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Comparison of fracture strength, surface hardness, and color stain of conventionally fabricated, 3D printed, and CAD-CAM milled interim prosthodontic materials after thermocycling

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PURPOSE. The purpose of this *in vitro* study was to investigate the fracture resistance, surface hardness, and color stain of 3D printed, CAD-CAM milled, and conventional interim materials. **MATERIALS AND METHODS.** A total of 80 specimens were fabricated from auto polymerizing polymethyl methacrylate (PMMA), bis-acryl composite resin, CAD-CAM polymethyl methacrylate resin (milled), and 3D printed composite resin (printed) (n = 20). Forty of them were crown-shaped, on which fracture strength test was performed (n = 10). The others were disc-shaped specimens (10 mm × 2 mm) and divided into two groups for surface hardness and color stainability tests before and after thermal cycling in coffee solution (n = 10). Color parameters were measured with a spectrophotometer before and after each storage period, and color differences (CIEDE2000 [DE00]) were calculated. The distribution of variables was measured with the Kolmogorov Smirnov test, and one-way analysis of variance (ANOVA), Tukey HSD, Kruskal-Wallis, Mann-Whitney U tests were used in the analysis of quantitative independent data. Paired sample t-test was used in the analysis of dependent quantitative data ($P < .05$). **RESULTS.** The highest crown fracture resistance values were determined for the 3D printed composite resin ($P < .05$), and the lowest were observed in the bis-acryl composite resin ($P < .05$). Before and after thermal cycling, increase in mean hardness values were observed only in 3D printed composite resin ($P < .05$) and the highest ΔE_{00} value were observed in PMMA resin for all materials ($P < .05$). **CONCLUSION.** 3D printing and CAD-CAM milled interim materials showed better fracture strength. After the coffee thermal cycle, the highest surface hardness value was again found in 3D printing and CAD-CAM milled interim samples and the color change of the bis-acryl resin-based samples and the additive production technique was higher than the PMMA resin and CAD-CAM milled resin samples. [J Adv Prosthodont 2024;16:115-25]

KEYWORDS
Flexural strength; 3D printing; Computer-aided design, Polymethyl metacrylate; Aging

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INTRODUCTION

The use of temporary restorations in dentistry is crucial for maintaining esthetics, stability, and function during the period before the placement of permanent restorations. Temporary restorations should possess mechanical strength to withstand chewing forces, protect the pulp and periodontium, stabilize the affected tooth, and exhibit good marginal fit and aesthetics.[1]

Their importance lies in their ability to provide immediate esthetic improvement in patients requiring indirect restorations. Temporary restorations must not only achieve initial color matching but also retain their esthetics appearance over their service life, as noticeable discoloration can affect their acceptability.[2] The discoloration of temporary restorations can be an esthetic problem, especially when the treatment plan requires long-term use. Some resins change color over time and therefore color stability governs material selection when a long service life is expected.[3]

Traditionally, autopolymerized polymethylmethacrylate (PMMA) has been the primary material for constructing temporary fixed restorations. PMMA has remained a popular choice due to its adequate chewing force resistance and superior color stability over time.[3] Polyethylmethacrylates (PEMA), introduced in the 1960s, with slightly lower resistance to chewing forces and color stability offer advantages and disadvantages compared to PMMA.[3] More recently, composite-based resins have gained popularity as temporary restoration materials, offering durability through cross-linking of polymers after polymerization.[3]

Today, it is possible to make more durable temporary restorations with computer aided design/computer aided manufacturing technology (CAD-CAM) techniques. CAD-CAM milling provisionals shorten the patient's sitting time and offer superior mechanical and physical properties in terms of marginal fit, durability, and fabrication. In this method, which is based on the reduction principle, considered as a disadvantage, some of the materials used in production are wasted from the blocks.[4,5]

In the past ten years, the addition technique-based 3D production has become more and more common in modern dentistry. Drill guides for dental implants, physical models for prosthodontics, orthodontics, and surgery, dental, craniomaxillofacial, and orthopedic implants, as well as copings and frameworks for implant and dental restorations are all now available thanks to 3D printing, which is developing digital dentistry.[6] Additionally, it enables rapid production of interim repair that is precise and repeatable.[7] Three-dimensional addition techniques are based on the production of the object using layer-by-layer polymerization of liquid photopolymer in a chamber with the help of an ultraviolet laser with a strong light source or an LCD panel.

Despite extensive research on the staining susceptibility and surface hardness of interim restorative materials,[8-11] there is a lack of studies investigating these properties specifically in 3D printed materials.

In this study, we aim to compare the fracture strength, hardness, and color stability of maxillary 1st premolar crowns and specimens produced from four different temporary materials: autopolymerizing polyethylmethacrylate (PEMA), bis-acryl composite resin, CAD-CAM polymethyl methacrylate resin (milled), and 3D printed composite resin (printed). Three different production techniques, including auto polymerization, reduction, and addition methods, will be assessed. Our hypotheses are that the fracture strength, hardness, and color stability of 3D printed composite resin (printed) samples produced using the addition method will outperform other materials in this comparative analysis.

MATERIALS AND METHODS

In this study, the fracture strength of the crown-shaped specimens (n = 40), Vickers hardness values and the color stability of the disc-shaped specimens (n = 40) before and after the coffee thermal cycle were investigated from four different temporary restoration materials (Table 1): autopolymerized PEMA (PEMA), bis-acryl composite resin (BRC), CAD-CAM PMMA resin (milled), and photopolymer resin (Printed). All materials are used in color A2 according to the Vita classical scale (VITA Zahnfabrik, Bad Säckingen, Germany).

First of all, by the aid of 3D computer graphics program (3DS Max, Autodesk. Inc., San Francisco,

Table 1. Materials used

Group name	Trade name	Type	Lot number	Manufacturer
Milled	Tempo CAD	CAD-CAM polymethyl methacrylate resin	21001	Ondent, Izmir, Türkiye
Printed	Cura Temp	Photopolymer resin	AKRTBO200023001	Ackuretta, Taipei, Taiwan
PEMA	Dentalon Plus	Auto-polymerized acrylic powder/liquid	K010036	Kuzler, Hanau, Germany
BRC	Prevision Temp	Bis-acrylic auto polymerizing compound	71909103	Kuzler, Hanau, Germany

CA, USA), a maxillary first premolar tooth form was designed in real sizes based on the dental anatomy book[12] (Fig. 1A). Then, a die form was prepared with 6-degree convergence angle, 1 mm wide shoulder-type step[1] and occlusal reduction to provide at least 1.5 mm material thickness (Fig. 1B) and then a crown was designed as stereolithography CAD software file (STL) for an ideal metal-ceramic crown preparation (Fig. 1C).

Premolar-shaped crowns and also disc shaped samples (10 mm × 2 mm), which referred to ADA No.12,[13] were milled from the CAD-CAM PMMA block (Tempo CAD base PMMA blocks; Ondent, Izmir, Türkiye) at the dental laboratory (CMB Dental laboratory, Ankara, Türkiye) using a CAM-device (Dentifa ECO2 CNC machine, IFA Machinery, Istanbul, Türkiye) by the aid of created Standard Triangle Language (STL) file.

The crown and disc samples were produced by the STL file with a 100 µm layer thickness from photopolymer resin (Printed, Accuretta, Taipei, Taiwan) with the addition method using the 3D printer (FreeShape 120, Accuretta, Taipei, Taiwan). First of all, the designed crown was positioned perpendicular (90°) to the production table,[14] and the surfaces of the crown that formed an angle of less than 45 degrees were supported with rod connections. All crowns were produced on the same table in 60 minutes and all disc-shaped samples were produced on the same

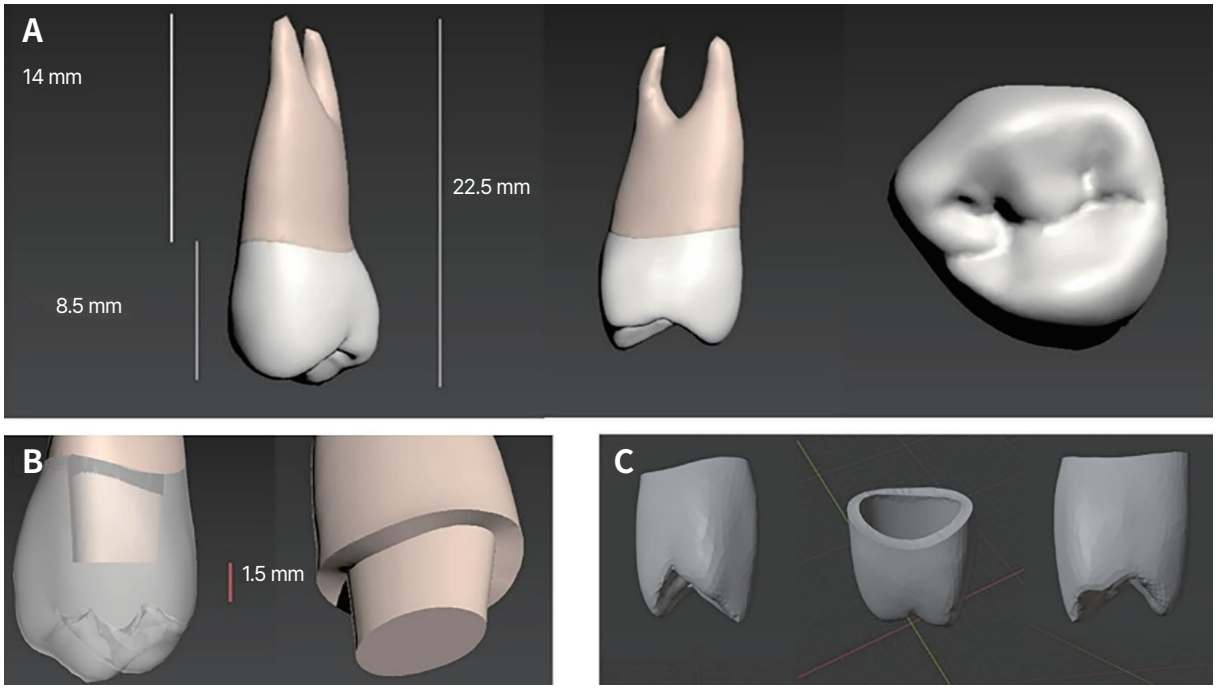

Fig. 1. Preparation of crown and die CAD model. (A) Dimensions used in the design of the upper 1st premolars, (B) Prepared tooth form of the upper 1st premolar designed in 3Ds Max software, (C) Designed crown restoration.

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table in 15 minutes. After production, the specimens were cleaned in an ultrasonic cleaning device (Ackuretta CLEANI Ultrasonic Cleaning Unit, Accuretta, Taipei, Taiwan) for 5 minutes using isopropyl alcohol and cured in the UV Box (Acuretta UV Box, Accuretta, Taipei, Taiwan) oven at a wavelength of 405 nm.

Mold for premolar crown production were produced from Cr-Co alloy using the laser sintering device (3D Systems Pro X100, DMP Dental, Denver, CO, USA) (Fig. 2A). In accordance with the manufacturer's instructions, acrylic resin was loaded in the mold, previously isolated with Vaseline, and combined with the metal die (Fig. 2B, C) till the polymerization was completed under finger pressure (450 sec.). After the polymerization was complete, the crowns were removed, and the overhanging material was cleaned (Fig. 2D).

The others were disc shaped and were produced with the aid of a 10 mm diameter and 2 mm thick stainless-steel mold according to manufacturer's instructors (PEMA, Kulzer, Hanau, Germany). The stainless-steel mold was placed between two glasses and fixed with the help of hand pressure until the sample was polymerized.

The crown specimens produced from bis-acrylic autopolymerizing material were placed in molds prepared from Cr-Co alloy (Fig. 2B), which was previously isolated with vaseline, thanks to the automatic mixing system, and the parts were combined and waited under finger pressure until the polymerization was completed (3 minutes). The production of crowns made of autopolymerized acrylic and bis-acrylic auto polymerizing material was carried out by the same researcher.

The same stainless-steel mold was used to produce the bis-acrylic autopolymerizing compound disc samples. Bis-acrylic autopolymerizing compound was loaded in the stainless-steel mold with the help of the automatic mixing tip and the mold was fixed between two glasses and waited for 3 minutes to polymerize. After the polymerization was completed, the samples were removed from the mold.

The samples in all groups prepared as discs were polished by the same researcher under water with SiC emery at 400, 800, 1200 and 2500 grits, respectively. The thickness of the polished samples was checked to see if they were 2 mm ± 0.2 mm by measuring with a digital caliper (HSL 246-15, Karl Hammacher GmbH, Solingen, Germany).

Universal testing machine (Lloyd LRX Universal Test Machine, Fareham, England) was used for the fracture

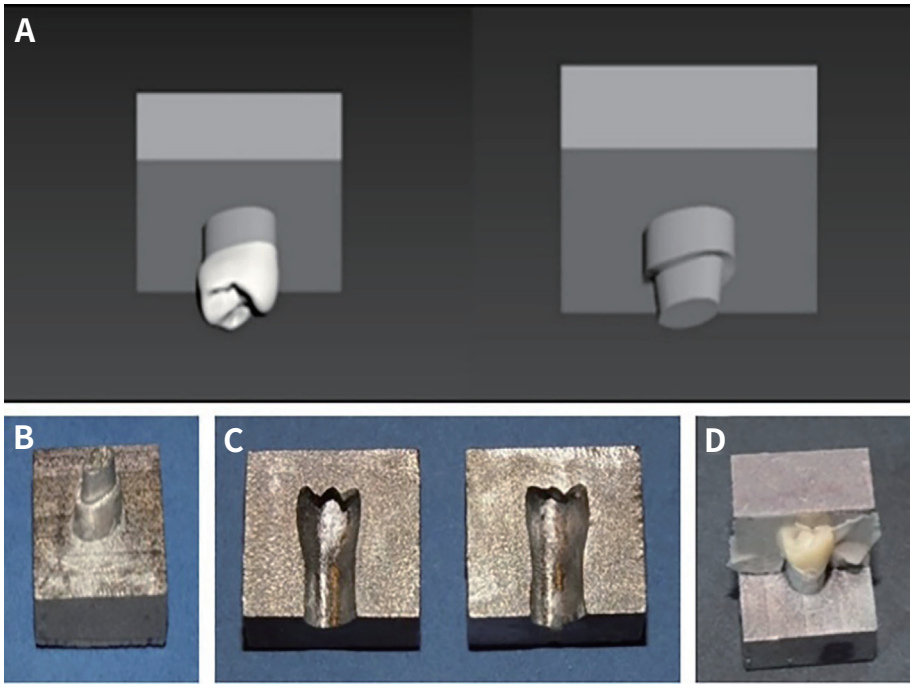

Fig. 2. Removal of crown specimens made of autopolymerized acrylic temporary restoration material from molds and correction of overhanging material. (A) CAD design of the Cr-Co mold, (B) Base part of the mold, (C) Removable part of the mold, (D) Polymerized crown before correction.

strength test at Ankara University Faculty of Dentistry Research Laboratory (Ankara, Türkiye). Samples were loaded under a standard compression load at a crosshead speed of 1 mm/minute and the force recorded using the universal testing machine (Lloyd Universal Testing Machine, LRX 2K5, Hants, Fareham, UK) with a 2500 Newton loaded cell for three minutes. A plunger with a steel ball (4.24 mm diameter) was used to transmit the compressive force until fracture occurred. In this study, the compression force was applied from the middle of the buccal and palatal cusps perpendicular to the central fossa by using a steel ball tip until the crowns were broken.

Surface hardness measurement of 2 mm thick and 10 mm diameter disc samples were made using digital display microhardness device (HSV-1000, Shanghai Shangcai Testing Machine Co., Ltd, Shanghai, China). To measure the Vickers hardness value, 100 gf (0.9810 N) was applied to each sample for 15 seconds. Three measurements were taken from the centers and peripheries of each sample before the thermal cycle, and the averages were taken, and the measurements were repeated in the same way after the coffee thermal cycle.

In order to compare the color stability of temporary materials, color measurements of disc samples were made before and after the coffee thermal cycle. The optical properties of the specimens were evaluated using a spectrophotometer (VITA Easyshade V, VITA Zahnfabrik, Bad Säckingen, Germany). Three color measurements (from the center and periphery of the samples) were made from each sample and the average of L1, a1, b1 values were recorded. After the coffee thermal cycle, 3 measurements were made again from the samples, and the average L2, a2, b2 values were recorded. Measurements were made between time 12:00 and 15:00 in the afternoon with the recommendation of the company, adopting a standard color evaluation protocol in a custom-made black box to mimic the oral environment, and all color measurements were made in the same room under exposure of sunlight D65 light source. Before each measurement, the device was calibrated by placing it in the calibration section on the stand and containing a ceramic chamber.[15]

Color change values of the specimens were calculated by using the CIEDE2000 (ΔE_{00}) color difference formula[16]:

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

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ are the differences in lightness, chroma, and hue values between the two samples compared, respectively. S_L, S_C, and S_H are the weighting functions for the lightness, chroma, and hue values, respectively. K_L, K_C, and K_H are parametric factors that need to be adjusted for different imaging parameters. In this study, K_L, K_C, and K_H were set to 1. The ΔE_{00} was evaluated on the basis of perceptibility and clinical acceptability thresholds, which were set at ΔE_{00} 0.8 and ΔE_{00} 1.8 units, respectively.[17]

Disc shaped samples prepared in ISO standards were subjected to coffee (Nescafe Gold, Nestle, Vevey, Switzerland) thermal cycling (SD Mechatronik Thermocycler, SD Mechatronik GMBH, Westerham, Germany) for 1,000 thermal cycles between 5°C and 55°C with a dwelling time of 30 s in each bath and a transferring time of 5 s. Coffee solution was prepared according to the manufacturer's instructions (2 g of coffee per 200 ml of water).

Mean, standard deviation, median, and the lowest and the highest, frequency and ratio values were used in the descriptive statistics of the data. The distribution of variables was measured with the Kolmogorov Smirnov test. One-way ANOVA, Tukey HSD, Kruskal-Wallis, Mann-Whitney U tests were used in the analysis of quantitative independent data. Paired sample t-test was used in the analysis of dependent quantitative data. Analyses were performed using SPSS 27.0 program and $P < .05$ was taken.

RESULTS

The fracture strength values of autopolymerized acrylic (PEMA) and bis-acrylic autopolymerizing compound (BRC) groups were found to be significantly lower than photopolymer resin (Printed) specimens and CAD-CAM PMMA (Milled) groups ($P < .05$). Maximum fracture value did not differ significantly between PEMA and BRC groups ($P > .05$). Again, no significant difference was found in the fracture strength values between Printed and Milled groups ($P > .05$)

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(Fig. 3).

According to Tukey HSD test results, the hardness value (HV) of BRC and Milled groups were found to be significantly higher than Printed and PEMA groups before thermal cycles ($P < .05$). There was no significant difference between BRC and Milled groups ($P > .05$). Again, no significant difference was found between Printed and PEMA groups ($P > .05$).

ANOVA statistical test results revealed that there was a significant difference between the surface hardness values of the groups ($P = .00$) (Fig. 4). As per the Tukey HSD analysis, the HV value of the Milled group significantly exceeded those of the PEMA and BRC groups ($P < .05$). There was no significant difference ($P > .05$) in HV value after thermal cycle among Printed, PEMA and BRC groups.

As per the ANOVA statistical test, thermal cycling caused significant changes in the surface hardness of the samples ($P < .05$). In the Printed group, the hardness value showed a significant increase after the thermal cycle ($P = .038$). In the PEMA and Milled group, the hardness value after the thermal cycle did not change significantly, respectively ($P = .054$) ($P = .327$). In the BRC group, the HV value after the thermal cycle decreased significantly ($P < .05$). In the BRC group, HV change after the thermal cycle was found to be significantly different from the Printed group ($P < .05$). There was no significant difference in HV change after thermal cycle among Printed, PEMA and Milled groups ($P > .05$). HV change did not differ significantly among Milled, PEMA and BRC groups after thermal cycle ($P > .05$). The change in surface hardness of the temporary materials before and after the coffee thermal cycle is shown graphically in Fig. 4.

Kruskall-Wallis test revealed that the types of materials and thermal cycle had a statistically significant influence on color stain ($P = .00$). According to Mann-Whitney U test; ΔE_{00} values in PEMA and Milling groups were found to be significantly lower than Printed and BRC groups ($P < .05$). ΔE_{00} value did not differ significantly between PEMA and Milling groups ($P > .05$) and between Printed and BRC groups ($P > .05$).

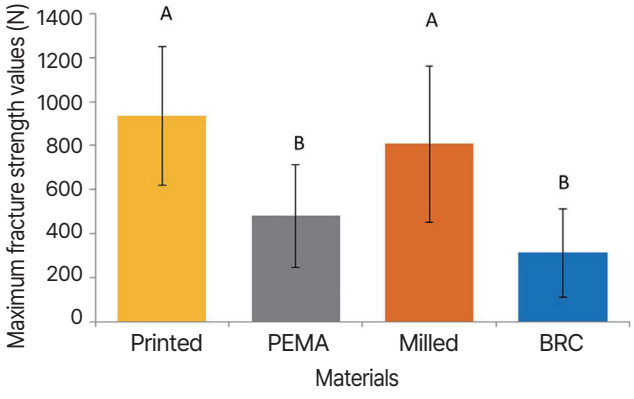

Fig. 3. Mean maximum fracture ± SD values of tested groups. Material codes as shown in Table 1. Mean difference significant at $P < .05$; same numbers mean not statistically different.

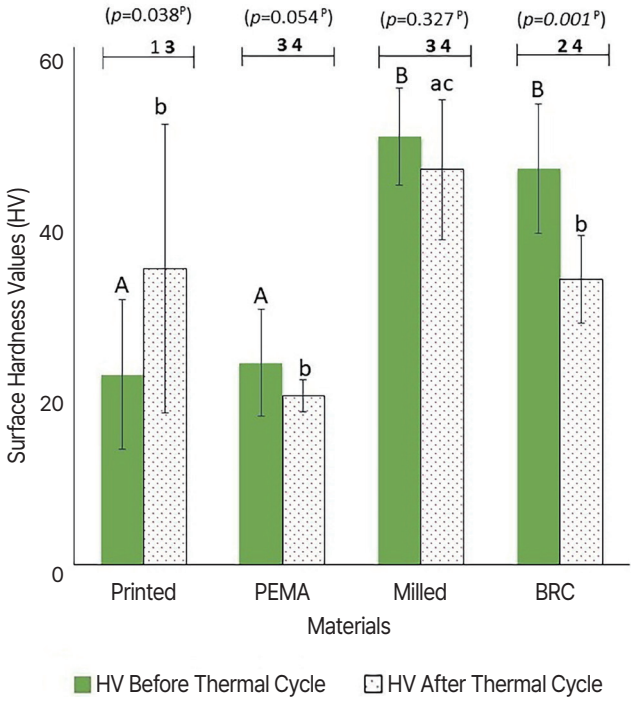

Fig. 4. Mean HV ± SD values of tested groups before-after thermal cycle. Material codes as shown in Table 1. Different uppercase letters denote statistical differences among materials before thermal cycling. Different lowercase letters denote statistical differences among materials after thermal cycling. Different numbers denote statistical differences before and after thermal cycle comparison between materials ($P < .05$) (Paired sample t-test).

The color change graph of the groups according to the ΔE_{00} formula after the coffee thermal cycle is shown in Fig. 5. According to the ΔE_{00} formula, the color change of PEMA and Milling groups was found above the 50% perceptibility value of 0.8 units, but below the 50% acceptability value of 1.8 units. Printed and BRC materials showed a color change above 50% acceptability value.[17]

DISCUSSION

The present *in vitro* study investigated the fracture strength of the temporary crowns obtained from the digital techniques (Milled & Printed) and the autopolymerizing acrylic resins (BRC & PEMA). In addition, surface hardness and color stability of disc samples produced from the same materials were investigated after the coffee thermal cycle. Based on the results of this study, both null hypotheses were rejected.

In order to remove a further influencing factor, a temporary luting cement was left out on purpose. It was believed that the luting cement would have boosted the fracture strength; further research on this topic is needed.

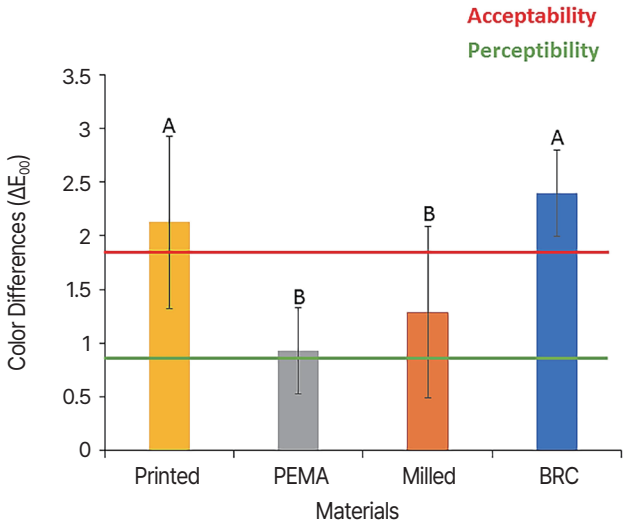

Fig. 5. Mean $\Delta E_{00} \pm$ SD values of tested groups after thermal cycling. Material codes as shown in Table 1. Different uppercase letters denote statistical differences among materials ($P < .05$).

Temporary restorations should have sufficient fracture strength even when they are used for a limited time. In the present study, Printed had the highest fracture strength values and also no significant difference was found between Printed and Milling groups ($P > .05$). There are similar studies representing higher fractural strength of CAD-CAM provisionals.[4,18-23] In a previous study, Karaman *et al*.[24] reported that the fracture strength was higher in the CAD-CAM PMMA provisional crowns obtained from the bis-acrylic resin and the self-curing composite materials. This result is also similar to the present study as no significant difference was found between Printed and Milling groups ($P > .05$).

In contrast, there are notable studies indicating the fracture strength superiority of bisacrylic composite temporary materials.[25-27] In a previous study, Karaokutan *et al*.[27] compared bisacrylic composite resin, Polymethyl methacrylate, and CAD-CAM Highly cross-linked methyl methacrylate and stated that bisacrylic composite resins showed higher fracture strength values. Similarly in other studies, Nejatidanesh *et al*.[25] and Lang *et al*.[26] reported the higher fractural strength of BRC resins vs PMMA groups and attributed the finding to difunctional bis-acryl resin composite materials, and capability of cross-linking with another monomer chain. This cross-linkage provides strength and durability of the material. Also, additional inorganic fillers further improve strength and microhardness.

Similar to previous reports,[23,28] in the present study, CAD-CAM provisional restorative materials are statistically affected by thermocycling[28] and bis-acryl resin composite materials exhibited superior microhardness over traditional methyl methacrylate resins.[29] In another study, Digholkar *et al*.[30] reported the highest microhardness of provisionals produced by 3D printing over CAD-CAM PMMA milling and conventional method. They stated that composite resins contain multifunctional cross-linked monomers and other inorganic fillers to increase the hardness of these resins compared to PMMA.

In the present study, the hardness values of BRC disc samples were observed to decrease following exposure to the coffee thermal cycle. However, it's noteworthy that even after this thermal treatment, the

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hardness values of the BRC disc samples remained higher when compared to the hardness values of the PEMA material. This difference in hardness can be attributed to the composition of the materials under investigation. Specifically, the BRC disc samples contain bis-acryl resin, which incorporates inorganic fillers into its structure. These inorganic fillers play a crucial role in enhancing the material's properties. The inclusion of these fillers contributes to the BRC disc samples' improved resistance to issues such as polymerization shrinkage and abrasion.[30] As a result, the BRC disc samples exhibit greater durability and hardness in comparison to the PEMA material. The decrease in hardness values of the BRC disc samples following the coffee thermal cycle might be attributed to the effects of heat exposure and potential interactions with the coffee medium. However, the initial hardness advantage of the BRC disc samples over the PEMA material persists due to the reinforcing influence of the inorganic fillers present in their composition. The increase of hardness values of Printed group can be explained as during the 3D printing the resin undergoes a curing process to solidify and form the desired shape. Exposure to heat, such as the hot coffee, might cause additional curing or cross-linking of the resin molecules, leading to an increase in surface hardness. Also, the printed samples are subjected to thermal cycles with hot coffee followed by cooling, the resin material undergoes thermal expansion and contraction. This repeated expansion and contraction could potentially cause molecular rearrangement within the resin, resulting in increased density and surface hardness, and might induce stress relaxation and healing of these defects, resulting in a denser and harder surface.

Under the light of the previous studies,[9] less free monomer and porosity and more homogenous structure is the common characteristic of CAD-CAM PMMA-based polymers. Therefore, the water absorption of these materials was lower than that of the hand-mixed self-cured PMMA resins. This could explain the superior mechanical properties of CAD-CAM PMMA based polymers over conventional PMMA resins. Also, as expected, manually produced temporary materials absorb more water into their structures due to the polymerization method, higher residual monomer ratio, and the presence of high porosity.[9] This may explain that the surface hardness values of BRC and PEMA groups after thermal cycle show lower surface hardness values than the materials used with CAD-CAM techniques.

In the present study, the specimens were exposed to coffee thermal cycle and the mean ΔE_{00} values were the highest for BRC followed by Printed, Milling and PEMA. These findings are consistent with those of the studies that assessed the stain of interim materials.[23,31]

In present study, PEMA showed the higher staining resistance and this can be attributed to the polar structure of the material.[23,31,32] However, in the present study, no significant difference in color change was noted in several measurements between PEMA and Milled groups as in previous study. Similar to a previous study,[33] in the present study, BRC showed higher color variation compared to PEMA and Milled. Bis-acryl resins are two-component materials containing multifunctional methacrylate esters and inorganic fillers. According to the manufacturer, the Prevision Temp monomer matrix consists of bis-GMA, dimethacrylate, and triethylene glycol dimethacrylate (TEGDMA). TEGDMA is a common comonomer used to reduce viscosity.[34] This monomer mixture for Prevision Temp may explain the low color stability compared to other bis-acryl and methacrylate resins. In contrast, several studies[8,33,35] reported the less discoloration of BRC materials and showed that using the automix system instead of hand mixing for BRC might reduce defects and porosities that might provoke water sorption and color change. The composition of the resin matrix and the polymerization methods have a great influence on the color stability.[36] Color stability may vary depending on the chemical and surface properties of the material.[37,38] Fluid absorption affinity, polymerization rate, surface roughness, and material thickness of temporary restoration materials are among the factors affecting color change in temporary restoration materials.[37-39]

Edge loss is a phenomenon where the light scattered from the translucent material is normally visible to the eye but cannot be measured by the instrument. This is due to the fact that the light from the edge opening does not return back to the sensor, where

it is emitted to the environment. Therefore, in order to avoid this phenomenon, color measurement was made from the polished flat surfaces of the disc samples.[40,41]

Universally, the color change of a material can be calculated with the ΔE_{00} formula. The CIEDE2000 (ΔE_{00})[42] color difference formula does not define a new color space. It is a new calculation to approximate the ability of the human eye to distinguish color difference in CIELAB (L, a, b color space) color space.[42] Therefore, calculations were made using color ΔE_{00} difference formulas in the present study with 50:50% detectability threshold at 95% confidence interval 0.8 units for ΔE_{00}; and the 50:50% acceptability threshold was accepted as 1.8 units for ΔE_{00}.[17,43] According to the ΔE_{00} color range formula, while the PEMA group showed less coloration than the detectability threshold, the Milled group showed coloration between the perceptibility and acceptability thresholds. Printed and BRC groups showed coloration above the acceptability threshold in coffee. The discoloration of temporary restorations can cause esthetic problems in long-term use. Although the use of stabilizers has reduced the chemical discoloration, temporary restoration materials tend to absorb liquid.[37] Therefore, they may undergo color change when exposed to colored foods such as tea and coffee in the oral environment.[44] Color change can take two forms: external factors and internal factors. External factors include plaque accumulation in the mouth, surface roughness, diet and surface staining. Polishing the surface can reduce the influence of these factors. Internal factors are caused by chemical changes of the material. It depends on factors such as the polymerization initiator systems used in the material, the polymerization method applied, and the duration. The coloring in the material matrix occurs in all layers and cannot be removed by polishing.[44]

Researchers attributed the low color stability of the samples produced with the additive manufacturing technique to many reasons. In the 3D additive manufacturing method, there are layers in the surface microstructure depending on the production technique.[45,46] In addition, it has been stated that the low level of polymerization of photopolymer resins compared to other materials[46] and the low type and amount of photoactivator may be other causes of color stability.[47] In the previous study, Tahayeri *et al*.[14] stated that the polymerization level of the photopolymer resins produced by the additive manufacturing technique is low compared to other materials, even though post-production curing processes are performed. In the previous study, Berli *et al*.[48] stated that the water absorption of the samples produced by the 3D additive method using photopolymer resin was higher than that of PMMA. High water absorptions can also lead to high color change.[46]

A limitation of our study is that the *in vivo* conditions could not be fully imitated because the fracture strength of the temporary crowns was measured by ignoring the chewing forces and thermal changes in the oral environment. Since the mechanical and physical properties of temporary materials with the same chemical content may vary in the products of different manufacturers, future studies are needed to examine more temporary restoration materials.

CONCLUSION

The fracture strengths of printed and milled crowns produced by additive and subtractive CAD-CAM manufacturing techniques were found to be higher than the fracture strengths of BRC and PEMA crowns obtained by the conventional method (autopolymerizing). After the coffee thermal cycle, the highest surface hardness value was again found in milled and printed samples. After the coffee thermal cycle, the surface hardness of the printed samples increased significantly, while the surface hardness of the BRC samples decreased significantly. Surface hardness values of PEMA and milled samples did not change. After the coffee thermal cycle, the color change of the bis acryl resin-based BRC and printed samples obtained by the additive production technique was higher than the PEMA and Milled samples.

REFERENCES

1. Shillingburg, HT, Hobo S, Whitsett LD, Jacobi R, Brackett SE. Fundamentals of fixed prosthodontics. 3rd ed. Chicago; Quintessence Publishing Co; 1997. p. 225-56.
2. Gupta G, Gupta T. Evaluation of the effect of various

beverages and food material on the color stability of provisional materials - An in vitro study. J Conserv Dent 2011;14:287-92.
3. Burns DR, Beck DA, Nelson SK; Committee on Research in Fixed Prosthodontics of the Academy of Fixed Prosthodontics. A review of selected dental literature on contemporary provisional fixed prosthodontic treatment: report of the Committee on Research in Fixed Prosthodontics of the Academy of Fixed Prosthodontics. J Prosthet Dent 2003;90:474-97.
4. Alt V, Hannig M, Wöstmann B, Balkenhol M. Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations. Dent Mater 2011;27:339-47.
5. Poticny DJ, Klim J. CAD/CAM in-office technology: innovations after 25 years for predictable, esthetic outcomes. J Am Dent Assoc 2010;141 Suppl 2:5S-9S.
6. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. Br Dent J 2015;219:521-9.
7. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. Int J Dent 2014;2014:783948.
8. Bitencourt SB, Kanda RY, de Freitas Jorge C, Barão VAR, Sukotjo C, Wee AG, Goiato MC, Pesqueira AA. Long-term stainability of interim prosthetic materials in acidic/staining solutions. J Esthet Restor Dent 2020;32:73-80.
9. Rayyan MM, Aboushelib M, Sayed NM, Ibrahim A, Jimbo R. Comparison of interim restorations fabricated by CAD/CAM with those fabricated manually. J Prosthet Dent 2015;114:414-9.
10. Song SY, Shin YH, Lee JY, Shin SW. Color stability of provisional restorative materials with different fabrication methods. J Adv Prosthodont 2020;12:259-64.
11. 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.
12. Ash Jr, MM, Nelson SJ. Wheeler's dental anatomy, physiology, and occlusion. 9th ed. St. Louis; Elsevier Inc; 2010. p. 141-51.
13. Swaney AC, Paffenbarger GC, Caul HJ, Sweeney WT. American Dental Association specification No. 12 for denture base resin: second revision. J Am Dent Assoc 1953;46:54-66.
14. Tahayeri A, Morgan M, Fugolin AP, Bompolaki D, Athirasala A, Pfeifer CS, Ferracane JL, Bertassoni LE. 3D printed versus conventionally cured provisional crown and bridge dental materials. Dent Mater 2018;34:192-200.
15. Da Silva JD, Park SE, Weber HP, Ishikawa-Nagai S. Clinical performance of a newly developed spectrophotometric system on tooth color reproduction. J Prosthet Dent 2008;99:361-8.
16. Sharma G, Wu W, Dalal EN. The CIEDE2000 color-difference formula: Implementation notes, supplementary test data, and mathematical observations. Color Res. Appl 2005;30:21-30.
17. Paravina RD, Ghinea R, Herrera LJ, Bona AD, Igiel C, Linninger M, Sakai M, Takahashi H, Tashkandi E, Perez Mdel M. Color difference thresholds in dentistry. J Esthet Restor Dent 2015;27 Suppl 1:S1-9.
18. Sadid-Zadeh R, Zirkel C, Makwoka S, Li R. Fracture strength of interim CAD/CAM and conventional partial fixed dental prostheses. J Prosthodont 2021;30:720-4.
19. Abdullah AO, Tsitrou EA, Pollington S. Comparative in vitro evaluation of CAD/CAM vs conventional provisional crowns. J Appl Oral Sci 2016;24:258-63.
20. Abdullah AO, Pollington S, Liu Y. Comparison between direct chairside and digitally fabricated temporary crowns. Dent Mater J 2018;37:957-963.
21. Peñate L, Basilio J, Roig M, Mercadé M. Comparative study of interim materials for direct fixed dental prostheses and their fabrication with CAD/CAM technique. J Prosthet Dent 2015;114:248-53.
22. Reeponmaha T, Angwaravong O, Angwarawong T. Comparison of fracture strength after thermo-mechanical aging between provisional crowns made with CAD/CAM and conventional method. J Adv Prosthodont 2020;12:218-24.
23. Rayyan MM, Aboushelib M, Sayed NM, Ibrahim A, Jimbo R. Comparison of interim restorations fabricated by CAD/CAM with those fabricated manually. J Prosthet Dent 2015;114:414-9.
24. Karaman T, Eser B, Altintas E, Atala MH. Evaluation of the effects of finish line type and width on the fracture strength of provisional crowns. Odontology 2021;109:76-81.
25. Nejatidanesh F, Momeni G, Savabi O. Flexural strength of interim resin materials for fixed prosthodontics. J Prosthodont 2009;18:507-11.

26. Lang R, Rosentritt M, Behr M, Handel G. Fracture resistance of PMMA and resin matrix composite-based interim FPD materials. Int J Prosthodont 2003;16:381-4.
27. Karaokutan I, Sayin G, Kara O. In vitro study of fracture strength of provisional crown materials. J Adv Prosthodont 2015;7:27-31.
28. Basak SS, Ozmen MF, Sagsoz O, Bayindir F. Effect of thermocycling on microhardness of CAD-CAM provisional materials. Int J Appl Dent Sci 2020;6:254-7.
29. Diaz-Arnold AM, Dunne JT, Jones AH. Microhardness of provisional fixed prosthodontic materials. J Prosthet Dent 1999;82:525-8.
30. Digholkar S, Madhav VN, Palaskar J. Evaluation of the flexural strength and microhardness of provisional crown and bridge materials fabricated by different methods. J Indian Prosthodont Soc 2016;16:328-34.
31. Bitencourt SB, Kanda RY, de Freitas Jorge C, Barão VAR, Sukotjo C, Wee AG, Goiato MC, Pesqueira AA. Long-term stainability of interim prosthetic materials in acidic/staining solutions. J Esthet Restor Dent 2020;32:73-80.
32. Elagra MI, Rayyan MR, Alhomaidhi MM, Alanaziy AA, Alnefaie MO. Color stability and marginal integrity of interim crowns: An in vitro study. Eur J Dent 2017;11:330-4.
33. Taşın S, Ismatullaev A, Usumez A. Comparison of surface roughness and color stainability of 3-dimensionally printed interim prosthodontic material with conventionally fabricated and CAD-CAM milled materials. J Prosthet Dent 2022;128:1094-101.
34. Anusavice KJ, Shen C, Rawls HR. Phillips' science of dental materials. 12nd ed. St. Louis; Missouri. Elsevier Health Sciences. 2012. p. 108.
35. Sham AS, Chu FC, Chai J, Chow TW. Color stability of provisional prosthodontic materials. J Prosthet Dent 2004;91:447-52.
36. Ruyter IE, Nilner K, Moller B. Color stability of dental composite resin materials for crown and bridge veneers. Dent Mater 1987;3:246-51.
37. Yannikakis SA, Zissis AJ, Polyzois GL, Caroni C. Color stability of provisional resin restorative materials. J Prosthet Dent 1998;80:533-9.
38. Anusavice KJ, Shen C, Rawls HR. Phillips' science of dental materials. 12nd ed. St. Louis; Elsevier; 2012. p. 483.
39. Bayindir F, Kürklü D, Yanikoğlu ND. The effect of staining solutions on the color stability of provisional prosthodontic materials. J Dent 2012;40 Suppl 2:e41-6.
40. Rosenstiel SF, Land MF. Contemporary fixed prosthodontics (E-Book). Elsevier Health Sciences; 2015. p. 856-57.
41. Haselton DR, Diaz-Arnold AM, Dawson DV. Color stability of provisional crown and fixed partial denture resins. J Prosthet Dent 2005;93:70-5.
42. Luo MR, Cui G, Rigg B. The development of the CIE 2000 colour-difference formula: CIEDE2000. Color Res Appl 2001;26:340-50.
43. Yılmaz Savaş T, Aykent F. Effect of fabrication techniques on the optical properties of zirconia-based systems. J Prosthet Dent 2021;125:528.e1-8.
44. Stawarczyk B, Sener B, Trottmann A, Roos M, Ozcan M, Hämmerle CH. Discoloration of manually fabricated resins and industrially fabricated CAD/CAM blocks versus glass-ceramic: effect of storage media, duration, and subsequent polishing. Dent Mater J 2012;31:377-83.
45. Revilla-León M, Özcan M. Additive manufacturing technologies used for processing polymers: current status and potential application in prosthetic dentistry. J Prosthodont 2019;28:146-58.
46. Shin JW, Kim JE, Choi YJ, Shin SH, Nam NE, Shim JS, Lee KW. Evaluation of the color stability of 3d-printed crown and bridge materials against various sources of discoloration: an in vitro study. Materials 2020;13:5359.
47. Shin DH, Rawls HR. Degree of conversion and color stability of the light curing resin with new photoinitiator systems. Dent Mater 2009;25:1030-8.
48. Berli C, Thieringer FM, Sharma N, Müller JA, Dedem P, Fischer J, Rohr N. Comparing the mechanical properties of pressed, milled, and 3D-printed resins for occlusal devices. J Prosthet Dent 2020;124:780-6.