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Discoloration Resistance of Various Computer Aided Design/Computer Aided Manufacturing Restorative Materials

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Abstract

Background: Evaluating the prolonged efficacy of restorative materials hinges significantly on their ability to resist discoloration. This study aims to assess the discoloration resistance of computer-aided design/computer-aided manufacturing restorative materials featuring distinct chemical compositions.

Methods: A1-colored samples from 4 diverse CAD/CAM restorative materials (Lava Ultimate, Tetric CAD, Vita Enamic, and IPS e.max CAD), each with a 2 mm thickness (n=12), were meticulously prepared. Baseline CIE $L^*a^*b^*$ values were measured using a spectrophotometer, and randomly assigned samples were subjected to a 28-day immersion in either distilled water (control group) or coffee (n=6). After the designated period, CIE $L^*a^*b^*$ values were reevaluated, and ΔE_{ab} values were computed. A 2-way analysis of variance test was employed to scrutinize the influence of both the restorative material type and solution type on quantitative variables ($P < .05$).

Results: In the comparison of samples immersed in coffee, IPS e.max CAD demonstrated significantly less staining than other samples, while Lava Ultimate exhibited significantly more staining ($P < .05$). No significant difference in ΔE_{ab} was observed among CAD/CAM restorative materials kept in distilled water. Although the ΔE_{ab} values of specimens immersed in distilled water remained below the CIELAB 50 : 50% acceptability threshold (ΔE_{ab}=2.7), samples immersed in coffee exceeded this threshold.

Conclusion: The resistance to discoloration is influenced by both the restorative material and the nature of the solution. Consequently, clinicians may opt for restorative materials displaying heightened discoloration resistance or provide comprehensive guidance to patients regarding staining beverages and effective oral hygiene practices.

Keywords: Computer-aided design/computer-aided manufacturing, color stability, discoloration, resin-matrix ceramics

INTRODUCTION

Modern dentistry increases the demand for aesthetic restorations, and color harmony is a very important criterion for aesthetics.[1] Maintaining the achieved color harmony is a critical factor in determining the success of the restoration. In this context, important breakthroughs have been made in material development in recent years.[2] One of these is dental computer-aided design/computer-aided manufacturing (CAD/CAM) systems, which have been used in dentistry owing to technical developments in hardware, software, and materials. This technique offers a more rapid, compatible, and superior indirect prosthetic treatment.[3,4] Another important development is the diversification of metal-free fixed restorations due to aesthetic concerns. For this purpose, ceramics containing leucite, lithium disilicate, or zirconia have come to the fore.[4] However, since these materials have different physical, chemical, optical, and mechanical properties, there is no single system suitable for all cases. For example, leucite-containing glass ceramics are generally recommended for single-unit restorations because they are brittle materials, but the milling process is relatively short and can be produced in the office. Zirconia-containing oxide ceramics, on the other hand, have high fracture strength, so multi-unit restorations can be

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made, but they are not very suitable for in-office production due to the long milling and sintering time.[3,5] Besides these, glass and oxide ceramics have further disadvantages: They are difficult to adjust, take more time to ensure ideal contacts and occlusal relationship, require glaze firing and firing for characterization to ensure adequate mechanical strength, and can cause abrasion in the opposing dentition.[3,6-9] Due to the inherent disadvantages associated with glass ceramics and oxide ceramics, manufacturers continually strive to meet the growing demand by introducing new products and innovative production techniques.[10] One such advancement in this domain is the emergence of resin-matrix ceramics. Marketed under various brands and assigned different generic names like resin nanoceramics, resin composite, and polymer-infiltrated ceramic network, these products showcase diverse compositions and production methods that amalgamate the advantageous properties of both resin and ceramic materials.[5,9-13]

In comparison to glass ceramics and oxide ceramics, resin-matrix ceramics present several notable advantages. They exhibit a more reasonable fragility index and stand out by not requiring additional firing, distinguishing them from partially sintered CAD/CAM materials. With a lower hardness (H), they result in diminished wear on the opposing arch and boast quicker production capabilities when employed with CAD/CAM devices. Furthermore, their enamel-like flow properties and reduced hardness contribute to superior stress distribution, while a lower frequency of crack progression is observed due to deviations in crack patterns. These ceramics demonstrate higher damage tolerance and experience less frequent chipping. Moreover, their adjustability both inside and outside the oral cavity, coupled with the ability to be repaired using composites, adds to their versatility and appeal in dental applications.[5,7,9,14,15] However, the efficacy of dental restorations is contingent not only on their mechanical and physical attributes but also on achieving an aesthetically pleasing appearance.[9,16,17] Esthetic restorative materials must exhibit exceptional color matching and display high discoloration resistance throughout functional use.[9] Restorative materials are regularly exposed to various oral conditions, including consumption of food, beverages, and smoking, which may contribute to discoloration.[17] Composite resin restorations, in particular, have been noted for their susceptibility to discoloration in the oral environment due to water absorption.[14] Previous investigations have highlighted that both extrinsic and intrinsic factors can lead to discoloration in composite resins.[17] Extrinsic factors involve exposure to staining substances like coffee, tea, and cola, the material's surface properties, dietary composition, and oral hygiene, while intrinsic factors encompass aspects such as the composition of the resin matrix, polymerization degree, and filler size.[16,17] Given its propensity for staining, coffee immersion is regarded as a valid testing method to assess the propensity of materials with resin-matrix to discolor. It was anticipated that CAD/CAM resin-matrix ceramic materials, owing to their industrially idealized process of polymerization, would exhibit greater resistance to discoloration.[16]

The Commission Internationale de l'Eclairage (CIE) $L^*a^*b^*$ color system is a system often used in instrumental color analysis, relating it to human color perception. The CIE $L^*a^*b^*$ color system contains 3 coordinates that determine color. Color difference, represented by ΔE_{ab}, is a mathematical calculation that expresses both the direction and magnitude of the disparity between 2 points in a 3-dimensional color space.[14,18] Numerous studies have assessed both the perceptibility threshold and acceptability threshold concerning ΔE_{ab} values. These thresholds play a crucial role as a quality verification tool, guiding the preference of materials that possess optimal aesthetic characteristics. The perceptibility threshold represents the level of color difference that can be detected by the eye.[19] On the other hand, the acceptability threshold denotes the extent of color variation that is considered acceptable for tooth-colored restorative materials. These criteria provide valuable insights into the perceived color differences and the acceptable range for esthetically pleasing restorations.[4,18,20]

In numerous studies, the impact of various beverages on the color stability of resin composites has been investigated, and it has been revealed that the color change in resin composites may vary depending on the organic matrix type and inorganic particle content.[2,14,17] Therefore, this study aimed to compare the influence of coffee, a beverage known for its high staining potential, on the discoloration resistance of resin-matrix ceramic CAD/CAM material with different content and manufacturing techniques using ΔE_{ab} values. Lithium disilicate-based glass ceramic served as the control group for restorative materials, and distilled water served as the control group for the immersing solution. The null hypotheses were set as follows: (1) there is no difference in color change between the different CAD/CAM restorative materials used in the study; and (2) different immersing solution types affect the CAD/CAM restorative materials at the same rates in terms of discoloration.

MATERIAL AND METHODS

In this investigation, all procedures conformed to the guidelines outlined in the Declaration of Helsinki. As the study did not involve materials of human origin or any other living thing, ethics committee approval was not required.

Four A1-colored, high translucent CAD/CAM restorative materials including a resin nanoceramic block (Lava Ultimate [LU; 3M/ESPE, St. Paul, Minn, USA]), a resin composite block (Tetric CAD [TET; Ivoclar Vivadent AG, Schaan, Liechtenstein]), a polymer-infiltrated ceramic block (Vita Enamic [VE; Vita Zahnfabrik GMbH, Bad Säckingen, Germany]), and a lithium disilicate glass-ceramic block (IPS e.max CAD [EMX; Ivoclar

Table 1. Materials Used in the Study

Material	Batch	Type	Composition
Lava Ultimate (LU; 3M ESPE, St. Paul, Minn, USA)	N619802	Resin nano-ceramic	Bis-GMA, UDMA, Bis-EMA, TEGDMA. Filler: SiO_2 (20 nm), ZrO_2 (4-11 nm), Si/ZrO_2 cluster (0.6-10 μm), 80% by weight.
Tetric CAD (TET; Ivoclar Vivadent AG, Schaan, Liechtenstein)	X44070	Resin composite	Bis-EMA, Bis-GMA, TEGDMA, UDMA. Filler: barium aluminum silicate glass (<1 μm), SiO_2 (<20 nm), 71% by weight
Vita Enamic (VE; Vita Zahnfabrik H. Rauter, Bad Sackingen, Germany)	78560	Polymer-infiltrated ceramic network	TEGDMA, UDMA. Filler: feldspar ceramic enriched with aluminum oxide, 86% by weight.
IPS e.max CAD (EMX; Ivoclar Vivadent AG, Schaan, Liechtenstein)	Z00921	Lithium disilicate glass-ceramic	SiO_2 (57%-80%), Li_2O (11%-19%), K_2O (0%-13%), P_2O_5 (0%-11%), ZrO_2 (0%-8%), ZnO (0%-8%), Al_2O_3 (0%-5%) MgO (0%-5%), coloring oxides (0%-8%) by weight.

Bis-EMA, bisphenol A polyethylene glycol diether dimethacrylate; Bis-GMA, bisphenol A diglycidyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, urethane dimethacrylate.

Vivadent AG, Schaan, Liechtenstein]) were analyzed in this study. The materials' compositions are displayed in Table 1.

Specimen Preparation

From each CAD/CAM restorative material, 12 samples were prepared with a precision cutter (Mecatome T180, PRESI, Eybens, France). The crystallization of EMX was performed following the manufacturer's instructions. The specimen's thickness of 2 mm was verified using a digital micrometer (C-master; Mitutoyo, Japan). Any outliers were identified and subsequently replaced with new specimens adhering to the specified dimensions. Then, the samples were polished with 600-, 800-, 1200- and 2000-grit sandpapers, respectively. Subsequently, the samples were ultrasonically cleaned in deionized water for 10 min and dried with compressed air for 30 seconds before the spectrophotometric analysis.

Spectrophotometric Color Analysis

The baseline CIE $L^*a^*b^*$ values of each sample were measured from the polished surface, against a white background ($L^*=98.20$, $a^*=-3.52$, and $b^*=4.65$), using a calibrated spectrophotometer (Vita Easyshade V, Vita Zahnfabrik, Bad Sackingen, Germany).[10,12,21] The illumination from the light source corresponded to the characteristics of average daylight (D65). Then, the samples were randomly separated into 2 groups (n=6) depending on the immersion solution type: distilled water (control group) and coffee. The coffee was prepared by dissolving 2 g of instant coffee powder (Nescafe Gold, Nestle, Vevey, Switzerland) in 200 mL of hot water as recommended by the manufacturer. Six samples of each CAD/CAM restorative material were soaked in each of the solutions (coffee and distilled water). The solutions were renewed daily, and to minimize the precipitation of particles in the solutions, they were stirred 2 times a day. After a 28-day immersion period, the specimens were washed with pressurized water for 3 minutes to remove the remnants of solutions and air-dried. Then, the color measurement values of the samples were repeated as in the initial color measurement. The ΔE_{ab} was determined according to the L^*, a^*, and b^* against a white background using the following equation:

$$\Delta E_{ab}=[(L^*_0-L^*_1)^2+(a^*_0-a^*_1)^2+(b^*_0-b^*_1)^2]^{1/2}$$

where L^* denotes brightness, a^* indicates redness to greenness, and b^* represents yellowness to blueness. The subscripts 0 and 1 indicate the color coordinates before and after immersion, respectively.[22-24] ΔE_{ab} = 1.2 was determined as the CIELAB 50:50% perceptibility threshold, meaning 50% of the observers perceived this amount of color change while 50% of the observers did not. ΔE_{ab} = 2.7 was determined as the CIELAB 50:50% acceptability threshold, meaning 50% of the observers considered this amount of color change acceptable while 50% of the observers did not.[18]

Statistical Analysis

Statistical analysis was performed using The Statistical Package for Social Sciences version 21.0 software (IBM Corp.; Armonk, NY, USA). The mean values of ΔE_{ab} data and their corresponding standard deviations were determined, and the Shapiro–Wilk tests were used to find out whether the data distribution was normal. A 2-way analysis of variance (ANOVA) test was applied to examine the influence of the material types and solutions on discoloration resistance, and the significance level was determined as $P < .05$.

RESULTS

As seen in Figure 1, no significant difference in ΔE_{ab} was observed between the CAD/CAM restorative materials (LU, $\Delta E_{ab}=1.70 \pm 1.07$; TET, $\Delta E_{ab}=0.73 \pm 0.14$; VE, $\Delta E_{ab}=1.24 \pm 0.23$; and EMX: $\Delta E_{ab}=0.74 \pm 0.12$) kept in distilled water. However, significant differences were found in terms of ΔE_{ab} among all the coffee-immersed CAD/CAM restorative materials. When compared, LU ($\Delta E_{ab}=19.64 \pm 0.80$) was observed as the least resistant to discoloration. On the other hand, EMX samples ($\Delta E_{ab}=4.11 \pm 0.85$) were discolored significantly less than the rest of the CAD/CAM restorative material samples. In addition, VE ($\Delta E_{ab}=15.15 \pm 0.69$) discolored significantly less than TET ($\Delta E_{ab}=16.79 \pm 0.88$) ($P < .05$).

Regarding the CIELAB 50:50% perceptibility threshold, only the ΔE_{ab} value of the water-immersed LU samples exceeded

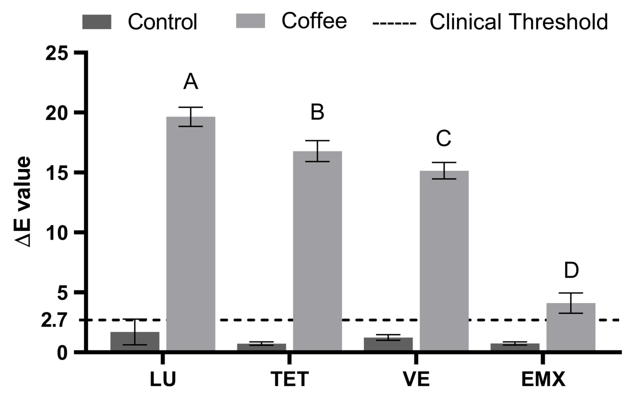

Figure 1. Color change of the CAD/CAM restorative materials. Different uppercase letters on the graphic bars imply significant differences among CAD/CAM restorative materials. LU, Lava Ultimate; TET, Tetric CAD; VE, Vita Enamic; EMX, IPS e.max CAD.

ΔE_{ab}=1.2, while ΔE_{ab} values of all the samples kept in coffee exceeded this threshold. Regarding the CIELAB 50:50% acceptability threshold, none of the samples' ΔE_{ab} values, kept in distilled water, exceeded ΔE_{ab}=2.7, while ΔE_{ab} values of all coffee-immersed CAD/CAM restorative materials exceeded this threshold.

DISCUSSION

In this in vitro study, significant differences in color stability were found between different coffee-immersed CAD/CAM restorative materials. However, no significant differences were observed between CAD/CAM restorative materials immersed in distilled water. Additionally, different immersion solutions were found to affect the color change of CAD/CAM restorative materials at different rates. Therefore, the first part of the null hypothesis is rejected, while the second part is fully accepted.

The previous studies reported that the color change is dependent on both the immersion solution and the restorative material, which is parallel with the present study.[12,16] The reason for the differences between the amount of color changes of restorative materials is mostly related to their different structure and composition.[12,16,25] For instance, EMX demonstrated significantly less discoloration compared to the other CAD/CAM restorative materials in this study, parallel to the results of the previous studies.[7,12,26,27] This can be attributed to its lack of resin matrix, regular microstructure, and the hydrophobic nature of ceramics in EMX.[1,21] In addition, VE displayed better resistance to discoloration than LU and TET, which could be explained by its higher percentage of ceramic fillers (86%) compared to these restorative materials, its monomer types, and its manufacturing technique.[2,26] Regarding the manufacturing technique, VE has a ceramic network composed of feldspar ceramic enriched with aluminum oxide, and the polymers composed of urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA) monomers are infiltrated into it. On the other hand, LU and TET have a resin matrix composed of bisphenol A diglycidyl methacrylate (Bis-GMA) and bisphenol A polyethylene glycol diether dimethacrylate, apart from UDMA and TEGDMA monomers, and the fillers are integrated into this resin matrix.[8] Regarding the monomer types, Bis-GMA and TEGDMA are recognized for their elevated water absorption rates.[21,24] In contrast, the lack of a hydroxyl side group in UDMA yields a less hydrophilic and more viscous matrix, contributing to enhanced color stability.[12,21,24] Though LU and TET also have UDMA as a component, the manufacturers did not declare the ratio of these monomers and UDMA in LU and TET might be less than VE, and the ratio of Bis-GMA and TEGDMA in LU and TET might be more than UDMA. This might explain why VE is more resistant to discoloration since water sorption is correlated with color stability as it results in the absorption of the staining pigments into the resin matrix.[16,28] Previous research has also found that the stainability of LU is more than VE when immersed in coffee for long periods and attributed this to the differences in monomer components.[1,17,25,26,28,29] However, LU was found to be less resistant to discoloration than TET, despite the same types of monomers they contain. The reason for that might be again the different ratios of these monomers, different industrial polymerization processes, and types, sizes, and distribution of their filler particles which affect water sorption.[1,16] Smaller filler sizes have been reported to provide a more regular microstructure, which also results in better optical and chemical properties.[21] Lava Ultimate has Si/ZrO_2 clusters of 0.6-10 μm as its fillers which are greater than TET's filler particles, which might explain the superior color stability of TET over LU.

In this study, aligning with the previous studies, there were no significant changes in the color of restorative materials soaked in water, while significant changes occurred in restorative materials soaked in coffee, indicating that the discoloration resistance depends not only on the restorative material but also on the type of solution.[7,11] Previous research also reported that the discoloration effects induced by staining solutions on resin composites are influenced by the characteristics of the pigments, pH, and the intensity of the solutions.[26,30] The propensity for staining is perceived to increase in low-pH beverages due to surface roughness.[29] This study specifically chose coffee as a staining solution due to its abundance of chromogenic substances such as tannin and chlorogenic acid, surpassing other beverages.[27] Reports indicate that solutions with a pH between 4 and 6 have a higher potential for infiltrating resin materials, with the mildly acidic nature of coffee (4.9-5.2) acting as an enhancing factor.[7,27] Furthermore, when examining the impact of coffee on discoloration, it has been noted that the yellow colorants in these solutions possess low polarity, allowing them to adhere to the surface and penetrate deeper.[7,14] All these properties make coffee an ideal immersion solution for testing discoloration resistance, so it is commonly used.[1,8,25]

In this study, according to the CIELAB 50:50% acceptability threshold after 28 days of coffee immersion, all tested samples exceeded the acceptability threshold, parallel to the previous studies.[11,26] However, previous research has proposed that coffee immersion for 1 day is comparable to the staining effect incurred from 1 month of regular coffee consumption, assuming the coffee remains in the oral cavity while drinking. Therefore, a 28-day coffee immersion of specimens for the assessment of resulting staining effects might be an overestimation compared to real-world scenarios.[16] Nevertheless, another study mentioned that 28 days of immersion corresponds to 10 minutes exposure to coffee per day for 11 years, which is close to the survival period of an all-ceramic restoration, thereby this duration is preferred in this study.[25,31,32] On the other hand, another study testing discoloration resistance of EMX, VE, and LU immersed in coffee for 28 days reported that none of these materials exceeded the acceptable threshold. However, in that study, the solution underwent stirring every 5 minutes for 10 seconds until it reached room temperature. Subsequently, it was filtered through a paper filter, diluting the solution intensity. In addition, the CAD/CAM samples used in that study were polished with a polishing device that might have reduced roughness.[7] These differences in the test setup might have caused the results that contradict our study since the surface properties, thermal stress, and solution intensity are factors that might affect the discoloration resistance of a restorative material.[1]

In this study, which investigates the discoloration resistance of CAD/CAM restorative materials, it was observed that EMX exhibited the highest resistance, while LU showed the least resistance. However, it was noted that all restorative materials exceeded the CIELAB 50:50% acceptability threshold after being immersed in coffee for 28 days. It is highlighted that the discoloration in these restorative materials is predominantly extrinsic.[2] To prevent or minimize discoloration of restorations, the researchers recommended paying regular attention to oral hygiene. In cases where discoloration cannot be prevented, the researchers suggested the application of teeth whitening or prophylactic polishing procedures to address the discoloration.[2,23,24,28]

This in vitro study aimed to assess the discoloration effects of immersing CAD/CAM restorative materials in coffee and distilled water for 28 days. While this investigation provides valuable insights into the discoloration dynamics of these restorative materials, it is essential to acknowledge the inherent limitations. Restorative materials in the oral environment encounter a range of exposures, including various liquids, temperature fluctuations, load stress, and oral hygiene procedures.[6,10,16] One notable limitation of this study is the inability to completely replicate the intricate nature of the intraoral conditions and its potential influence on the discoloration of CAD/CAM restorative materials. Recognizing these limitations is crucial for interpreting the study's findings and extrapolating them to real-world clinical scenarios. However, in vitro studies are preferred in terms of high standardization of experimental conditions, control of variables that may affect the results, obtaining data that cannot be measured in the clinic, working with more samples in a relatively short time, and reproducibility of experiments. In addition, CIE has more recently developed the CIEDE00 formula, but the CIE $L^*a^*b^*$ formula was used in this study for ease of calculation and comparison with other studies due to its widespread use, and because a strong correlation between ΔE_{ab} and ΔE_{00} has been reported.[21,25,33] Furthermore, while the spectroradiometer is considered the gold standard for the measurement of color parameters for its laboratory-level precision, but since the measurement position is very sensitive and the device is not widely available, the use of a spectrophotometer, which is easier and widespread, highly consistent with 96.4% reliability, was preferred in our study.[12,21,34,35] Further studies are recommended to assess the influence of supplementary contributing factors on discoloration resistance of CAD/CAM restorative materials using a spectroradiometer. Additionally, the effects of staining beverages on the CAD/CAM restorative materials' surface properties and other optical properties should also be tested.

Within the limits of this in vitro study, the following conclusions were reached:

1. Statistically significant differences in discoloration resistance were observed between CAD/CAM restorative materials immersed in coffee ($P < .05$).
2. The ΔE_{ab} values for samples immersed in distilled water remained below the CIELAB 50:50% acceptability threshold. In contrast, the ΔE_{ab} values for samples immersed in coffee surpassed this threshold. Therefore, the restorative materials used in this study can be safely used in individuals who do not consume coloring agents such as coffee, while those who consume coloring agents can be considered to remove discoloration by polishing or bleaching with routine controls.

Ethics Committee Approval: No ethical approval was required for this study since it did not involve any studies with human participants or animals performed by the author.

Informed Consent: For this type of study, informed consent is not required.

Peer-review: Externally peer-reviewed.

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Declaration of Interests: The authors have no conflicts of interest to declare.

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