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Effect of cigarette smoke and denture cleansers on the surface properties and color stability of CAD-CAM and conventional denture base resins

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This study aimed to evaluate the hardness, roughness, and color stability of heat- and microwave-polymerized polymethyl methacrylate (PMMA), polyamide, and CAD-CAM PMMA resins when exposed to cigarette smoke (CS) and immersed in a denture cleanser (DC). Specimens of each resins were divided into four subgroups (n=10). The DC and CS+DC specimens were immersed in a DC; the CS and CS+DC specimens were exposed to CS; and the control (C) specimens were kept in distilled water. Hardness, roughness, and color measurements were performed. DC and CS significantly affected the roughness and color of all resins (p<0.05). However, these did not affect the hardness of the CAD-CAM PMMA resin (p>0.05). The CAD-CAM PMMA resin presented the lowest roughness, highest hardness, and lowest ΔE_{00} values. While the roughness of all resins exposed to CS when immersed in DC decreased, the ΔE_{00} values of the conventional PMMAs also decreased. Although this decreases were not significant, it may be advisable to use DC for smokers to decrease discoloration and roughness especially for conventional PMMAs resins.

Keywords: CAD-CAM, PMMA, Polyamide, Denture base material, Denture cleanser

INTRODUCTION

Polymethyl methacrylate (PMMA) has been widely used as a denture base material to make removable partial or complete, implant-supported, and interim prostheses[1,2]. The improvement of PMMA properties and advances in laboratory techniques have led to the widespread use of many polymerization methods such as auto-polymerization, microwave processing, injection molding, and visible light polymerization[3,4]. Despite using various methods to initiate the polymerization of denture base resins, unreacted methyl methacrylate (MMA) monomers, called residual monomers, remain in the resins[5]. The amount of residual monomer and its plasticizing action may affect the physical and mechanical properties of PMMA, such as surface roughness and response to colorants[6-8].

Nylon polyamides were introduced as denture base materials because of their heat and chemical resistance, reliability for patients with allergies to the MMA monomer and metal-reinforced acrylic resin, and improved aesthetic properties[8,9]. It has been reported that the high elasticity of polyamide imparts more comfort to patients who have tissue undercuts[10,11]. In contrast, the disadvantages of polyamide, such as difficulty in processing, insufficient dimensional stability, being prone to microbial contamination, staining with colorants, and need for mechanical retention with soft liners and acrylic artificial teeth, limit its clinical applications[4,12,13].

Pre-polymerized PMMA discs produced for the CAD-CAM milling process have been introduced as an alternative to conventional denture resins[3,14]. Because these discs are produced under high-pressure and high-temperature conditions, some studies have reported that milled CAD-CAM resins show improved optical and surface properties, reduced residual monomer amount, and higher mechanical properties[14,15].

Because color change is an indication of aging of the material or an unaesthetic appearance, it is desirable that the color is stable during the use of prostheses[16,17]. The color stability of denture base resins is closely related to their physical properties such as water absorption, solubility, hydrophilicity, hardness, and roughness[15,17]. Surface roughness plays a key role in plaque adhesion and biofilm accumulation, while hardness is responsible for the abrasiveness and wear of acrylic resins[2].

The maintenance of denture hygiene is essential to keep oral health and to prevent denture related stomatitis. Cleaning methods are usually mechanical methods with brushing, chemical methods including denture cleansers or disinfectant solutions, and the combination of both methods. Since many older people with removable dentures may not be able to clean their denture properly, overnight storage in water with a denture cleaning tablet containing alkaline peroxide is recommended[18-20].

Denture base resins were exposed to various intrinsic and extrinsic factors in the oral cavity, which can affect the physical and mechanical properties of the material. Cigarette smoke is one of the harmful factor, containing toxic ingredients such as tar, carbon monoxide, nickel, cadmium and arsenic. Cigarette smoking is reported as a public health problem by World Health Organization affecting over 1.3 billion people. There are some studies reporting that cigarette smoke can change the surface properties of denture base resins and denture teeth materials[20-24].

In the literature, studies have evaluated the physical properties of PMMAs or polyamides produced by

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conventional methods against various variables[7,8,13,24-28]. However, studies evaluating the effect of denture cleansers and smoking on the physical properties of newly introduced pre-polymerized CAD-CAM PMMA resins and comparing them with conventional denture base resins are in the minority. The purpose of this study was to evaluate the hardness, roughness, and color stability of two differently polymerized (heat- and microwave-treated) PMMA, polyamide, and pre-polymerized CAD-CAM PMMA resins upon immersion in a denture cleanser and exposure to cigarette smoke. The null hypothesis was that denture cleanser and cigarette smoke would not affect the hardness, roughness, or color stability of the tested resins.

MATERIALS AND METHODS

A power analysis was performed to calculate the sample size by using GPower3.1.2. The alpha error=0.05, beta error=0.20 and the effect size was selected as 1.6 according to the previous data[29]. The required sample size was obtained as n=8 for each group. However, considering the potential loses, the total final sample size was provided 160 (n=10, for each group).

Heat (QC-20) and microwave polymerized PMMA (Acron MC), polyamide (Deflex), and pre-polymerized CAD-CAM PMMA were selected for this study and are listed in Table 1.

A total of 160 disc-shaped specimens (2 mm thickness, 10 mm diameter) were prepared from each resin (n=10). PMMA mixtures were prepared using the monomer: liquid ratio recommended by the manufacturers. Heat-polymerized resins were fabricated at 100°C for 30 min in a water bath; after curing, the flasks were bench-cooled. The microwave polymerized specimens were polymerized in a microwave oven (Vestel, Goldstar, Manisa, Turkey) at 500 W for 3 min. To prepare the polyamide specimens, the wax patterns were flasked, eliminated, and prepared for the injection process according to the manufacturer's instructions. The polyamide in the pre-packed cartridge was melted using an injection machine (Nuxen, Buenos Aires, Argentina) at 280°C for 15 min, and injected into the flask for 30 s under a pressure of 6 bar. The dimensions of all specimens were checked using digital calipers (IP67, Yamer, İzmir, Turkey).

The CAD-CAM PMMA specimens were designed using a software (Autodesk, San Rafael, CA, USA), then saved as a standard tessellation language (STL) file. PMMA discs were milled using Exocad software (Exocad, Darmstadt, Germany) according to the obtained STL file.

The surfaces of all specimens were finished with waterproof carbide papers (200-, 400-, and 600-grit) using a polishing machine (Grin PO 2V grinder, Metkon Instruments, Bursa, Turkey). To obtain smooth surfaces, pumice-water slurry (Imipomza, Imicyrl, Konya, Turkey) was applied to all specimens, and the surfaces were then polished with a polishing paste containing aluminium oxide, ammonium oleate, petroleum distillate, and water (Universal Polishing Paste, Ivoclar Vivadent, Schaan, Liechtenstein). The specimens were stored in distilled water at 37±1°C for 24 h before testing.

The specimens of each resin were divided into four subgroups. The first group of specimens was kept in distilled water at room temperature and called the control (C). The second group of specimens (CS) was placed in a box wherein the polished surface was directly exposed to cigarette smoke from a distance of 10 mm. For each specimen, 20 cigarettes were used, and each cigarette was burned for a standard time of 10 min. The specimens were then washed under running water. The third group of specimens (named as DC) was immersed in a denture cleanser solution containing sodium perborate (Protefix, Queisser Pharma, Flensburg, Germany) prepared according to the manufacturer's instructions. One cleanser tablet was dissolved in a 200 mL glass of warm water (not hot as recommended by the manufacturer). Care was taken to completely cover the specimens immersed in the solution with the cleaning solution. A new solution was prepared to simulate the daily use for each specimen. The specimens were kept in the solution for 5 min, and at the end of the time, each specimen was rinsed thoroughly under running water. The fourth group of specimens (CS+DC) was exposed to cigarette smoke and then immersed in a denture cleanser using the same procedure as that for the preparation of the third group specimens. These procedures were

Table 1 Denture base resins used in this study

Denture Base Resins	Type	Manufacturer	Color	Polymerization technique
QC-20	Polymethyl methacrylate (PMMA)	Dentsply De Trey G, Wallenhorst, Germany	Pink	Conventional; heat-polymerized
Acron MC	Polymethyl methacrylate (PMMA)	GC Lab Technologies, Alsip, IL, USA	Live Pink	Conventional; microwave-polymerized
Deflex	Polyamide/nylon	Nuxen, Buenos Aires, Argentina	Light pink	Injection molding
HaHasmile CAD-CAM PMMA disc	Prepolymerized polymethyl methacrylate	HaHasmile Dental, Changsha, China	Pink A	CAD-CAM milling

repeated daily for 30 days. All specimens were stored in distilled water for the remaining time.

The Vickers hardness number (VHN) of each specimen was measured with a Vickers hardness tester (Struers, Balerup, Denmark) using a 100 gf load for 30 s. Measurements were performed at three different locations on each specimen, and the final hardness value was calculated using the arithmetic average. All measurements were performed by the same researcher.

The surface roughness of each specimen was measured with a contact profilometer (SJ-201P, Mitutoya, Kawasaki, Japan) using a 0.4 gf load for 5 s. Three measurements were performed from different sides of the specimen surfaces. The arithmetic means of the values were recorded to obtain the final surface roughness values.

The color analysis was performed using a colorimeter (ShadeEye NCC, Shofu, Kyoto, Japan) under D65 standard illumination on a gray background. The specimens were dried with absorbent paper and the colorimeter was calibrated before analysis. The $L^*a^*b^*$ values of each specimen were measured thrice by positioning the colorimeter in the middle of the specimens. The final color was recorded by calculating the arithmetic mean of three measurements. The color difference values of the specimens in gray were calculated using the CIEDE2000 color difference formula as follows. While $\Delta L'$, $\Delta C'$, $\Delta H'$ values used in ΔE_{00} calculations indicate changes in lightness, chroma and hue, R_T (rotation function) is used to calculate the interaction between chroma and hue differences in the blue areas. Weighting functions S_L, S_C, S_H adapt the location of color difference pairs in L^*, a^*, b^* coordinates to the total color difference variation. The parametric factors K_L, K_C, K_H represent the correction conditions in the experimental conditions and are usually set to 1 in the studies[30]. In this study, the CIEDE2000 values were evaluated in terms of perceptibility and acceptability. Ren *et al*.[31] reported that the 50% perceptibility threshold was 1.72 CIEDE2000 units and the 50% acceptability threshold was 4.08 CIEDE2000 units for denture base resins. These were considered as perceptibility and acceptability thresholds in this study.

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

Scanning electron microscopy (SEM) images (EvoLS10, Zeiss, CA, USA) were taken to observe the surface topography of the specimens from each experimental group at 500 magnification. The specimens were coated with Au-Pd films before imagining.

The normality of data distribution was analyzed by using the Shapiro-Wilk test. Since the data were not normally distributed, non-parametric tests were used. The Kruskal-Wallis test was conducted to compare the differences among all groups, followed by the Dunn-Benferroni correction for multiple comparisons (SPSS v22.0). A value of <0.05 was considered statistically significant at a 95% confidence interval.

RESULTS

The median (minimum–maximum) values and multiple comparisons of Vickers hardness (kg/mm^2) are listed in Table 2 (p<0.05). For the control groups of the resins, CAD-CAM PMMA presented the highest hardness values, and polyamide had the lowest. The DC specimens showed significantly decreased hardness for conventional PMMAs and polyamide (p<0.05), while the hardness of CAD-CAM PMMA was not affected (p>0.05). The decrease in hardness was not significant for PMMA and polyamide among the CS specimens (p>0.001). For the CS+DC specimens, the decrease was significant (p<0.001).

The median (minimum–maximum) values and multiple comparisons of the surface roughness (μm) are summarized in Table 3 (p<0.05). Among the control specimens, CAD-CAM PMMA presented the lowest roughness, whereas polyamide had the highest. The CS specimens showed a significant increase in the roughness among all resin materials (p<0.05), whereas the DC specimens did not show any significant change in the roughness (p>0.05). The CS+DC specimens showed lower roughness values than the CS specimens; however, this decrease was not significant (p>0.05). The CS+DC specimens showed higher roughness than the control specimens for all resin materials. While this increase was significant for PMMA and CAD-CAM PMMA (p<0.05), it was not significant for polyamide (p>0.05).

The median (minimum–maximum) values and multiple comparisons of the color difference (ΔE_{00}) values are listed in Table 4 (p<0.05). Among the control specimens, microwave-polymerized PMMA and polyamide presented the highest ΔE_{00} values, whereas CAD-CAM PMMA had the lowest. Immersion in DC did not change the color of the resin material (p>0.05). However, all CS specimens showed significant color changes (p<0.05). The color change was also significant for the CS+DC specimens (p<0.001). The images of the tested specimens, one from each experimental group, are presented before (1st day) and after (30th day) immersions and smoking (Fig. 1). Significant color changes were observed in CS subjected specimens (Fig. 1).

The surface roughness, Vickers hardness, and ΔE_{00} values for resins are listed in Table 5 (p<0.05). A significant difference was found in the roughness and hardness between the control groups (p<0.05). The CS, DC, and CS+DC specimens showed significant differences in terms of roughness, hardness, and color change (p<0.05). CS or DC produced a significant difference in roughness and color change between conventional PMMAs and CAD-CAM PMMA (p<0.05). While the CS specimens showed a significant difference in roughness and color change between heat-polymerized PMMA and polyamide, significant differences were observed in terms of the roughness only for the DC specimens (p<0.05). Moreover, the CS specimens showed a significant difference in the hardness between polyamide and other resins (p<0.05). The DC specimens

Table 2 Median (minimum–maximum) values and multiple comparisons of Vickers hardness (kg/mm^2) according to surface treatment procedures

Materials	Surface treatments	Median (minimum–maximum) values	p value	Multiple comparisons between groups
QC-20	Control (c)	15.16 (14.86–15.32)	<0.001	c-dc; <0.001* c-(cs+dc); <0.001* c-cs; 1.000 dc-(cs+dc); 1.000 dc-cs; 0.008* (cs+dc)-cs; 0.004*
	Cigarette Smoke (cs)	14.97 (14.72–15.21)		
	Denture Cleanser (dc)	13.18 (13.09–13.39)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	13.19 (13.02–13.45)		
Acron MC	Control (c)	15.17 (14.92–15.37)	<0.001	c-dc; <0.001* c-(cs+dc); <0.001* c-cs; 1.000 dc-(cs+dc); 1.000 dc-cs; 0.003* (cs+dc)-cs; 0.010*
	Cigarette Smoke (cs)	15.03 (14.87–15.15)		
	Denture Cleanser (dc)	13.70 (13.59–14.02)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	13.81 (13.51–14.09)		
Deflex	Control (c)	9.19 (9.07–9.42)	<0.001	c-dc; <0.001* c-(cs+dc); 0.001* c-cs; 1.000 dc-(cs+dc); 1.000 dc-cs; <0.001* (cs+dc)-cs; 0.020*
	Cigarette Smoke (cs)	9.10 (9.01–9.28)		
	Denture Cleanser (dc)	8.13 (8.01–8.22)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	8.20 (8.14–8.29)		
Cad-Cam PMMA	Control (c)	15.21 (15.12–15.62)	0.004	c-dc; 1.000 c-(cs+dc); 0.004* c-cs; 1.000 dc-(cs+dc); 0.028* dc-cs; 1.000 (cs+dc)-cs; 0.069
	Cigarette Smoke (cs)	15.19 (15.06–15.55)		
	Denture Cleanser (dc)	15.20 (15.01–15.31)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	15.02 (14.87–15.23)		

*: indicates the groups with significant differences as a result of the multiple comparisons between the subgroups of each resin material (p<0.05)

showed a significant difference in hardness and color change between polyamide-CAD-CAM PMMA and polyamide-microwave-polymerized PMMA, whereas their roughness was not affected. In addition, the DC specimens showed a significant difference in hardness and color change between polyamide-CAD-CAM PMMA and polyamide-microwave-polymerized PMMA (p<0.05). The CS+DC specimens showed a significant difference in roughness, hardness, and color change among polyamide, microwave-polymerized PMMA, and CAD-CAM PMMA (p<0.05). The differences in roughness, hardness, and color change between heat-polymerized PMMA and CAD-CAM PMMA were also significant for the CS+DC specimens (p<0.05).

SEM images of the denture base resins were presented in Figs. 2–5. In the control group of the resin (Figs. 2A, 3A, 4A, 5A) the surfaces were smoother when compared to the CS and DC subjected resins. The most irregularities were observed in CS subjected resins (Figs. 2B, 3B, 4B, 5B).

DISCUSSION

The null hypothesis was partially disproved because DC and CS significantly affected the roughness and color of all resins. The effect of DC and CS on the hardness was significant for heat- and microwave-polymerized PMMA and polyamide, but not for CAD-CAM PMMA.

During clinical use of removable prostheses, denture base materials are subjected to variable conditions such as thermal changes during eating or drinking and occlusal loading under chewing forces[8]. Besides the presence of saliva within *in vivo* conditions and cleaning dentures with denture cleansers or disinfectant solutions may affect the physical and mechanical properties[13,25]. Thus, effects of these factors should be evaluated to improve the longevity of the restorations. Gad *et al.*[29] evaluated the strength and surface properties of a 3D-printed denture base polymer and compared with a heat polymerized denture base after thermal cycling treatment simulating 1 year of clinical use. They reported that thermal aging significantly reduced the flexural strength and hardness, and increased surface roughness, but did not affect the impact strength of 3D-printed resin.

Hardness is an indicator of resistance to plastic deformation caused by occlusal wear or mechanical indentation. Prostheses produced from a material with low surface hardness may be deformed as a result of

Table 3 Median (minumum–maximum) values and multiple comparisons of surface roughness values (μm) according to surface treatment procedures

Materials	Surface treatments	Median (minimum–maximum) values	*p* value	Multiple comparisons between groups
QC-20	Control (c)	0.20 (0.20–0.22)	<0.001	c-dc; 0.332 c-(cs+dc); 0.001* c-cs; <0.001* dc-(cs+dc); 0.332 dc-cs; 0.001* (cs+dc)-cs; 0.332
	Cigarette Smoke (cs)	0.47 (0.47–0.49)		
	Denture Cleanser (dc)	0.27 (0.27–0.28)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	0.33 (0.32–0.33)		
Acron MC	Control (c)	0.21 (0.20–0.22)	<0.001	c-dc; 0.334 c-(cs+dc); 0.001* c-cs; <0.001* dc-(cs+dc); 0.334 dc-cs; 0.001* (cs+dc)-cs; 0.334
	Cigarette Smoke (cs)	0.44 (0.43–0.44)		
	Denture Cleanser (dc)	0.26 (0.26–0.27)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	0.32 (0.32–0.33)		
Deflex	Control (c)	0.26 (0.22–0.28)	<0.001	c-dc; 1.000 c-(cs+dc); 0.051 c-cs; <0.001* dc-(cs+dc); 0.005* dc-cs; <0.001* (cs+dc)-cs; 0.553
	Cigarette Smoke (cs)	0.42 (0.41–0.44)		
	Denture Cleanser (dc)	0.23 (0.22–0.28)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	0.39 (0.38–0.42)		
Cad-Cam PMMA	Control (c)	0.17 (0.16–0.18)	<0.001	c-dc; 0.249 c-(cs+dc); 0.001* c-cs; <0.001* dc-(cs+dc); 0.575 dc-cs; 0.001* (cs+dc)-cs; 0.249
	Cigarette Smoke (cs)	0.23 (0.22–0.24)		
	Denture Cleanser (dc)	0.20 (0.19–0.21)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	0.22 (0.20–0.22)		

*: indicates the groups with significant differences as a result of the multiple comparisons between the subgroups of each resin material ($p<0.05$)

the mechanical effects and plaque involvement, and discoloration may occur, which may shorten the clinical life of the prosthesis[32]. In this study, the control specimens of CAD-CAM PMMA presented higher hardness values than the CS+DC, DC, and CS specimens. In agreement with a previous study by Prpić *et al.*[32], reporting those CAD/CAM materials showed better mechanical properties than heat polymerized resins[24]. The polymerization of CAD-CAM resins under high temperature and pressure and the addition of supplementary inorganic fillers to the resins increase the dimensional stability and limit polymerization shrinkage. With the formation of partially cross-linked polymer chains, CAD-CAM resins with a denser structure exhibit improved mechanical properties[33]. These properties are possibly attributable for the high surface hardness of CAD-CAM resins not being affected even after immersion in DC or immersion in DC after exposure to CS. In addition, manufacturers claim that CAD-CAM PMMA contains a lower amount of residual monomers than conventional PMMAs, resulting in improved mechanical properties. DC significantly reduced the hardness of conventional PMMAs and polyamide ($p<0.001$). Neppelenbroek *et al.*[25] reported that disinfectant solutions reduced the hardness of heat-polymerized resins, while it has been reported that sodium-perborate-containing solutions reduced the hardness of both polyamide and PMMA[13,26]. This decrease in the hardness of heat-polymerized resins may be due to the unreacted residual monomers that weaken the chemical structure of the polymer, providing the surfaces more prone to wear by free active radicals[27]. The hardness of a resin material is related to the structure of its monomers, degree of cross-linking, and chemical nature of the material[34,35]. Polyamide resins are able to absorb water[8]. Therefore, DC alters the surface structure, causing a decrease in hardness and an increase in roughness.

Surface roughness is associated with the clinical lifetime of materials and plaque accumulation[13]. Irregularities on the surface of materials can act as an infection reservoir that harbors microorganisms even after denture cleaning[36]. Bollen *et al.*[37] determined that the threshold level of surface roughness for plaque accumulation was 0.2 μm. It has been reported that rough surfaces have negative effects on the health of the surrounding tissues, patient comfort, color stability, service life, and aesthetics of the prosthesis[8,13,28]. In this study, among the control groups, CAD-CAM PMMA

Table 4 Median (minimum–maximum) values and multiple comparisons of color changes (ΔE_{00}) according to surface treatment procedures

Materials	Surface treatments	Median (minimum–maximum) values	*p* value	Multiple comparisons of surface treatments groups
QC-20	Control (c)	0.70 (0.58–0.87)	<0.001	c-dc; 0.334 c-(cs+dc); 0.001* c-cs; <0.001* dc-(cs+dc); 0.334 dc-cs; 0.001* (cs+dc)-cs; 0.334
	Cigarette Smoke (cs)	3.48 (3.41–3.81)		
	Denture Cleanser (dc)	1.54 (1.37–1.81)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	2.32 (2.21–2.38)		
Acron MC	Control (c)	0.72 0.62–0.88)	<0.001	c-dc; 0.334 c-(cs+dc); 0.001* c-cs; <0.001* dc-(cs+dc); 0.334 dc-cs; 0.001* (cs+dc)-cs; 0.334
	Cigarette Smoke (cs)	3.44 (3.38–3.69)		
	Denture Cleanser (dc)	1.53 (1.29–1.64)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	2.04 (1.91–2.24)		
Deflex	Control (c)	0.72 (0.61–0.78)	<0.001	c-dc; 0.334 c-(cs+dc) <0.001* c-cs; 0.001* dc-(cs+dc); 0.001* dc-cs; 0.286 (cs+dc)-cs; 0.451
	Cigarette Smoke (cs)	2.30 (2.23–2.41)		
	Denture Cleanser (dc)	1.91 (1.74–1.99)		
	Cigarette Smoke+Denture Cleaner (cs+dc)	2.52 (2.35–2.68)		
Cad-Cam PMMA	Control (c)	0.65 (0.56–0.72)	<0.001	c-dc; 0.227 c-(cs+dc); <0.001* c-cs; <0.001* dc-(cs+dc); 0.014* dc-cs; 0.158 (cs+dc)-cs; 1.000
	Cigarette Smoke (cs)	1.30 (1.23–1.72)		
	Denture Cleanser (dc)	1.20 (1.11–1.29)		
	Cigarette Smoke+Denture Cleanser (cs+dc)	1.39 (1.28–1.47)		

*: indicates the groups with significant differences as a result of the multiple comparisons between the subgroups of each resin material ($p<0.05$)

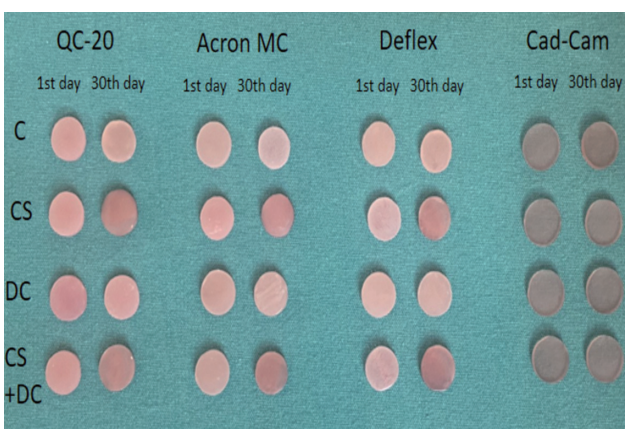

Fig. 1 Figure of disc-shaped samples representing each group (Each column shows a different resin material.
Material order: QC-20, Acron MC, Deflex, Cad-Cam PMMA. Each row shows a different subgroup. Subgroup order: C, CS, DC, CS+DC)

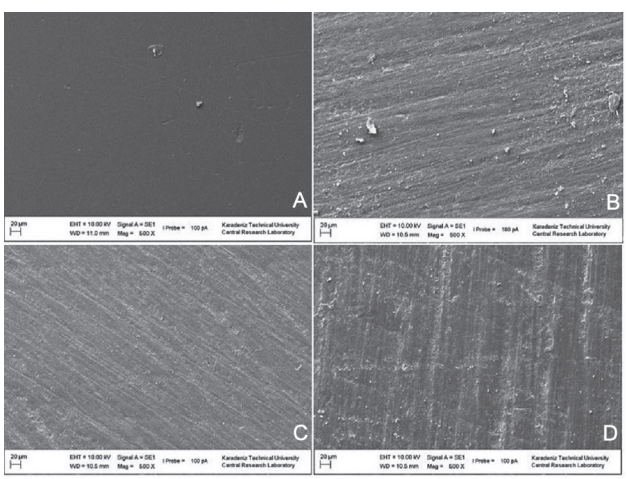

Fig. 2 SEM images of QC-20 surfaces (×500 original magnification).
(A) control, (B) cigarette smoke, (C) denture cleanser, (D) cigarette smoke+denture cleanser

Table 5 Multiple comparisons of Vickers hardness (kg/mm^2), surface roughness values (μm), and color changes (ΔE_{00}) according to different acyrlic materials

		Vickers hardness (kg/mm^2)		Surface roughness (μm)		Color changes (ΔE_{00})	
Surface treatment	Material	*p* value	Multiple comparisons	*p* value	Multiple comparisons	*p* value	Multiple comparisons
Control (C)	QC-20 (Q) Acron MC (A) Deflex (D) Cad-Cam PMMA (CC)	<0.001	Q-CC; 1.000 A-CC; 1.000 CC-D; <0.001* Q-A; 1.000 Q-D; 0.010* A-D; 0.002*	<0.001	Q-CC; 0.075 A-CC; 0.005* CC-D; <0.001* Q-A; 1.000 Q-D; 0.010* A-D; 0.127	0.155	—
Cigarette Smoke (CS)	QC-20 (Q) Acron MC (A) Deflex (D) Cad-Cam PMMA (CC)	<0.001	Q-CC; 0.055 A-CC; 0.341 CC-D; <0.001* Q-A; 1.000 Q-D; 0.038* A-D; 0.004*	<0.001	Q-CC; <0.001* A-CC; 0.002* CC-D; 0.207 Q-A; 0.207 Q-D; 0.002* A-D; 0.783	<0.001	Q-CC; <0.001* A-CC; <0.001* CC-D; 0.333 Q-A; 1.000 Q-D; 0.008* A-D; 0.069
Denture Cleanser (DC)	QC-20 (Q) Acron MC (A) Deflex (D) Cad-Cam PMMA (CC)	<0.001	Q-CC; 0.001* A-CC; 0.334 CC-D; <0.001* Q-A; 0.334 Q-D; 0.334 A-D; 0.001*	<0.001	Q-CC; <0.001* A-CC; 0.002* CC-D; 0.077 Q-A; 0.318 Q-D; 0.017* A-D; 1.000	<0.001	Q-CC; 0.013* A-CC; 0.045* CC-D; <0.001* Q-A; 1.000 Q-D; 0.051 A-D; 0.014*
Cigarette Smoke+ Denture Cleanser (CS+DC)	QC-20 (Q) Acron MC (A) Deflex (D) Cad-Cam PMMA (CC)	<0.001	Q-CC; 0.001* A-CC; 0.334 CC-D; <0.001* Q-A; 0.334 Q-D; 0.334 A-D; 0.001*	<0.001	Q-CC; 0.017* A-CC; 0.034* CC-D; <0.001* Q-A; 1.000 Q-D; 0.034* A-D; 0.017*	<0.001	Q-CC; 0.001* A-CC; 0.299 CC-D; <0.001* Q-A; 0.341 Q-D; 0.441 A-D; 0.001*

*: indicates the resin materials where surface treatments cause significant differences in, Vickers hardness (kg/mm^2), surface roughness values (μm), and color changes (ΔE_{00}) in multiple comparisons (p<0.05)

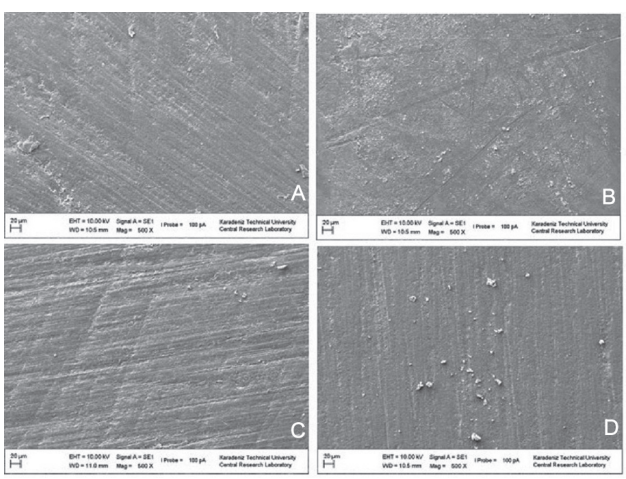

Fig. 3 SEM images of Acron MC surfaces (×500 original magnification).
(A) control, (B) cigarette smoke, (C) denture cleanser, (D) cigarette smoke+denture cleanser

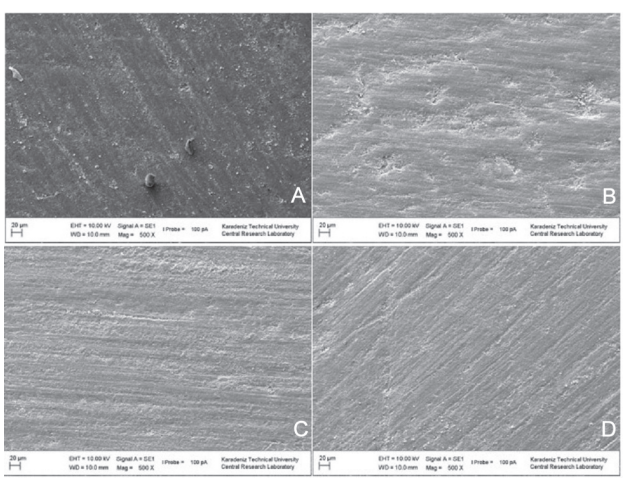

Fig. 4 SEM images of Deflex surfaces (×500 original magnification).
(A) control, (B) cigarette smoke, (C) denture cleanser, (D) cigarette smoke+denture cleanser

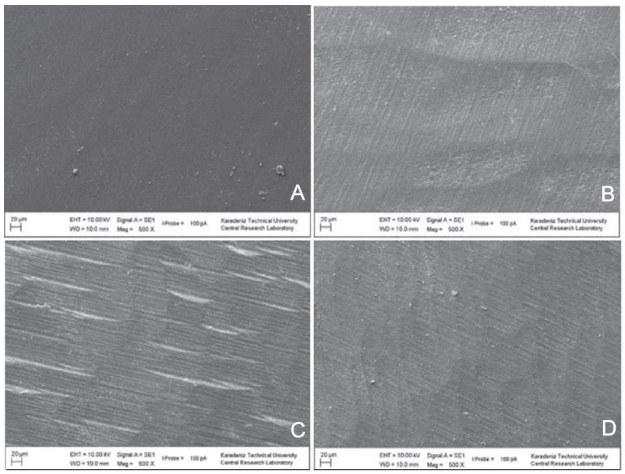

Fig. 5 SEM images of Acron MC surfaces (×500 original magnification).
(A) control, (B) cigarette smoke, (C) denture cleanser, (D) cigarette smoke+denture cleanser

presented the lowest roughness, while polyamide had the highest. The roughness values of all control specimens were lower than or equal to the threshold value, unlike those of polyamide. This may be due to the disadvantages of polyamide such as being prone to color change, warpage, water absorption, surface roughness, and difficulty in polishing[4]. All denture base materials tested in this *in vitro* study were polished with a polishing paste to have a smooth and standardized surfaces before the measurements. Polyamide resins were not easy to polish because of semi-flexible structure. Besides, polyamide is a crystalline polymer different from PMMA, having an amorphous structure, low surface energy and hardness[38]. These material properties may be the possible reasons for relatively higher surface roughness of polyamides in the present study. The roughness of CAD-CAM PMMA remained close to the threshold value despite the applied procedures. This result can be attributed to the fact that CAD-CAM PMMA are densified resins with higher polishability and minimal porosity than those of conventional resins because of improved production conditions[39,40]. Limirio *et al.*[33] evaluated the mechanical properties of the PMMA resin for manufacturing denture bases on the basis of *in vitro* studies by comparing heat-polymerized and CAD-CAM fabricated resins and reported a significant difference in terms of flexural modulus and roughness.

In this study, there was no significant difference in the ΔE_{00} values between the control specimens, and DC did not change in the roughness or color of all resins. Sodium perborate decomposes, and alkaline peroxide is formed in the prepared solution by dissolving DC tablets in water. Oxygen bubbles released from the solution provide both chemical and mechanical cleaning[41,42]. While there are studies supporting that this mechanism can cause significant changes in the roughness or color of materials[7,13], some studies have reported that effervescent tablets with sodium perborate as the active ingredient do not change the roughness of heat-polymerized resins[41,42]. Such differences in results may have occurred because of the type and content of the DC, immersion time, soaking temperature, composition of denture base resin used, and production process. In this study, conventional laboratory polishing techniques were used to obtain flat and smooth surfaces, which provide more effective polishing by minimizing roughness unlike that achieved by using chairside polishing kits[43,44]. Therefore, DC may not have effected the roughness and color of resins with initially smooth surfaces.

Ren *et al.*[31] reported that the CIEDE2000 color difference formula provides a better fit than CIELab for assessing the perceptible color difference threshold of the denture base *in vitro*. Therefore, it was deemed appropriate to use the CIEDE2000 color difference formula in this study. CAD-CAM PMMA had the lowest ΔE_{00} value even after surface treatment. Studies have reported that CS changes the color of the enamel, dentin, composite resins, denture teeth, and denture base materials[22,45]. When denture base materials are exposed to CS, harmful components such as carbon monoxide, formaldehyde, radioactive polonium, ammonia, nickel, arsenic, tar, and heavy metals induce biodegradation that can alter the physical and mechanical properties of the materials[24]. These substances remain on the surface of materials and are probably not completely removed when washed with water, making the surfaces irregular and resulting in increased roughness.

Mathias *et al.*[46] reported that the thermal effect of smoking can increase the roughness. In parallel with the study, the surface roughness of all resins exposed to CS increased significantly in this study ($p<0.001$). According to the SEM images, denture base resins which exposed to CS, present some irregularities on the surfaces, confirming the higher roughness values when compared to the other groups. In addition, CS caused a significant increase in ΔE_{00} values of all resins ($p<0.001$). According to the results of the present study, materials with increased roughness are seen more prone to color change. On the other hand, CS+DC decreased the roughness values of all resins, although not significantly ($p>0.05$). The SEM images of CS+DC group present smoother surfaces than those of the CS group. This can be attributed to the fact that only some of the harmful substances adhering to the surface of the resins caused by smoking can be removed by DC. Besides, there were some scratches and fissures appearances on the SEM images of the DC group. Although the staining effect of CS weakened, resins could not retain their initial color. This may be because DC only removes extrinsic stains on the surface and does not effectively remove intrinsic stains formed by the absorption of harmful substances from CS on the resin matrix[46]. Therefore, the use of DC can be recommended to smokers to prolong the clinical life of prostheses as it will allow the reduction of the roughness and the prevention of color change caused by CS. Limitations of this study included the lack of human saliva and denture biofilm simulating the oral

conditions. Secondly the fact that immersion in denture cleanser and subjection to cigarette smoke was done for 30 days period. Further studies should be conducted for longer time intervals and repeated measures to evaluate the long term effect. Moreover, it is recommended to investigate different denture base materials like 3D-printed resins and compare them with the other denture bases.

CONCLUSION

Upon comparing the hardness, surface roughness, and color change among the tested denture base materials, it can be concluded that the CAD-CAM PMMA resins presented better surface hardness and roughness and color stability when compared to those of conventional PMMAs and polyamide materials. DC and CS significantly affected the roughness and color of all resins ($p<0.05$). These did not affect the hardness of the CAD-CAM PMMA resin ($p>0.05$). The roughness of all resins exposed to CS when immersed in DC decreased and the ΔE_{00} values of the conventional PMMAs also decreased. This decreases are not significant, however smokers may be advised to use DC to decrease discoloration and roughness for especially conventional PMMAs resins.

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