_{D2}$) determines the differences in the whiteness indices of the groups ($\Delta WI_D = WI_{D2} - WI_{D1}$) [31]. In addition, the $\Delta WI_D$ threshold values for perceptibility and acceptability levels were established at 0.72 and 2.62 units, respectively [32].

### Statistical analysis

All the statistical analyses were conducted via SPSS software (version 21). The Shapiro–Wilk test was used for normality. The results revealed that the data exhibited a normal distribution. Thus, one-way analysis of variance (ANOVA) was employed to assess whether there was a statistically significant discrepancy between the variables. To calculate the homogeneity of variance, Levene's test was used. The test revealed that the variances were homogeneous. Thus, Tukey's test was performed for multiple comparisons. Descriptive analyses, including the

**Table 2** Staining beverages used in the investigation

| Product | Material type | Manufacturer |
|---|---|---|
| Cola Cola | Cola | The Coca Cola Co. İstanbul, Türkiye |
| Altınbaş | Black Tea | Caykur, Rize, Türkiye |
| Nescafe Classic | Coffee | Nestle, Vevey, Switzerland |
| SEK Süt | Milk | Tat Gıda Co. İstanbul, Türkiye |
| Cappy Vişne | Cherry Juice | The Coca Cola Co. İstanbul, Türkiye |

**Table 3** Mean total color differences ($\Delta E_{00}$) of the groups, intergroup comparisons and Tukey groupings

| Groups | Sample size (*n*) | $\Delta E_{00}$ (Mean ± SD) | $\Delta E_{00}$ threshold for clinical detection | F | *p* | Tukey grouping* |
|---|---|---|---|---|---|---|
| Control | 20 | 4.69 ± 1.58 | 1.8 | 74.90 | < 0.001 | *a* |
| Transbond XT | 20 | 8.02 ± 1.58 | | | | *b* |
| Kurasper F | 20 | 11.32 ± 2.65 | | | | *c* |
| Bisco ORTHO | 20 | 14.80 ± 3.0 | | | | *d* |
| Light Bond | 20 | 16.36 ± 3.03 | | | | *d* |
| Total | 100 | 11.04 ± 4.95 | | | | |

*indicates the same letter is not significantly different at the $p = 0.05$ level

**Table 4** Mean values of the difference in whiteness index ($\Delta WI_D$) of the groups, intergroup comparisons and Tukey groupings

| Groups | Sample size (*n*) | $\Delta WI_D$ (Mean ± SD) | $\Delta WI_D$ threshold for clinical detection | F | *p* | Tukey grouping* |
|---|---|---|---|---|---|---|
| Control | 20 | -8.65 ± 7.85 | 2.62 | 12.06 | < 0.001 | *a* |
| Transbond XT | 20 | -11.82 ± 8.7 | | | | *ab* |
| Kurasper F | 20 | -20.64 ± 9.76 | | | | *bc* |
| Bisco ORTHO | 20 | -24.93 ± 11.00 | | | | *c* |
| Light Bond | 20 | -26.14 ± 12.46 | | | | *c* |
| Total | 100 | -18.44 ± 12.14 | | | | |

* indicates the same letter is not significantly different at the $p = 0.05$ level

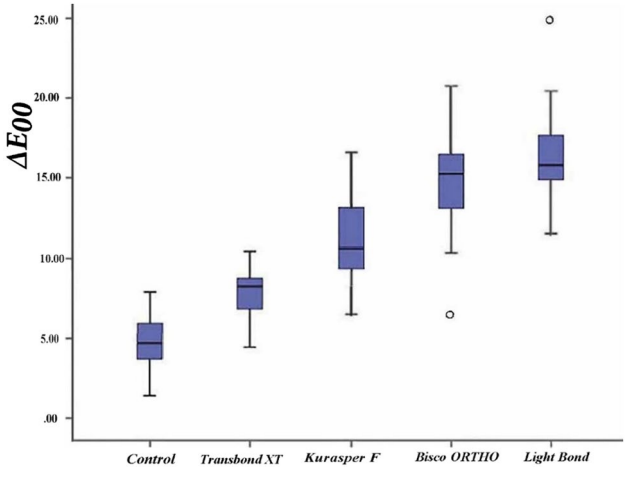



**Fig. 1** Color differences ($\Delta E_{00}$) among all the tested groups

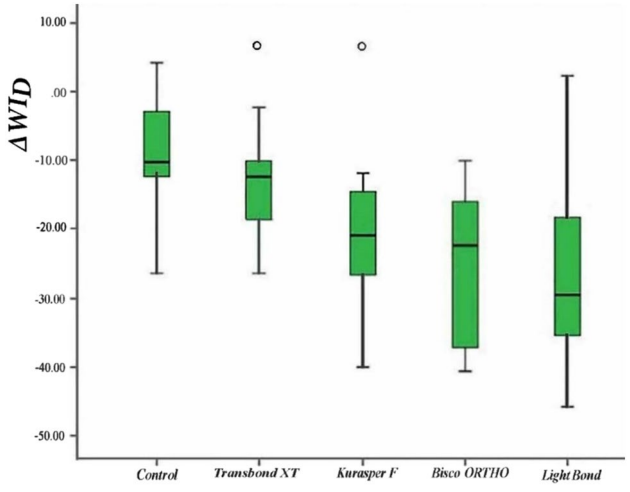



**Fig. 2** Differences in the whiteness indices of all the tested groups ($\Delta WI_D$)

means and standard deviations, were conducted for the control and treatment groups. The level of statistical significance was set at 0.05.

## Results

The mean values and standard deviations of the $\Delta E_{00}$ and $\Delta WI_D$ values of the groups, as well as the results of the intergroup comparisons, are listed in Tables 3 and 4 and illustrated with box plots (Figs. 1 and 2), respectively. Based on the CIEDE2000 color system and 50:50 acceptability threshold values ($\Delta E_{00} = 1.8$ and $\Delta WI_D = 2.62$), the results indicated that the color and whiteness of teeth in all groups, including those without bonding, were adversely affected following the combined artificial aging protocol. The $\Delta E_{00}$ values of the bracket-bonded teeth groups displayed clinically visible color changes after cumulative aging from 8.02 to 16.36 units. In addition, the unbonded control group also exhibited clinically unacceptable discoloration, with an average of 4.69 units (Table 3). The analysis of variance revealed statistically significant differences between at least two bracket-bonded groups in terms of the $\Delta E_{00}$ values ($p < 0.001$). Among all the groups, the control group was the least affected, whereas the Light Bond and Bisco ORTHO groups were the most affected groups ($p < 0.05$). However, among the bracket-bonded groups, Transbond XT was the least affected group ($p < 0.05$). There was no statistically significant difference between the mean $\Delta E_{00}$ values of the Bisco ORTHO and Light Bond groups ($p > 0.05$).

Statistically significant differences were found between the $\Delta WI_D$ values in the intergroup comparisons ($p<0.001$). The $\Delta WI_D$ values for all groups were negative. The highest value was observed in the control group, whereas the lowest value was noted in the Light Bond group (Table 4; Fig. 2). The differences in the $\Delta WI_D$ values among the Kurasper F, Bisco ORTHO, and Light Bond groups were not significant ($p>0.05$). Furthermore, statistical analysis revealed no significant difference between the Transbond XT and control groups or between the Transbond XT and Kurasper F groups. ($p>0.05$).

## Discussion

The results of this study showed that exposure of bracket-bonded and unbonded teeth to a combined artificial aging protocol resulted in clinically unacceptable changes in the color and whiteness of the teeth. The unbonded teeth showed less noticeable alterations than the bracket-bonded teeth did, and there were significant differences in the degree of discoloration and whiteness among the bracket-bonded groups. The null hypothesis was rejected on the basis of the findings, which indicated significant differences among the groups in question.

Facial attractiveness is influenced by how the teeth appear when smiling. In many cultures and societies, issues related to the color, shape and alignment of teeth, particularly the anterior teeth, are considered to be common cosmetic concerns, leading to an increased demand for treatments to improve oral aesthetics [5]. Furthermore, there is an increase in the adult patient population in orthodontic clinics [33], and these individuals have special expectations regarding the aesthetic qualities of their teeth. In fixed orthodontic treatment, forces are delivered to the teeth via brackets or attachments that are bonded to the enamel via an adhesive. The combination of fixed orthodontic treatment and dynamic alterations in the oral cavity has the potential to affect the enamel, which could result in the development of discoloration if appropriate care is not provided. This substantial issue remains a primary concern for orthodontists and their patients [17, 34].

Artificial aging methods involve subjecting dental samples to controlled conditions that replicate complex factors in the mouth. The design of goal-directed artificial aging procedures can improve the understanding of the processes responsible for tooth discoloration and thus enable the development of more specific materials, procedures and preventive strategies to manage aesthetic problems in orthodontics. The literature contains various in vitro studies employing different artificial aging methods, such as beverage staining [12, 16, 35, 36], thermal cycling [4, 34], and light exposure [14], to examine the impact of materials (including bracket types, primers, and adhesive systems) and procedures (such as acid etching, bonding/removal, and polishing) utilized in orthodontic treatment of the enamel surface and discoloration. However, these studies typically applied aging tests individually, and the findings were evaluated separately. Thus, the evidence regarding the effect of orthodontic intervention on enamel color may be inconsistent and inconclusive [37], which may be due to differences in study designs. A consistent strategy using artificial aging procedures that can effectively mimic oral circumstances is necessary for conducting in vitro research [19]. According to a review, designing methods for assessing the aging of dental materials is critical, and water-based aging evaluations provide a limited perspective on the clinical efficacy of biomaterials, whereas studies that simulate dynamic stress variations can more accurately reflect clinical scenarios [18]. In accordance with the aforementioned recommendations, a combined artificial aging method was formulated, comprising contact and thermal stresses, as well as the beverages consumed most frequently by individuals in daily life. The unique aspect of this experimental study was the examination of the cumulative effect of different artificial aging tests on tooth color, which is a novel approach. This study also represents a contribution to the field of orthodontics, as it is the first to examine the cyclic effects of chewing on the color of teeth with and without bracket samples.

In this research, first, cyclic dynamic methods were used to simulate the fatigue and wear processes that can occur in incisors during mastication by sequentially applying mechanical and thermal stresses. Following the execution of the designated tests, the samples were finally exposed to the colored beverages. Although no orthodontic procedures were applied to the enamel surface in the control group, the combined aging method markedly discolored and reduced the whiteness of the teeth. This finding indicates that alterations in enamel structure following cyclic stress increase the diffusion of colored chemicals into and between enamel crystals. Despite the lack of visible cracks or defects on the enamel surfaces of the samples at the beginning of the study, contact fatigue of the enamel during mechanical cyclic loading might have initiated or facilitated the formation of microcracks in the enamel. The subsequent exposure of the enamel to thermal cycling may have caused the preexisting microcracks to grow, spread or even form new microcracks. The literature indicates that preexisting microcracks in enamel grow significantly after several thousand thermal cycles [23]. If mechanical and thermal stresses had been applied independently instead of consecutively, the formation of enamel microcracks would have diminished, potentially resulting in a less severe form of tooth discoloration. In an alternative approach, tooth discoloration would likely have been reduced if the samples

had initially been subjected to colored solutions before undergoing dynamic tests. More research is needed to gain a better understanding of this issue, specifically to establish which one or which combination produces the most discoloration in this combined aging protocol.

Compared with the control group, the bracket-bonded groups demonstrated more discoloration in this study; this may be attributed to the synergistic effects of the combined aging process, bracket bonding/debonding procedures, and resin tags that remain in the enamel after polishing. All of these factors may contribute to increased stress on the enamel surface and consequent structural alterations. An experimental study using scanning electron microscopy to examine teeth with visible microcracks without any aging methods revealed that debonding metal and ceramic brackets and removing residual adhesives increased the width and length of the initial microcracks but did not significantly affect their number [38]. Alterations in the enamel surface in the bracket bonding region can be identified through the detection of microcracks and surface irregularities in this area. Moreover, the composition of the adhesive materials and polishing methods employed may affect the surface roughness of enamel [13]. According to a clinical study, enamel polishing reduces the impact of tungsten carbide burs but does not affect the overall effect of orthodontic treatment on tooth color [10]. All procedures, including color measurement, were carried out by the same researcher in the present study. Additionally, the same type of bracket was used in all bracket bonding groups. The brackets were removed via the same method, and the same polishing technique was also applied. The only differences between the treatment groups were the adhesive systems used, and the irradiation times applied for curing. The irradiation duration for Kurasper F and Light Bond was 40 s, whereas the other adhesives were irradiated for 20 s. These irradiation durations were determined in accordance with the manufacturer's recommendations. The teeth bonded with the Transbond XT adhesive demonstrated the greatest resilience to alterations in color and whiteness among the treatment groups. On the other hand, Light Bond and Bisco Ortho resulted in greater discoloration and diminished whiteness. The curing time of the adhesives may not influence the observed color change, given that a high-irradiance light-emitting device was incorporated into this experimental setup. The adhesive composition influences the essential physical and chemical properties of bonded materials, including the conversion rate and extent, solubility, flexural strength and modulus, cohesive strength, and moisture absorption [39]. The chemical composition of adhesive materials can affect enamel color, but the extent of this effect varies [35]. The resin tags in enamel may discolor during treatment due to external (e.g., superficial adsorption or absorption of color pigmentation from the diet) or internal (chemical structure) influences. Resin-based adhesives generally also cause more color changes than resin-modified glass ionomer cements do [40]. All the adhesives used in the current study were resin-based and contained various organic and inorganic constituents in different ratios, as detailed in Table 1. The differences in tooth color alterations among the bracket-bonded groups may be attributed to differences in the composition of orthodontic adhesives, which affect the physicochemical properties of the adhesive and thus affect its adherence to the enamel. All of these factors can have a synergistic effect on tooth color, influencing the reflection of light from the enamel surface and thus the perceived tooth color. Consequently, the color shift of the tooth might be affected in three ways in these simulated situations: the tooth itself, surface modification of the enamel, and the inability of the resin to protect its own color during its lifetime.

Recently, the use of a spectrophotometric colorimeter device in color studies has become the gold standard. Many studies indicate that color measurements with a calibrated device are superior to those with visual techniques [41]. In this study, enamel color was determined with a device before and after the test procedures. Unlike many in vitro studies [12, 14, 34, 36], the use of lower incisors instead of premolars was preferred in this study. One of the reasons for this preference is that the incisors are the teeth located in the front of the mouth, so they attract more attention when smiling, and their color is just as important. Another reason is that the labial crown of this tooth is flatter than that of other teeth, allowing more accurate color measurements. Although there are in vivo studies indicating that tooth type has no effect on color change [42, 43], color is measured with the light reflected from the tooth surface with a color measuring device, so a flat or convex enamel surface may affect color.

The results of experimental studies performed in the laboratory should be interpreted carefully. Although in vitro studies cannot fully simulate the oral environment, the results obtained from the behavior of the samples under standard conditions can be evaluated more objectively. In other words, randomized and systematic errors can be minimized in laboratory studies compared with those in clinical studies. Nevertheless, the inability to imitate conditions such as pH changes, bacterial invasion, force absorption of the periodontal ligament and tooth brushing are limitations of this study. Incorporating these factors into this study would likely have reduced the high color change values among the groups. The lubricating and buffering properties of saliva, the removal of staining agents on the enamel and around the bracket with tooth brushing, and the reduction in contact fatigue

of the periodontal ligament on the tooth could reduce the negative effects of mechanical, thermal and dietary factors. However, bacterial invasion could also play a role in enhancing discoloration. In the future, in vitro studies designed to predict changes in tooth and/or adhesive color may benefit from the use of combined aging methods that include these environmental conditions, thus facilitating the realization of more realistic experimental conditions.

## Conclusions

Within the limitations of this study, the following conclusions were drawn:

(1) For experimental research on tooth color alteration, including orthodontic adhesives, a combined artificial aging method of mechanical loading, hydrothermal cycling, and colorant solutions might be suggested for the in vitro simulation of oral conditions.
(2) The enamel color is influenced by the composition of the orthodontic adhesive and the artificial aging methods used.
(3) The color alteration may differ if orthodontic adhesives are light-cured for shorter durations.
(4) In the dental smile area, discoloration of teeth during fixed orthodontic treatment might cause patient dissatisfaction. Oral hygiene is a critical factor in preclusive exaggerated color shifts in teeth.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-024-05353-9.

Supplementary Material 1

### Author contributions

This study was developed and conducted by a single author, including data acquisition and collection, writing, and checking procedures.

### Funding

No funding.

### Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

### Ethics approval and consent to participate

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The research study protocol was approved by the Erciyes University Research Ethics Committee. Written informed consent was obtained from all individuals included in the study.

### Consent for publication

Informed consent was obtained from all individual participants included in the study.

### Competing interests

The authors declare no competing interests.

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