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Effects of common beverage colorants on color stability of dental composite resins: The utility of a thermocycling stain challenge model in vitro

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ABSTRACT

Objectives: To study the color stability of dental composite resins using a thermocycling stain challenge model accounting for the complex effects of oral environment and tooth brushing.

Methods: Composite resin discs were made from Filtek Supreme Ultra (FiltekSU), TPH3 and Renamel, and subjected to thermocycling challenges in warm coffee (55 °C/pH 5.2) and a cold tea and fruit juice mixtures (5 °C/pH 3.6) for a total of 1000 cycles with 30 seconds dwell time in each solution per cycle. Color was assessed in the CIELAB color space using a Crystaleye dental spectrophotometer before and after thermocycling, and after brushing vigorously for 3 min. The thermocycling stain challenge was repeated for a second 1000 cycles and the discs were brushed again. Color changes were compared among the 3 groups using Kruskal–Wallis test.

Results: All 3 groups showed statistically significant color changes after stain challenge, with ΔE^* as 5.74 for FiltekSU, 3.21 for TPH3 and 2.52 for Renamel. Color change was more significant in FiltekSU than in TPH3 and Renamel ($p < 0.05$). After brushing, color recovered mostly to its original CIELAB values in TPH3 and Renamel but less so in FiltekSU. The second round of thermocycling stain challenge resulted in color changes in FiltekSU that largely could not be removed by vigorous brushing.

Conclusions: Color stability of FiltekSU is inferior to that of TPH3 and Renamel. The thermocycling stain challenge model can potentially differentiate surface staining that can be removed by brushing from true discoloration of the material that is refractory to oral hygiene procedures.

1. Introduction

Composite resins are among the most frequently used dental materials for aesthetic restorations in dental practices due to their abilities to bond to enamel and dentine, resemblance to tooth structures in color and mechanical properties, ease of chair-side applications and relatively low costs.[1] Though the quality of composite resin restorations has improved with the advent of new technology in material sciences in recent years, discoloration of the composite resin materials remains to be a major problem in long-term clinical studies.[2–5] Bulk discoloration was one of the most common reasons for

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replacement of composite resin restorations.[6–8] Color stability has therefore been considered as one of the most important factors when selecting composite resin materials for aesthetic restorations. Assessment of color stability and discoloration has also been included in commonly used outcome measurement tools that rate the success and failure of composite resin restorations in clinical practices.[9]

Discoloration of composite resin materials can be caused by intrinsic and/or extrinsic factors. Intrinsic discoloration is determined by the quality of the resin matrix, the photoinitiator and the inorganic filler.[10–12] Extrinsic discoloration is mainly caused by colorants contained in beverages and foods through adsorption and absorption. Numerous studies in vitro have demonstrated that common drinks and food ingredients, such as coffee, tea or red wine,[13–16] fruit juices,[17–20] cola drinks,[21–23] soy sauce[23,24] and mustard and Ketchup,[24] could cause significant change in surface color of the composite resin materials. It was found that certain food colorants (e.g., coffee) may cause more severe staining than other (e.g., cola) though they have similar color parameters.[23,25,26] Recent studies showed that the effects of intrinsic discoloration were small in fully polymerized composite resin materials as no perceptible color changes were observed after water storage alone.[23,25] Significant color changes occur only when the materials are exposed to dietary colorants and chemical dyes,[27] and when the composite resins are not fully polymerized.[12,28] These findings suggest that extrinsic discoloration is the most important factor affecting the color stability and long term success of composite resin restorations, which highlights the needs for dental researchers and material scientists to improve the resistance to discoloration of new resin-based materials for aesthetic restorations.

Besides the obvious effects of colorants in beverages and foods, extrinsic discoloration are also clearly associated with the chemical, physical and structural properties of the composite resin materials. Compositions of the resin matrix affect water sorption, solubility, hydrophilicity and microstructures of the composites,[29–32] which may dictate the long-term color stability of the composite resin restorations. Composites that contain mainly the oligomers of bisphenol A glycidyl methacrylate (Bis-GMA) may exhibit higher hydrophilicity and increased water sorption than those that contain mainly urethane dimethacylate (UDMA).[33] Addition of small amount of triethylene glycol dimethacrylate (TEGDMA) into a Bis-GMA based resin matrix may significantly increase the water sorption of the composite material.[34] TEGDMA contains a central repeating ethoxy group that has high affinity with water molecule through hydrogen bonding to oxygen,[35] thus resulting in increased surface hydrophilicity of composite materials. Composite resins with high water sorption and hydrophilicity are more susceptible to discoloration as colorants are likely absorbed with water into the resin matrices. It has also been speculated that the inorganic fillers in the composite materials affect color stability as their size, type, distribution and affinity with resin matrix may influence adsorption and absorption of colorants to composite materials.[18,32,36,37] These studies suggest that both the organic matrices and inorganic fillers may affect the long-term aesthetic outcomes of composite resin restorations. But it is yet to know what combinations of resin matrices and fillers constitute ideal composite formulations that may allow an optimal aesthetic outcome without compromising the mechanical properties necessary for a satisfactory functional outcome.

Composite discoloration is a result of interactions between external colorants and the composite resin materials. The adsorption of external colorants onto the surface and the absorption of such into the resin matrices can both cause color changes and compromise the aesthetic outcomes. However, the remedial strategies towards discoloration caused by colorant adsorption on material surfaces can be significantly different from that caused by colorant absorption into the resin matrices. Colorants adsorbed on material surfaces may be removed through vigorous home hygiene procedures, while colorants absorbed deep into the matrices may require replacement of the restorations. Though numerous experimental models have been used to study the color stability and stain resistance of composite resin materials, few have differentiated adsorption from absorption in terms of their relative contributions to discoloration. Most color stability study models involve immersion of composite resin discs in static colorant beverages at 37 °C for a lengthy period of time and measure the color changes following a simple rinse of the discs.[18,20,23,25,38–43] What these models measure reflects the colorants precipitated and adsorbed on the surfaces of the materials but does not represent the true discoloration of the materials caused by absorption. The clinical significance of these studies are therefore of limited value as we do not know how much of the staining can be effectively removed through oral hygiene procedures and if replacements of the restorations are indicated due to internal discoloration that cannot be easily removed. A single colorant was usually used separately in these static immersion models,[18,20,23,25,38–43] while in reality a multitude of dietary colorants may dynamically interact with composite resin restorations in an oral environment on a daily basis. Furthermore, few studies have considered the thermal stress and pH environments of the oral cavity during consumption of colorant-containing beverages and foods. Both thermal stress and pH variations may affect the surface and structural integrities of composite resin materials and render the restorations more susceptible to staining and discoloration.[44,45] As experimental testing in vitro remains to be a vital tool in assessing the color stability and stain resistance of new aesthetic restorative materials, it is important to devise a new model that considers the effects of thermal stress, pH variation, complexity of dietary colorants, and dynamic nature of fluid flow and allows differentiation of adsorption from absorption.

The objective of the present study was to assess the effects of common dietary colorants on color stability of composite resins using a thermocycling stain challenge model in vitro. We selected three composite resins recommended for aesthetic restorations and subjected the composites to cyclic treatments in hot coffee and a concoction of cold and acidic beverages under constant agitation. The stained composite disc surfaces were thoroughly cleaned to remove adsorbed colorants before final color assessment. We hypothesized that the thermocycling stain challenge model could better represent the complex nature of the interactions between dietary colorants and composite resins and differentiate adsorption from absorption, thus enhance our ability to assess the aesthetic quality of composite resin materials.

2. Methods

2.1. *Composite selection and disc preparation*

Three composite resins marketed for aesthetic restorations were selected as experimental materials: Filtek Supreme Ultra (FiltekSU) (3M ESPE, St. Paul, MN, USA), TPH3 (Dentsply Caulk, Milford, DE, USA), and Renamel (Cosmedent, Chicago, IL, USA). Shades A2 (TPH3 and Renamel) and A2B (FiltekSU) were chosen. The compositions of the resin matrices and fillers of these composite resins are listed in Table 1. Composite resins were injected into Teflon moulds (10 mm in diameter and 1.3 mm deep) and placed on a glass plate with Mylar strip. The moulds containing slightly overfilled composite resins were covered by a second Mylar strip and glass plate. Finger pressure was applied to the covering glass plate to expel excess materials and create a smooth surface. The composite resins were then polymerized in a halogen light curing unit (Triad®2000, Dentsply Prosthetics, York, PA, USA) for 4 min to allow thorough polymerization. The discs were removed from the moulds, stored in deionized water for 4 weeks to allow thorough leaching of any non-polymerized resins and establishing equilibrium in water uptake, and then polished with Sof-Lex® (3M ESPE, St. Paul, MN, USA) polishing discs in sequences of 4 from coarse to superfine following the manufacturer's instruction. The polished discs were stored in deionized water for 24 h before use. A total of 48 discs, 16 in each group, were prepared.

2.2. *Baseline color assessment*

Color of the polished composite discs was assessed in the Commission Internationale de l'Eclairege $L^*a^*b^*$ (CIELAB) color space using a Crystaleye® dental spectrophotometer (Olympus Corp., Tokyo, Japan). The CIELAB system is a chromatic value color space that measures the value and chroma on three coordinates: L^* – the lightness of the color measured from black ($L^* = 0$) to white ($L^* = 100$); a^* – color in the red ($a^* > 0$) and green ($a^* < 0$) dimension; and b^* – color in the yellow ($b^* > 0$) and blue ($b^* < 0$) dimension. The central portion of the disc, defined as the middle third of the disc away from the peripheral and approximately 3 mm × 3 mm in size, was measured to derive the baseline $L^*a^*b^*$ values for the 3 selected composites. The spectrophotometer was calibrated against a reference plate mounted on its cradle before each measurement. Three measurements were obtained from each disc and the mean L^*, a^* and b^* values were used for the final analyses. All measurements were done with the resin disc on a white background under a custom-made 18 in. × 12 in. cardboard hood with black interior lining that shielded the contact cap of the spectrophotometer from external light sources.

2.3. *Dietary colorant selection and preparation*

Dietary colorants used in this study were common beverages with natural and artificial colors that may cause staining of composite resin surfaces. Five different beverages were used in this experiment: coffee (Maxwell House 100% pure coffee, Kraft Food Inc., Northfield, IL, USA), tea (Oolong Tea, StrongAmerica Ltd., Long Island City, NY, USA), grape juice (Welch's 100% Cherry Concord Grape, Concord, MA, USA), orange juice (Tropicana 100% Orange Juice, Tropicana Inc., Bradenton, FL, USA) and a Kiwi and Strawberry fruit punch (Hawaiian Punch, Mott's LLP, Plano, TX, USA). For preparation of coffee or tea solution, 10 g of coffee or tea was added to 1000 ml of water and boiled for 4 min, respectively. The coffee solution was cooled to 55 °C and tea chilled to 5 °C before use. Equal parts of fruit beverages, chilled to 5 °C, were mixed together to yield 1000 ml of juice mixture and added to the iced tea as prepared above. The color spectrum of individual beverages and the tea and juice mixture, together with their CIELAB and pH values, is shown in Table 2.

Table 1 – Compositions of selected composite resins.

Brand name	Resin matrix	Fillers
Filtek Supreme Ultra	Bis-GMA, Bis-EMA, UDMA, TEGDMA, PEGDMA	63.3% (v/v) (78.5%, w/w) Aggregated zirconia/silica cluster (zirconia and silica particles, 4–20 nm), 0.6–10 μm; nonagglomerated zirconia/silica, 4–20 nm
TPH3	Urethane modified Bis-GMA, Bis-EMA, TEGDMA	57% (v/v) (77%, w/w) Bariumaluminumborosilicate, <1 μm, bariumfluoroaluminioborosilicate, <1 μm, highly dispersed silicon dioxide, 10–20 nm
Renamel Microfill	UDMA, BDMA	59% (v/v) (60%, w/w) Pyrogenic silicic acid filler, 20–40 nm

Bis-GMA: bisphenol A glycidyl methacrylate; Bis-EMA: ethoxylated bisphenol A glycol dimethacrylate; UDMA: diurethane dimethacrylate; TEGDMA: triethylene glycol dimethacrylate; PEGDMA: polyethylene glycol dimethacrylate; BDMA: butanediol dimethacrylate.

Table 2 – Colorants containing beverages used in the present study and their CIELAB (L^*, a^*, b^*) and pH values.

	Coffee	Tea/juice mix	Tea	Orange juice	Grape juice	Kiwi punch
L^*	31.9	18.2	45.3	71.0	0.8	70.3
a^*	25.6	25.9	17.4	3.20	7.0	−34.4
b^*	49.5	8.30	50.0	70.8	−2.89	71.0
pH	5.24	3.61	5.20	3.90	2.65	2.95

2.4. Thermocycling stain challenges

The hot coffee solution and the cold tea and juice mixture were added to a proprietary thermocycling apparatus with computer controlled mechanical arms transporting the composite discs between the hot coffee (55 °C) and cold tea/juice (5 °C) tanks with a dwell time of 30 s and a transportation time of 15 s. A total of 75 s are needed to complete one cycle. The coffee and tea/juice solutions were continuously stirred at 150 rpm in the hot tank and circulated with an immersion circulator at 5 L/min in the cold tank to reflect the dynamic nature of beverage ingestions and to prevent any colorant precipitation. The discs were thermocycled for 1000 cycles in approximately 21 h, and then removed, gently washed for 30 s and placed in deionized water before color assessment.

2.5. Color assessments after stain challenge and after brushing

The composite discs were blotted dry and assessed with the Crystaleye® dental spectrophotometer as described above to derive the $L^*a^*b^*$ values after stain challenge. These values represent the effects of colorants adsorbed on the surfaces and absorbed into the resin matrices. The discs were then thoroughly cleaned for 3 min under 200 g pressure with a manual toothbrush (ADA standard toothbrush with soft bristles, provided by American Dental Association, Chicago, IL, USA) and a toothpaste containing hydrated silica abrasives (Colgate Regular, Colgate-Palmolive Co., New York, NY, USA). This vigorous brushing protocol ensures that all colorants adsorbed on the composite disc surfaces are completely removed. The cleaned discs were then rinsed with deionized water, blotted dry and submitted for color assessments to derive the $L^*a^*b^*$ values after brushing. These values excluded the effects of colorants adsorbed on the composite disc surfaces and therefore represent only the effects of colorants absorbed into the composite resin matrices.

2.6. Repeated thermocycling stain challenge and brushing

To assess the dynamic nature of colorant effects over time, the same composite discs were subjected to a second round of thermocycling stain challenge for 1000 cycles, followed by cleaning for 3 min with a toothbrush and toothpaste, and the color of the discs were assessed again in the CIELAB color space after stain challenge and after brushing as described above.

2.7. Statistical analysis

The sample size was estimated based on our pilot testing and previous publications. A sample size of 16 in each group has 90% of power to detect a 20% difference in overall color change (ΔE^*) between two comparison groups at an alpha level of 0.01 for a two-tailed test. Mean and standard deviation are presented for the CIELAB color parameters (L^*, a^*, and b^*) at baseline, after initial stain challenge (Stain 1), after initial brushing (Brush 1), after second stain challenge (Stain 2) and after second brushing (Brush 2). Color changes in each composite resin were compared between the baseline and the after staining and after brushing measurements using the Wilcoxon Signed Rank test. Color differences among the 3 composite resin groups at different stages of the experiment were analysed with Kruskal–Wallis test and a post hoc Mann–Whitney test with Bonferroni correction.

3. Results

3.1. Color changes within each composite resin

Table 3 shows the results of the CIELAB color assessments at different stages of the experiment. Wilcoxon Signed Rank test was used to compare color changes of each composite from its baseline L^*, a^* and b^* values in the CIELAB color system.

After the initial cycle of thermocycling stain challenges, all 3 composite resins showed a statistically significant lower L^* (decrease in lightness) and higher a^* (increase in redness) values ($p < 0.01$). FiltekSU and TPH3 had also higher b^* (increase in yellowness) values ($p < 0.01$). No significant change in b^* values of Renamel was found after the stain challenges ($p > 0.05$), indicating that this composite resin was more resistant to yellow staining than FiltekSU and TPH3.

After 3 min of brushing, the CIELAB values of all 3 composite resins regressed towards their original values, with the exception of b^* values in the FiltekSU group where a statistically significant difference from the baseline remained ($p < 0.01$), indicating that this composite resin is prone to yellow discoloration that cannot be removed by vigorous oral hygiene procedures.

After the second cycle of thermocycling stain challenges, a similar tendency of color changes was observed among the 3 composite resins with lower L^* and higher a^* and b^* values ($p < 0.05$).

After the second 3 min brushing, the CIELAB values did not fully regress to the baseline as occurred in the first cycle. Statistically significant differences remained for all measures of the 3 composite resins with the exception of a^* values in the FiltekSU group where no difference from the baseline was found. These findings indicated that the dark (lower L^*) and yellow (higher b^*) stains of the composite resins became refractory to oral hygiene procedures with time, and that FiltekSU appeared to be more resistant to red stains than TPH3 and Renamel.

3.2. Color differences among the composite resins

Fig. 1 shows the color changes (ΔL^*, Δa^* and Δb^*) among the 3 composite resins at different stages of the experiment as compared to the baseline. Kruskal–Wallis test was used to compare the color differences among the 3 groups and a Mann–Whitney test with Bonferroni correction was used for post hoc pair-wise comparisons.

After initial thermocycling stain challenges, there were statistically significant differences in ΔL^* and Δb^* among the 3 groups ($p < 0.01$). FiltekSU showed significantly higher ΔL^* and Δb^* values than TPH3 and Renamel ($p < 0.01$). There were no significant differences in Δa^* among the 3 groups (Fig. 1A).

After the 3 min brushing, there remained statistically significant differences in Δb^* among the 3 groups ($p < 0.01$).

Table 3 – CIELAB values (mean and standard deviation) of composite discs at baseline and after first and second colorant thermocycling and brushing treatments.

	Filtek			TPH			Renamel		
	L^* (SD)	a^* (SD)	b^* (SD)	L^* (SD)	a^* (SD)	b^* (SD)	L^* (SD)	a^* (SD)	b^* (SD)
Baseline	82.0 (0.6)	2.4 (0.2)	20.1 (0.7)	80.5 (0.6)	2.5 (0.2)	18.1 (0.5)	80.9 (0.7)	1.4 (0.3)	24.5 (1.1)
Stain 1	77.6 (1.2)	2.8 (0.3)	23.7 (0.8)	77.8 (1.0)	2.9 (0.3)	19.6 (0.4)	78.8 (0.5)	2.0 (0.3)	24.9 (0.6)
Brush 1	81.5 (0.7)	2.3 (0.3)	22.1 (0.4)	80.6 (0.6)	2.5 (0.3)	18.7 (0.6)	80.9 (0.7)	1.4 (0.2)	24.5 (0.5)
Stain 2	77.9 (1.1)	2.7 (0.3)	23.0 (0.5)	77.5 (0.5)	3.2 (0.2)	19.6 (0.5)	78.2 (0.5)	2.3 (0.3)	25.1 (0.6)
Brush 2	79.9 (0.8)	2.4 (0.3)	22.8 (0.7)	79.5 (0.6)	2.6 (0.2)	19.4 (0.5)	80.1 (0.7)	1.7 (0.2)	25.4 (0.5)

Stain 1 and 2, Brush 1 and 2 denote values after the first and second stain challenges and after the first and second toothbrush cleaning of the composite resin discs, respectively.

FiltekSU showed significantly higher residual Δb^* values than TPH3 and Renamel after vigorous brushing of the composite resin discs ($p < 0.01$) (Fig. 1B).

After the second cycle of thermocycling stain challenges, there were statistically significant differences in ΔL^*, Δa^* and Δb^* among the 3 groups ($p < 0.01$). FiltekSU showed significantly higher ΔL^* and Δb^* but lower Δa^* values than TPH3 and Renamel ($p < 0.01$) (Fig. 1C).

After the second 3 min brushing, there remained statistically significant differences in ΔL^* and Δb^* among the 3 groups ($p < 0.01$). FiltekSU showed significantly higher ΔL^* and Δb^* values than TPH3 and Renamel ($p < 0.01$). There were no significant differences in Δa^* among the 3 groups (Fig. 1D).

As shown in Table 4 and Fig. 2, the overall color (ΔE^*) was significantly different among the 3 groups at each experimental stage. FiltekSU showed more color change than TPH3 and Renamel after the stain challenges and after brushings ($p < 0.01$).

Vigorous brushing of the discs with a toothbrush and toothpastes for 3 min recovered 57.9% of the color changes for FiltekSU, 59.4% for TPH3 and 44.0% for Renamel after the first cycle of thermocycling stain challenge, and 31.4% for FiltekSU, 48.6% for TPH3 and 41.9% for Renamel after the second cycle of stain challenge, respectively. These findings indicate that composite resin discoloration might mainly be caused by adsorption in the early stage, but more by absorption with the progress of time. This tendency is especially true for FiltekSU, where only 40% of the discoloration may be explained by absorption after the first cycle, but as much as 70% after the second cycle of thermocycling challenge.

4. Discussion

The findings of the present study indicate that color stability was significantly different among the selected composite resins, with Filtek Supreme Ultra showing more severe discoloration than TPH3 and Renamel following thermocycling stain challenges from common dietary colorants.

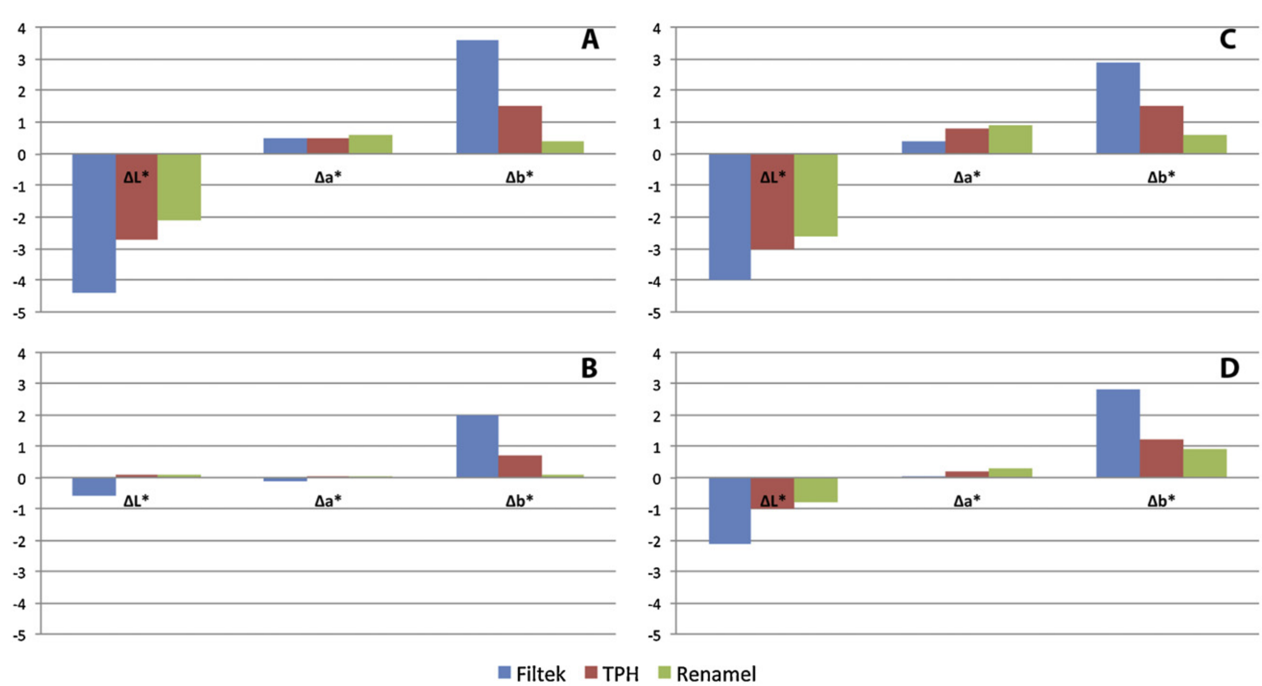

Fig. 1 – Color differences among the 3 composite resins at different stages of the experiments. (A) After the first cycle of thermocycling stain challenges; (B) after 3 min of vigorous brushing following the first cycle of stain challenges; (C) after the second cycle of stain challenges; (D) after 3 min of vigorous brushing following the second cycle of stain challenge.

Table 4 – Changes in overall color (ΔE^*) from baseline at different experimental stages.

	Filtek	TPH	Renamel	Kruskal–Wallis H	p
After Stain 1	5.7 (1.3)	3.2 (0.9)	2.5 (1.1)	29.827	<0.0001
After Brush 1	2.4 (0.7)	1.3 (0.5)	1.4 (0.8)	15.520	<0.001
After Stain 2	5.1 (1.1)	3.5 (0.8)	3.1 (0.9)	21.308	<0.0001
After Brush 2	3.6 (0.7)	1.8 (0.8)	1.8 (1.0)	25.087	<0.0001

In comparison to TPH3 and Renamel, Filtek Supreme Ultra was particularly prone to staining by yellow but less susceptible to staining by red colorants in common beverages. Increase in yellowness of Filtek Supreme Ultra after stain challenges could largely be explained by absorption of the yellow colorants into the resin matrices as the $+b^*$, which represents yellow in the CIELAB color space, could not be reduced through a vigorous cleaning process using a toothbrush and a toothpaste containing silica abrasives. After two rounds of 1000 cycles of thermocycling stain challenges, the residual color change after surface cleaning for Filtek Supreme Ultra was greater than 3.3, a threshold value that was considered unacceptable aesthetically.[46] These findings indicate that aesthetic restorations using Filtek Supreme Ultra may need replacement due to discoloration sooner than Renamel and TPH3 (Fig. 2).

The thermocycling stain challenge model used in the present study incorporates the effects of thermal stress, acidic pH, complex dietary colorants, fluid dynamics, time and mechanical cleanings on color stability of composite resin restorations in the oral cavity. It has been shown that thermal stress and acidic challenges may affect the surface integrity of the composite resins and render them susceptible to discoloration.[44,45] As composite resin restorations in oral cavity endure thermal stress and acidic challenges associated with ingesting hot and cold acidic beverages on a daily basis, any color stability study model must consider the effects of changing temperatures and pH values. As common beverages and foods are in a multitude of combinations of colors, immersion of composite resin discs in a single type of colored fluid does not reflect the staining potential of human drinking and eating behaviour. Furthermore, beverage and food ingestion is a dynamic process that does not allow sustained static retention of fluid in the oral cavity. Yet, almost all available color stability study models involve static immersion of composite resin discs in a single colorant fluid for a prolonged period of time, often for hours, days and weeks without disturbing the medium.[18,20,23,25,38–43] As most beverages including coffee are colloidal suspensions that will precipitate sediments after standing in stagnation, the staining outcome by prolonged immersion may have no resemblance to clinical realities. Many studies have reported ΔE^* values greater than 15, and as high as 32–39 after immersion in coffee for a prolonged period of time.[20,22,23,41] The large ΔE^* values (ranging from 15 to 32) were clearly associated with large ΔL^* values (ranging from 12 to 32) following immersion in coffee for one week, which suggests that the color change might mainly be caused by very dark sediments on the composite surfaces.[23] Fontes et al. reported that immersion of Filtek Z350 discs in coffee 4 h a day for one week resulted in a ΔE^* of 9.1,[18] while Türkün and Türkün found that immersion of Filtek A110 discs in coffee 24 h a day for one week resulted in a ΔE^* of only 0.91.[47] Though the two studies used different spectrophotometers that may potentially create discrepancies in color assessments, the variations in ΔE^* values among different instruments were usually small.[48] Such great a discrepancy in staining outcomes could not be explained by differences in composite compositions either, as Filtek Z350, composed of Bis-GMA, UDMA, TEGDMA and Bis-EMA, should have a better stain resistance profile than Filtek A110, composed of Bis-GMA and TEGDMA, as the addition of UDMA may decrease hydrophilicity and water sorption and

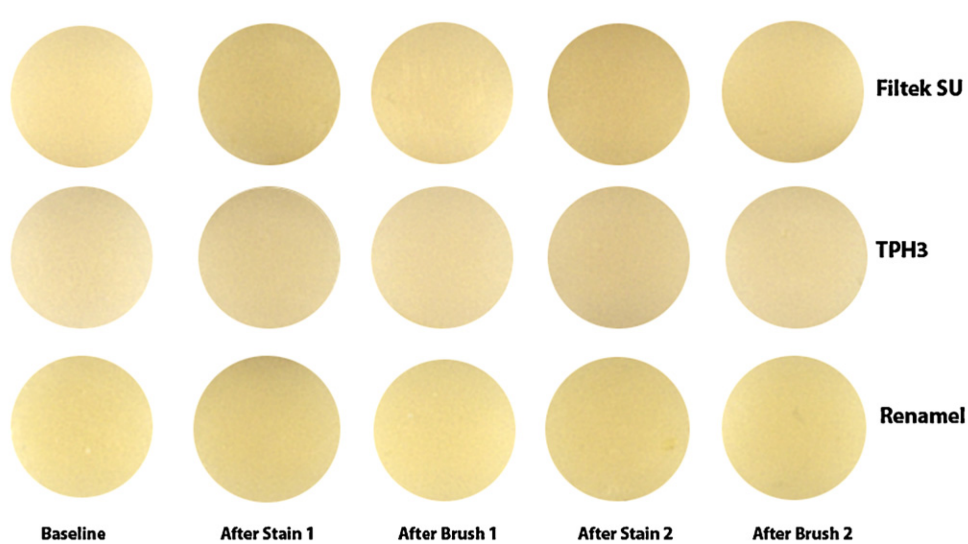

Fig. 2 – Typical images of composite resin discs at different stages of experiment. As compared to TPH3 and Renamel, Filtek Supreme Ultra showed the most severe stain after thermocycling stain challenges.

increase color stability of composite resins.[42,49] The primary difference between these two studies lies in the procedures of post-staining surface cleaning before color measurement – the specimens were simply ‘‘washed’’ in the Fontes study,[18] but were cleaned in a ultrasonic cleaner for 1 min in the Türkün study.[47] These studies provided indirect evidence that static immersion of composite resin discs in coffee may result in color change associated mainly to colorant adsorption on composite resin surfaces. The adsorbed colorants could be easily removed through a mechanical process such as ultrasonic cleaning or brushing. Color change caused by colorant absorption into resin matrix will be refractory to mechanical cleaning and has greater clinical significance as it may signify a need for replacement of restorations. Therefore, a useful color stability model should include a vigorous surface cleaning procedure that can adequately remove the adsorbed colorants on the composite resin surfaces. The findings of the present study showed that thermocycling stain challenges caused color changes in composite resins that could only be partially removed by mechanical cleaning. The residual ΔE^* values after thorough brushing may better reflect the color stability of the studied composite resins.

An interesting finding of the present study is that different composite resins may have different affinity to different dietary colorants. Though small in magnitude, TPH3 and Renamel seemed to have increased affinity to red colorants as compared to Filtek Supreme Ultra, while the latter showed high affinity towards yellow colorants but appeared to be more resistant to red. The significance of this type of differential color affinity is unknown but may be worthy of further study as it may improve our understanding on the mechanisms of composite resin-colorant interactions. As resin polymers and dietary colorants have different polarities, composite materials with a resin matrix that is compatible with the polarities of yellow colorants may facilitate the absorption of yellow colorants into the organic phase of the material.[23] Modification of the resin polymer polarities may therefore potentially improve the stain resistance of composite resin materials.

Our findings showed that Filtek Supreme Ultra had poor color stability as compared to TPH3 and Renamel, which is in agreement with many previous studies that have consistently reported that the Filtek Supreme series products were prone to staining and discoloration.[25,39,41,50,51] The inferior color stability of Filtek Supreme materials has been attributed to its resin matrix and filler compositions.[39,41] The resin matrix of the Filtek Supreme products contains Bis-GMA and TEGDMA, which are considered vulnerable to staining due to their increased hydrophilicity.[34] The fillers of the Filtek Supreme composites are described as micron-sized (0.6–10 μm) clusters formed by aggregated zirconia/silica nanoparticles, which may have porosity that facilitate colorant penetration.[39] As the resin matrix of TPH3 is similar to that of Filtek Supreme Ultra but demonstrated better color stability than the latter, the differences in filler compositions may have played a more important role in determining the stain resistance profile of the two composites. The fillers in TPH3 are submicron-sized (<1 μm) silicate-based solid particles and highly dispersed silicon dioxide nanoparticles, which may explain its improved color stability in comparison to Filtek Supreme Ultra. Renamel contains UDMA and butanediol dimethacrylate (BDMA) in its resin matrix and uses nanometre-scaled polygenic silicic acid as fillers, which proved to be a combination that could yield good color stability within the time frame of the present study.

In summary, the findings of the present study support the hypothesis that the thermocycling stain challenge model can better represent the complex nature of the interactions between dietary colorants and composite resins and can differentiate adsorption from absorption. As thermal stress, acidic pH, complex dietary colorants, fluid dynamics, time and mechanical cleanings are all factors that can potentially affect color stability assessments of composite resins, this model provides a means to look into the complex interactions between these factors and restorative materials in the oral environment. Combined with advanced imaging and laboratory testing tools, we can potentially explore compositional and structural factors of the materials that may affect the color stability of dental restorations. As with any experimental models in vitro, this model has its limitations, such as the lack of consideration for the roles of saliva and oral microbes. It nonetheless allows us to assess the color stability of composite resins better than the existing experimental models. This model was able to identify the product that was susceptible to discoloration and differentiate the relative contributions of surface staining that can be removed by brushing from true discoloration that is refractory to oral hygiene procedures. Information obtained with this model should prove valuable for clinicians to make informed decisions in selecting the best materials for aesthetic restorations for their patients.

Conflict of interest

There is no conflict of interests for all authors involved in this study. Dr. Lin Feng is supported by a research fellowship stipend from the Devision of General Dentistry, University of Rochester Eastman Institute for Oral Health as part of a collaborative programme between University of Rochester and Peking University. There was no external funding for the study.

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