THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Analysis of color differences in stained contemporary esthetic dental materials

Elif Figen Koçak, DDS, PhD,[a] Orhun Ekren, DDS, PhD,[b] William M. Johnston, PhD,[c] and Yurdanur Uçar, DDS, MS, PhD, PhD[d]

ABSTRACT

Statement of problem. Although contemporary analytical methods are available for application to data which exhibit a lack of equality of variances or a lack of normality in the error distribution, little guidance is provided for selecting the methods of data handling and analysis which best fit color difference data for stained esthetic materials.

Purpose. The purposes of this in vitro study were to apply information criteria of analysis of variance (ANOVA) methods of differing error distributions and covariance structures when analyzing color differences to determine the degree of alienation among 3 Commission Internationale de l'Eclairage (CIE) color difference formulae to assess the linearity of relationships among these formulae and to independently assess differences among various computer-aided design and computer-aided manufacture (CAD-CAM) materials in any color change after common forms of staining over time.

Material and methods. Hybrid ceramic, resin nanoceramic, feldspathic-ceramic, and lithium-disilicate ceramic specimens (N=128) were subjected to staining from water, tea, coffee, and red wine over 1, 7, and 30 days, with color differences calculated from baseline. Akaike information criteria (AIC) and Bayesian information criteria (BIC) values were determined for Gaussian and lognormal error distributions at covariance structures of standard variance components and compound-symmetry. The analysis of variance used to analyze any significant effects on these color differences was the one with the lowest AIC and BIC values. Then, for each solution, day, and CIE color difference formula, any significant difference in the color differences between all pairs of materials was found by Bonferroni-corrected Student *t* tests. Those statistically significant pairwise comparisons where the larger of the color differences met or exceeded the acceptability threshold were labeled as statistically and visually noteworthy.

Results. For this color difference data set, the lognormal error distribution and the covariance structure of compound symmetry provided the best AIC and BIC. Because the interaction between material, solution, and day was statistically significant ($P<.0001$), pairwise comparisons were made between all pairs of materials for each level of solution and day studied. Noteworthy differences were identified, where hybrid ceramic and resin nanoceramic each had color changes after staining in coffee and red wine that were greater than each of feldspathic-ceramic and lithium-disilicate ceramic.

Conclusions. AIC and BIC values evaluate distinctively the Gaussian and lognormal error distributions when analyzing highly varying color differences. Although there is a high linear correlation between the 3 color difference formulae studied, each formula is unique, and each represents a different assessment of the perceived color difference. CAD-CAM materials, staining liquids, and time points affected the notable color changes. (J Prosthet Dent 2020;■:■-■)

In addition to having sufficient mechanical properties and durability characteristics that approach or exceed those of natural teeth, contemporary esthetic restorative materials should match the color and appearance of

Supported by the Scientific Research Projects Coordination Unit of Cukurova University, project number TSA-2017-8175 and presented in part as an oral presentation during the VI. International TPID Symposium 2018, Diyarbakır, Turkey.

[a]Lecturer, Department of Prosthetic Dentistry, College of Dentistry and the Abdi Sutcu Vocational School of Health Services, Çukurova University, Balcalı, Adana, Turkey.
[b]Associate Professor, Department of Prosthetic Dentistry, College of Dentistry, Çukurova University, Balcalı, Adana, Turkey and Associate Professor, Department of Advanced Materials and Nanotechnology, Institute of Natural and Applied Sciences, Çukurova University, Balcalı, Adana, Turkey.
[c]Professor Emeritus, Division of Restorative and Prosthetic Dentistry, College of Dentistry, The Ohio State University, Columbus, Ohio.
[d]Professor, Department of Prosthetic Dentistry, College of Dentistry, Çukurova University, Balcalı, Adana, Turkey and Professor, Department of Biotechnology, Institute of Natural and Applied Sciences, Çukurova University, Balcalı, Adana, Turkey and Professor, Department Head, Department of Advanced Materials and Nanotechnology, Institute of Natural and Applied Sciences, Çukurova University, Balcalı, Adana, Turkey.

Clinical Implications

Assessing clinically relevant color changes from staining between materials involves both statistical and color science issues, each of which must be properly evaluated. The lack of notable susceptibility to staining by ceramic materials when compared with resin-containing materials is well supported in vitro.

natural teeth[1] or should at least generally simulate the optical properties of natural teeth. Then, these required characteristics must be maintained long-term in clinical service. Nevertheless, evaluating long-term optical stability issues of newly introduced materials in vivo would not provide the timely information needed to determine their suitability for current use. Therefore in vitro evaluations of simulated clinical environments have been used to assess the optical stability of contemporary esthetic materials.

Staining is a major factor affecting the long-term success of esthetic dental restorative materials. After the susceptibilities to discoloration of resin veneering materials[2] and composite resin interim materials[3] were shown, studies continued to reveal discoloration of various esthetic restorative materials. Discoloration was then shown for nanofilled composite materials,[4,5] microhybrid composite resins,[6] and resin-containing computer-aided design and computer-aided manufacture (CAD-CAM) materials.[7-9] These studies show that the staining of materials depends on the discoloring solution, exposure time and temperature, and composition of the material, and further studies have reported the effects of multiple staining solutions,[10] thermocycling in coffee (Cof),[8,11] thermocycling followed by a staining solution,[12] aging regimens,[13] surface characteristics,[14,15] and processing methods.[16] Stability with regard to color and translucency has also been evaluated.[11,17,18]

Newer CAD-CAM restorative materials are classified into polymer infiltrated ceramics[19,20] and resin nanoceramics (RCs).[21] Advantages of these hybrid polymer-ceramic materials include easier milling and adjustment compared with glass-ceramic materials and polycrystalline ceramics, elasticity more similar to dentin than conventional ceramics, and easier repair with composite resin.[22] Studies conducted on polymer-infiltrated ceramics have reported elastic modulus, hardness, and fracture toughness properties similar to those of dentin and enamel.[21,23] The mechanical properties of polymer infiltrated ceramic materials generally fall between ceramic and RC materials.[24]

RC materials are alternatives to glass-ceramic materials with similar mechanical properties.[25,26] For opposing tooth enamel erosion and tooth brushing abrasion, no difference was found between ceramic-reinforced polymers and lithium disilicate ceramic blocks, yet a decrease in brightness of resin ceramic was found after brushing.[23] Studies on the optical behavior of RC materials have reported the influence of fabrication.[27] A 2014 review[28] summarized developments in resin-composite materials for CAD-CAM applications. The correspondence in color and translucency has also been shown between human dentin and a hybrid ceramic (HC) system.[29] A clinical recommendation of the material for a restoration may be influenced by the effect of a patient's dietary habits on esthetic stability and based on the results of these studies.

Color and color difference calculation methods provided by the Commission Internationale de l'Eclairage (CIE)[30] have been used extensively to show the magnitude of changes in overall color and translucency in reflection. Although a claim was made that the CIELab and CIEDE2000 color differences were linearly correlated,[31] no analysis of the linearity or of the alienation measuring the lack of association[32] between color difference formulae was found in the literature by the authors. However, the CIEDE2000 formula reflected the color differences perceived by the human eye better than the CIELab formula (ΔE^*ab).[33] Perceptibility and acceptability thresholds have been determined for both the CIELab and CIEDE2000(1:1:1) color differences.[34] More recently, the CIEDE2000(2:1:1) color difference formula was reported to provide the best estimate of the visual perception of dental students.[35,36]

CAD-CAM materials are used for patients with a high esthetic expectation, especially in the anterior zone. Even slight color change following the clinical performance causes patient dissatisfaction, and detecting the color change of intraoral restorations precisely is extremely important. Therefore, obtaining the right color difference equation for evaluating the staining of dental restorations is essential. Yet, the perceptibility and acceptability of a color change with the human eye must be accurately quantified. Higher correlation of a color difference calculation and human perception and acceptance provides a more accurate clinical interpretation.

Methods of statistical analyses of color differences studied usually include an analysis of variance of the color differences found, although the nonparametric analysis of a Mann-Whitney U test[37,38] and a Kruskal-Wallis test[38] have also been used to analyze color difference data. When considering methods of analysis, analysis of variance (ANOVA) is generally the more powerful statistical procedure for detecting departures from the null hypothesis.[39] Methods of applying an ANOVA to data which exhibit either a lack of homoscedasticity or a lack of normality in the error distribution, both of which are assumed and required[39] for the

P values from a common ANOVA to be unbiased, are available. In none of the research presented here has an analysis of the Akaike information criterion (AIC)[40] or the Bayesian information criterion (BIC)[41] been used. Because various error distribution functions are possible for the analysis of variance of color difference data,[42] AIC and BIC provide indicators of the error distribution which best fits the data and act in a preliminary analysis to determine the best model[43] for testing the hypotheses of interest in these color difference evaluations. Further, the experimental designs used in assessing color differences can involve repeated measures of the same specimen,[1,7,38] often over time. The statistical analysis of repeated measures involved establishing the covariance structure, by using techniques of the standard variance components or compound symmetry as available in analysis programs.[42]

The purposes of this in vitro study were to determine the AIC and BIC of ANOVA methods of differing error distributions and covariance structures when analyzing highly varying color differences (aim 1) to determine the degree of correlation and alienation between the 3 CIE formulae for color difference and to assess the linearity of the relationships between these CIE formulae (aim 2) and to independently assess differences between various CAD-CAM materials in any color change because of common forms of staining in vitro, taking into consideration both statistical significance and visual acceptability (aim 3). The hypotheses tested were that the statistical analysis method would have different degrees of fit based on their information criteria, that the various color difference formulae would provide unique evaluations of color difference from staining, and that clinically and statistically significant differences would be found in staining between materials.

MATERIAL AND METHODS

The Vita A1 shade materials studied are presented in Table 1. Each of 8 blocks of each material was sectioned into 4 pieces measuring 12×14×1.2 mm with a water-cooled precision cutting machine (Minitom; Struers Inc). The surfaces were polished under water irrigation with abrasive paper disks of 600-, 800- and 1200-grit to adjust the final thickness (±0.1mm), with specimen thickness measured with digital calipers. Each of the 4 specimens from a block was placed into 1 of 4 different solutions. The solutions studied were distilled water (DW) (FarmaTron Sterile Distilled Water; FarmaTron Medical Care Healthcare and Cosmetic Inc), tea (Tea), Cof, and red wine (RW) (Yakut; Kavaklıdere Co). The Tea solution was prepared by immersing 2-g prefabricated doses of Tea (Yellow Label Tea; Lipton) into 150 mL of boiling water for 5 minutes; the Cof solution was prepared by dissolving the content of a 2-g sachet (Nescafe Classic; Nestle) into 200 mL of boiling water.

Table 1. Materials studied

Material	Brand	Code	Main Components*	Manufacturer
Hybrid ceramic	Vita Enamic	HC	UDMA, TEGDMA, 86% feldspar ceramic enriched with aluminum oxide	VITA Zahnfabrik
Resin nanoceramic	GC CeraSmart	RC	Bis-MEPP, UDMA, DMA, 71% silica (20 nm), barium glass (300 nm)	GC Dental Products Europe
Feldspathic-ceramic	Cerec Blocs	FC	SiO_2 (56%-64%), Al_2O_3 (20%-23%), Na_2O (6%-9%), K_2O (6%-8%), CaO (0,%3-0,6%), TiO_2 (0,0%-0,1%)	Dentsply Sirona
Lithium-disilicate ceramic	IPS E.max CAD	LSC	SiO_2 (57%-80%), Li_2O (11%-19%), K_2O, P_2O_5, ZrO_2, ZnO	Ivoclar Vivadent AG

Bis-MEPP, bisphenol A ethoxylate dimethacrylate; DMA, dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate. *Compositions supplied by manufacturers.

Before each color measurement, the spectrophotometer (SpectroShade Micro II; MHT Corp) was calibrated according to the manufacturer's recommendations by using the supplied calibration standard. The average of 3 color determinations by using the CIE Illuminant D65 and the Standard Colorimetric Observer (2 degrees)[30] was used for each color determination. Each specimen was measured with a spectrophotometer against a black background (CIE L*=2.0, a*=1.4, b*=-1.6) with air as an intermediary, to simulate the optical conditions in the mouth.[10,44]

After baseline color determination, each specimen was immersed in its solution for 24 hours and then removed from the staining solution and cleaned in DW for 15 seconds with an ultrasonic cleaner. The specimens were dried by wiping with gauze before being immersed in its freshly prepared staining solution for the next day. Color measurements were recorded for each dry specimen after immersion in the staining solutions for 1, 7, and 30 days. Color differences by using the CIELab, CIEDE2000(1:1:1) (CIE001), and CIEDE2000(2:1:1) (CIE002) formulae were calculated from its baseline according to the method of CIE[30] for each specimen and each day.

First, the normality of all color differences was determined by material, solution, and day by using the Shapiro-Wilk test for normality, and the resultant probabilities were adjusted for repeated testing by the step-down Bonferroni correction. All color differences were analyzed by using a repeated-measures ANOVA (PROC GLIMMIX, SAS Proprietary Software 9.4; SAS Institute Inc), where the between-subject effects were the material and the solution and the within-subject effects were the day and the CIE formula, with all interactions in the model. The AIC and BIC values were determined for each of the error distributions of Gaussian and lognormal at each covariance structure of standard variance

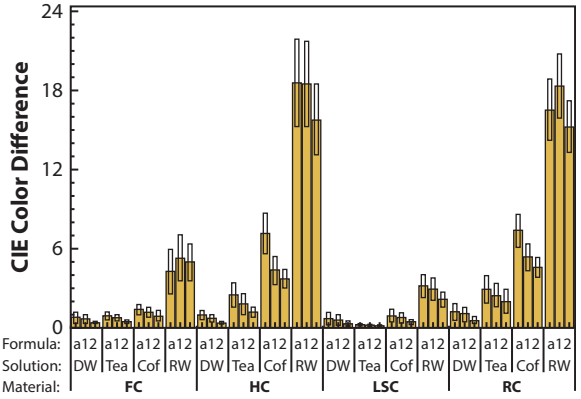


Figure 1. Means and 95% confidence intervals of all color difference formulae (a for CIELAB, 1 for CIE001 and 2 for CIE002) at day 30. CIE, Commission Internationale de l'Eclairage; DW, distilled water; FC, Feldspathic-ceramic; HC, hybrid ceramic; LSC, lithium-disilicate ceramic; RC, resin nanoceramic; RW, red wine.

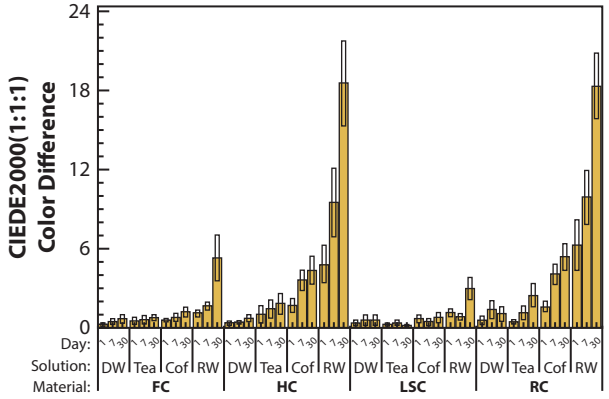


Figure 2. Means and 95% confidence intervals for CIEDE2000(1:1:1) color difference formula at all days studied. DW, distilled water; FC, Feldspathic-ceramic; HC, hybrid ceramic; LSC, lithium-disilicate ceramic; RC, resin nanoceramic; RW, red wine.

components and compound-symmetry. The ANOVA used to analyze any significant effects on these color differences was the one with the lowest AIC and BIC values. Then, for each solution, day and CIE color difference formula, any significant difference in the color differences between all pairs of materials were found by Bonferroni-corrected Student *t* tests, as appropriate for the results of the repeated-measures ANOVA selected as the final analysis to be used. Further, for each pairwise difference, the larger of the color differences was compared with the acceptability threshold (AT) for each of the respective color difference formulae (for DelEab, AT=2.65; for DelE001, AT=1.76; and for DelE002, AT=1.78).[35] Then, only for each pairwise comparison that was found to be statistically significant and where the larger of the color differences was found to meet or exceed the acceptability threshold was the pairwise comparison labeled as statistically and visually noteworthy.

The correlations among each of the 3 CIE color difference formulae were determined for the entire color difference data set. The linearity of the relationships between the 3 CIE formulae was assessed by executing a second order regression of each of the 2 CIEDE2000 color differences to the CIELAB color difference and by this regression of the CIEDE2000(2:1:1) color difference to the CIEDE2000(1:1:1) difference.

For day 30, the means and 95% confidence intervals of all 3 color difference formulae were calculated. For the CIEDE2000(1:1:1) difference formula, the means and 95% confidence intervals by day were also calculated.

RESULTS

Means and 95% confidence intervals are presented in Figure 1 for all CIE formulae, materials, and solutions at day 30, which was the longest time studied. Means and 95% confidence intervals are presented in Figure 2 for all materials, solutions, and days for the CIEDE2000(1:1:1) formula. At day 7, the recorded colors for 1 specimen of HC subjected to the DW solution were categorized as missing because the color data presented as extensive outliers.

Over all material, solution, day, and CIE Formula subgroups, the only significant issue of lack of normality was found for the CIEDE(2:1:1) color differences for HC in Tea at day 1 (P=.0425). To address aim 1, the AIC and BIC values for the 4 ANOVA models studied are provided in Table 2, from which the model determined to produce the best fit for these color differences was the one with the lognormal error distribution and the covariance structure of compound symmetry. To address aim 2 and its application to aim 3, the summary of the null hypotheses tested by the 4-way repeated measure ANOVA of all color difference values by using the model determined to have the best fit is provided in Table 3. As justified by the result that the interaction between material, solution, and day was statistically significant (P<.0001), pairwise comparisons were made between all pairs of materials for each level of solution and day studied. To directly address aim 3, then for each color difference formula, its threshold was compared, and the greater color difference of each pair was found to be statistically significant. Noteworthy differences between all pairs of materials for each solution, day, and CIE formula are presented in Table 4, where the pairs with greater discoloration at or above the acceptability threshold are listed.

To further resolve aim 2, the results of the correlations between each pair of CIE color difference formulae are provided in Table 5. For the studied regression analyses between these color difference values, the second order coefficient was always found to be statistically significant (Each P<.0001). The second order regressions of DelE001 and of DelE002 each on DelEab are shown in Figure 3.

Table 2. AIC and BIC values for models examined

		Values	
Error Distribution	**Covariance Structure**	**AIC**	**BIC**
Gaussian	Compound Symmetry	2638.1	2646.7
Gaussian	Variance Components	3378.6	3384.3
Lognormal	Compound Symmetry	1456.6	1465.2
Lognormal	Variance Components	1822.8	1828.5

AIC, Akaike information criterion; BIC, Bayesian information criterion.

Table 3. Summary statistics for 4-way repeated-measures ANOVA of all color differences

	Degrees of Freedom			
Source of Variation	**Numerator**	**Denominator**	**F-Ratio**	***P***
CIE Formula	2	892.51	192.935	<.0001
Day	2	892.92	458.620	<.0001
Material	3	111.50	129.654	<.0001
Solution	3	111.50	216.434	<.0001
Day × CIE Formula	4	892.51	0.538	.7079
Material × CIE Formula	6	892.51	1.563	.1548
Material × Day	6	892.91	31.399	<.0001
Material × Solution	9	111.50	9.686	<.0001
Solution × CIE Formula	6	892.51	9.004	<.0001
Solution × Day	6	892.91	22.211	<.0001
Material × Solution × CIE Formula	18	892.51	0.977	.4838
Material × Day × CIE Formula	12	892.51	0.132	.9998
Material × Solution × Day	18	892.89	10.646	<.0001
Solution × Day × CIE Formula	12	892.51	0.457	.9394
Material × Solution × Day × CIE Formula	36	892.51	0.228	>.9999

CIE, Commission Internationale de l'Eclairage.

DISCUSSION

The hypotheses tested were each supported by this research. With regard to the first aim and hypothesis, the color difference data in this study reported normality within each of the groups studied except one, yet the analysis of these data when applying traditional analysis of variance did not demonstrate normality of the residuals, also known as the model errors.[45] This then introduces concern about the validity of analyses of color differences, as any analysis of variance can be adjusted by the methods described here to account for different error distributions. As seen in Figures 1 and 2, the distributions of the subgroups with greater mean color differences exhibited greater variation. The lognormal error distribution can be expected to provide a more accurate error distribution when the data set includes both large and small color differences. It can also be expected that comparisons of color differences which are more uniform in the means could have an optimum error distribution that is normal. Therefore, the most appropriate error distribution should be determined for data being analyzed. Limitations of this study included that only 2 error distributions were evaluated. Nevertheless, the conventional analysis of variance, which is based on the assumption that the errors are normally distributed, is biased for at least this color difference data set.

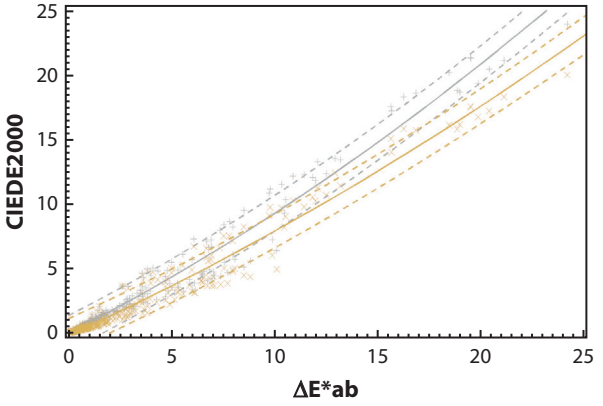


Figure 3. Second order regressions of CIEDE2000(1:1:1) [in black] and CIEDE2000(2:1:1) [in red] to CIELab with 95% confidence limits.

With regard to the second aim and hypothesis, the alienation between the 3 CIE formulae for color difference because of staining indicated that each of these formulae is unique, and each represents a different assessment of the perceived color difference. As noted in Table 4, these unique assessments can often result in the same conclusion for comparisons between materials, as can be expected when large differences in the color changes between 2 materials are noteworthy regardless of the formula used. However, the 4 occurrences of noteworthy differences for 1 color difference formula when the other formulae did not detect this difference indicate how specific the formulae are. Further, the reported lack of linearity between these formulae for these data further indicate that the DelEab cannot always be used as a linear estimate of either of the CIEDE2000 formulae. This study did not directly assess the acceptability of color differences but rather relied on 1 available published study which evaluated acceptability for all 3 color difference formulae when using the same observers.[36]

CIELab[9,13,16,18,37] and CIEDE2000(1:1:1)[8,12,15,38] have been used in studies evaluating the stainability of current CAD-CAM materials. Lee[31] examined the differences between the 2 equations and stated that they were correlated. However, other authors[8,12,38] have stated that the CIEDE2000 formula is more closely correlated with human visual observations of color differences. The human eye is less capable of perceiving the color differences caused by lightness compared with hue.[34,36] Recent studies reported that average participants' observations better correlated with CIEDE2000(2:1:1) compared with CIEDE2000(1:1:1) and CIELab.[35,36]

With regard to the third aim and hypothesis, the factors of material, staining solution, and time affected the magnitude of staining in the CAD-CAM materials studied. These results are consistent with those of

Table 4. Noteworthy pairwise comparisons indicating unacceptable and greater discoloration

			Day 1			Day 7			Day 30		
Solution	**Material 1**	**Material 2**	**CIELAB**	**CIE001**	**CIE002**	**CIELAB**	**CIE001**	**CIE002**	**CIELAB**	**CIE001**	**CIE002**
Coffee	FC	HC	–	–	HC*	HC	HC	HC	HC	HC	HC
Coffee	FC	LSC	–	–	–	–	–	–	–	–	–
Coffee	FC	RC	–	–	–	RC	RC	RC	RC	RC	RC
Coffee	HC	LSC	–	–	HC	HC	HC	HC	HC	HC	HC
Coffee	HC	RC	–	–	–	–	–	–	–	–	–
Coffee	LSC	RC	–	–	–	RC	RC	RC	RC	RC	RC
Tea	FC	HC	–	–	–	–	–	–	HC	–	–
Tea	FC	LSC	–	–	–	–	–	–	–	–	–
Tea	FC	RC	–	–	–	–	–	–	RC	RC	RC
Tea	HC	LSC	–	–	–	–	–	–	HC	–	–
Tea	HC	RC	–	–	–	–	–	–	–	–	–
Tea	LSC	RC	–	–	–	–	–	–	RC	RC	RC
Water	FC	HC	–	–	–	–	–	–	–	–	–
Water	FC	LSC	–	–	–	–	–	–	–	–	–
Water	FC	RC	–	–	–	–	–	–	–	–	–
Water	HC	LSC	–	–	–	–	–	–	–	–	–
Water	HC	RC	–	–	–	–	–	–	–	–	–
Water	LSC	RC	–	–	–	–	–	–	–	–	–
Wine	FC	HC	HC	HC	HC	HC	HC	HC	HC	HC	HC
Wine	FC	LSC	–	–	–	–	–	–	–	–	–
Wine	FC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC
Wine	HC	LSC	HC	HC	HC	HC	HC	HC	HC	HC	HC
Wine	HC	RC	–	–	–	–	–	–	–	–	–
Wine	LSC	RC	RC	RC	RC	RC	RC	RC	RC	RC	RC

CIE, Commission Internationale de l'Eclairage; FC, Feldspathic-ceramic; HC, hybrid ceramic; LSC, lithium-disilicate ceramic; RC, resin nanoceramic. *Material noted under color difference formula 1 of 2 significantly different materials with greater discoloration and unacceptable discoloration using that color difference formula.

Table 5. Correlation attributes between each pair of 3 CIE color difference formulae

Variable	Variable2	Correlation Coefficient	Coefficient of Determination	Coefficient of Nondetermination	Coefficient of Alienation
DelE002	DelE001	0.9976	0.9951	0.0049	0.0699
DelEab	DelE001	0.9830	0.9664	0.0336	0.1834
DelEab	DelE002	0.9809	0.9622	0.0378	0.1944

CIE, Commission Internationale de l'Eclairage.

previous studies.[3,7,12,18,38] It has been reported that alcohol softens the resin matrix and increases the staining,[18] although whether alcohol or the presence of pigments increased the staining potential of RW has not been clarified.[7,15,16] RW includes alcohol, acids, chromogens, and tannins.[18] Tannins increase the capacity of chromogens to adhere to the surfaces of the materials.[18] Discoloration from Tea and Cof exposure has been reported to be mainly from surface adsorption of the yellow colorants.[2]

In vitro studies have reported the staining behavior of CAD-CAM polymers or resin-based cement after immersing in different solutions.[8,9,12,15,16,18,37,38] The effect of staining solutions on different block materials was evaluated on days 1, 7, and 30. As seen in Table 3, a significant interaction was found between the materials, solutions, and days studied. Güler et al[3] stated that keeping specimens in Cof for 24 hours produced equivalent staining to 1 month of typical Cof consumption. For this reason, specimens kept in Cof for 1, 7, and 30 days correspond to 1, 7, and 30 months of Cof consumption, although the daily average effect of consumed wine and Cof quantities may not be equal. The interpretation of color changes according to the time in staining solutions should be considered according to the daily drink amount consumed and the contact time with the teeth.

The technique of identifying greater and unacceptable color differences from staining presented here considered both statistical and visual significance. Any comparison between staining solutions, between stained materials, or between times should be both statistically justified and visually noteworthy. For this study, an a priori decision was made to only compare pairs of materials within each of the staining solutions and times if justified by the analysis of all of the color difference data. However, for future studies, the clinical concern of the differences in the magnitude of staining between solutions for each material may be considered. Given that Bonferroni

adjustments consider the total number of pairwise comparisons being made in this experiment, an a priori limitation in the possible pairwise comparisons to be made will decrease β, the Type II error, or increase the power to detect noteworthy differences. Also, for this study, color differences which were clinically unacceptable were considered noteworthy, yet further studies might use visual imperceptibility as being noteworthy.

The HC and RC CAD-CAM materials were highly stained. This result was consistent with the results reported by others.[9,11,12,38] Resin-ceramic CAD-CAM materials may exhibit higher color change and staining depending on their composition and the content of the composite resin components.[13,16] Water absorption of the polymer compound can be explained by hydrolytic degradation.[16] HC and RC materials have triethylene glycol dimethacrylate (TEGDMA). Because TEGDMA with hydrophilic structure exhibits high water absorption, the staining solution can penetrate the resin much more.[8,10,26] Unacceptable color changes of HC and RC blocks may result from the material composition. When specimen surfaces were examined, regional color changes and surface property changes were observed. On the contrary, Al-Harbi et al[13] reported that the surface properties of RCs did not change after aging and thermocycling. However, the results of the current study suggest an incremental increase in staining and surface degradation over time.

Measurements were made on the black background to simulate the oral environment, similar to some measurements[2,8,10,11] but unlike others.[3-7,9,14] Ardu et al[44] reported that a black or gray background better simulated the intraoral environment than a white background. Care should be taken to evaluate the measurement method for its simulation of the oral environment.

Considering that restorations are cemented on a prepared tooth, the data presented in this study are somewhat overstated because actual restorations are exposed to intraoral fluids only from 1 side. However, the specimens in the current study were in contact with the solutions on both the top and bottom sides. This study reports the findings of an in vitro study. The interpretation of in vitro study results must be carefully made because the clinical evidence is not as high as a prospective in vivo study. The specimen shape was rectangular rather than crown-shaped. This yielded flat surfaces rather than the complex occlusal surface of a crown. Although this could be considered as a limitation of the current study, a flat shape was essential to measure the color change accurately, allowing for characterization of the material. A long-term controlled clinical prospective study is necessary to confirm these results. Nevertheless, assessing clinically relevant color changes because of staining between materials (aim 3) involve both statistical (aim 1) and color science (aim 2) issues, each of which must be properly evaluated. The lack of notable susceptibility to staining by ceramic materials when compared with resin-containing materials is well supported in vitro.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. AIC and BIC values evaluate distinctively the Gaussian and lognormal error distributions when analyzing highly varying color differences.
2. Although there is a high linear correlation between color difference formulae, each of the formulae studied is unique, and each represents a different assessment of the perceived color difference.
3. CAD-CAM materials, staining liquids, and time points used in the current study affected the color change. Some changes were both statistically significant and clinically unacceptable.

REFERENCES

1. Johnston WM, Reisbick MH. Color and translucency changes during and after curing of esthetic restorative materials. Dent Mater 1997;13:89-97.
2. Um CM, Ruyter IE. Staining of resin-based veneering materials with coffee and tea. Quintessence Int 1991;22:377-86.
3. Guler AU, Yilmaz F, Kulunk T, Guler E, Kurt S. Effects of different drinks on stainability of resin composite provisional restorative materials. J Prosthet Dent 2005;94:118-24.
4. Fontes ST, Fernández MR, de Moura CM, Meireles SS. Color stability of a nanofill composite: effect of different immersion media. J Appl Oral Sci 2009;17:388-91.
5. de Oliveira AL, Botta AC, Campos JÁ, Garcia PP. Effects of immersion media and repolishing on color stability and superficial morphology of nanofilled composite resin. Microsc Microanal 2014;20:1234-9.
6. Erdemir U, Yildiz E, Eren MM. Effects of sports drinks on color stability of nanofilled and microhybrid composites after long-term immersion. J Dent 2012;40:55-63.
7. Arocha MA, Basilio J, Llopis J, Di Bella E, Roig M, Ardu S, et al. Colour stainability of indirect CAD-CAM processed composites vs. conventionally laboratory processed composite after immersion in staining solutions. J Dent 2014;42:831-8.
8. Acar O, Yilmaz B, Altintas SH, Chandrasekaran I, Johnston WM. Color stainability of CAD-CAM and nanocomposite resin materials. J Prosthet Dent 2016;115:71-5.
9. Liebermann A, Vehling D, Eichberger M, Stawarczyk B. Impact of storage media and temperature on color stability of tooth-colored CAD/CAM materials for final restorations. J Appl Biomater Funct Mater 2019;17. 2280800019836832.
10. Ceci M, Viola M, Rattalino D, Beltrami R, Colombo M, Poggio C. Discoloration of different esthetic restorative materials: A spectrophotometric evaluation. Eur J Dent 2017;11:149-56.
11. Arif R, Yilmaz B, Johnston WM. In vitro color stainability and relative translucency of CAD-CAM restorative materials used for laminate veneers and complete crowns. J Prosthet Dent 2019;122:160-6.
12. Seyidaliyeva A, Rues S, Evagorou Z, Hassel AJ, Rammelsberg P, Zenthöfer A. Color stability of polymer-infiltrated-ceramics compared with lithium disilicate ceramics and composite. J Esthet Restor Dent 2020;32:43-50.
13. Al-Harbi FA, Ayad NM, ArRejaie AS, Bahgat HA, Baba NZ. Effect of aging regimens on resin nanoceramic chairside CAD-CAM material. J Prosthodont 2017;26:432-9.
14. Gonulol N, Yilmaz F. The effects of finishing and polishing techniques on surface roughness and color stability of nanocomposites. J Dent 2012;40:e64-70.
15. Bagheri R, Burrow MF, Tyas M. Influence of food simulating solutions and surface finish on susceptibility to staining of aesthetic restorative materials. J Dent 2005;33:389-98.
16. Alharbi A, Ardu S, Bortolotto T, Krejci I. Stain susceptibility of composite and ceramic CAD/CAM blocks versus direct resin composites with different resinous matrices. Odontology 2017;105:162-9.
17. Awad D, Stawarczyk B, Liebermann A, Ilie N. Translucency of esthetic dental restorative CAD-CAM materials and composite resins with respect to thickness and surface roughness. J Prosthet Dent 2015;113:534-40.

18. Quek SHQ, Yap AUJ, Rosa V, Tan KBC, Teoh KH. Effect of staining beverages on color and translucency of CAD/CAM composites. J Esthet Restor Dent 2018;30:9-17.
19. Nguyen JF, Ruse D, Phan AC, Sadoun MJ. High-temperature pressure polymerized resin-infiltrated ceramic networks. J Dent Res 2014;93:62-7.
20. Nguyen JF, Migonney V, Ruse ND, Sadoun M. Resin composite blocks via high-pressure high-temperature polymerization. Dent Mater 2012;28:529-34.
21. He LH, Swain M. A novel polymer infiltrated ceramic dental material. Dent Mater 2011;27:527-34.
22. Gracis S, Thompson VP, Ferencz JL, Silva NR, Bonfante EA. A new classification system for all-ceramic and ceramic-like restorative materials. Int J Prosthodont 2015;28:227-35.
23. Mormann WH, Stawarczyk B, Ender A, Sener B, Attin T, Mehl A. Wear characteristics of current aesthetic dental restorative CAD-CAM materials: two-body wear, gloss retention, roughness and Martens hardness. J Mech Behav Biomed Mater 2013;20:113-25.
24. Della Bona A, Corazza PH, Zhang Y. Characterization of polymer-infiltrated ceramic-network material. Dent Mater 2014;30:564-9.
25. Dupriez ND, von Koeckritz AK, Kunzelmann KH. A comparative study of sliding wear of non-metallic dental restorative materials with emphasis on micromechanical wear mechanisms. J Biomed Mater Res B Appl Biomater 2015;103:925-34.
26. Belli R, Geinzer E, Muschweck A, Petschelt A, Lohbauer U. Mechanical fatigue degradation of ceramics versus resin composites for dental restorations. Dent Mater 2014;30:424-32.
27. Güth JF, Zuch T, Zwinge S, Engels J, Stimmelmayr M, Edelhoff D. Optical properties of manually and CAD-CAM-fabricated polymer. Dent Mater J 2013;32:865-71.
28. Ruse ND, Sadoun MJ. Resin-composite blocks for dental CAD-CAM applications. J Dent Res 2014;93:1232-4.
29. Pop-Ciutrila IS, Dudea D, Eugenia BM, Moldovan M, Cîmpean SI, Ghinea R. Shade correspondence, color, and translucency differences between human dentine and a CAD-CAM hybrid ceramic system. J Esthet Restor Dent 2016;28:46-55.
30. Commission Internationale de l'Eclairage (CIE). Colorimetry, 4th ed. CIE Technical Report 015. Vienna, Austria: CIE Central Bureau; 2018.
31. Lee YK. Comparison of CIELAB Delta E and CIEDE2000 color differences after polymerization and thermo-cycling of resin composites. Dent Mater 2005;21:678-82.
32. Sokal RR, Rohlf FJ. Section 15.2 "The Product-Moment Correlation Coefficient". In: Biometry, 3rd ed. New York: W. H. Freeman and Co; 1995. p. 559-66.
33. Gómez-Polo C, Portillo Muñoz M, Lorenzo Luengo MC, Vicente P, Galindo P, Martín Casado AM. Comparison of the CIELab and CIEDE2000 color difference formulas. J Prosthet Dent 2016;115:65-70.
34. Paravina RD, Ghinea R, Herrera LJ, Della Bona A, Igiel C, Linninger M, et al. Color difference thresholds in dentistry. J Esthet Restor Dent 2015;27(Supplement 1):S1-9.
35. Pecho OE, Ghinea R, Alessandretti R, Pérez MM, Della Bona A. Visual and instrumental shade matching using CIELAB and CIEDE2000 color difference formulas. Dent Mater 2016;32:82-92.
36. Pecho OE, Pérez MM, Ghinea R, Della Bona A. Lightness, chroma and hue differences on visual shade matching. Dent Mater 2016;32:1362-73.
37. Sarıkaya I, Yerliyurt K, Hayran Y. Effect of surface finishing on the colour stability and translucency of dental ceramics. BioMed Center Oral Health 2018;18:40.
38. Barutçugil Ç, Bilgili D, Barutcigil K, Dündar A, Büyükkaplan UŞ, Yilmaz B. Discoloration and translucency changes of CAD-CAM materials after exposure to beverages. J Prosthet Dent 2019;122:325-31.
39. Sokal RR, Rohlf FJ. Assumptions of analysis of variance. In: Biometry, 3rd ed. New York: W. H. Freeman and Co; 1995. p. 392-447.
40. Akaike H. A new look at the statistical model identification. IEEE Transactions on Automatic Control 1974;19:716-23.
41. Schwarz GE. Estimating the dimension of a model. Annals of Statistics 1978;6:461-4.
42. SAS Institute Inc. The GLIMMIX procedure. In: SAS/STAT 14.1 User's Guide. Cary, NC: SAS Institute Inc; 2015. p. 3188-522.
43. Burnham KP, Anderson DR. Multimodel inference: understanding AIC and BIC in model selection. Sociological Methods & Research 2004;33:261-304.
44. Ardu S, Braut V, Di Bella E, Lefever D. Influence of background on natural tooth colour coordinates: an in vivo evaluation. Odontology 2014;102:267-71.
45. Sokal RR, Rohlf FJ. Introduction to analysis of variance. In: Biometry, 3rd ed. New York: W. H. Freeman and Co; 1995. p. 201-3.

Corresponding author:
Dr William M. Johnston
Division of Restorative and Prosthetic Dentistry
College of Dentistry
The Ohio State University
305 West 12th Ave
Columbus
Ohio, 43210
Email: Johnston.5@osu.edu

CRediT authorship contribution statement

Elif Figen Koçak: Investigation, Resources, Writing - original draft, Project administration. **Orhun Ekren:** Software, Visualization, Methodology. **William M. Johnston:** Validation, Formal analysis, Data curation, Writing - review & editing. **Yurdanur Uçar:** Conceptualization, Supervision, Methodology, Writing - review & editing.

Copyright © 2020 by the Editorial Council for *The Journal of Prosthetic Dentistry.*
https://doi.org/10.1016/j.prosdent.2020.08.006