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Performance of polyether ether ketone (peek) for dental applications: surface roughness and color stability

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Abstract

Polymeric materials are inevitably used in dental applications. Dental prostheses are cleaned during their service life, and surface roughness is an important criterion for these polymeric materials. In this study, the effect of different denture cleaning methods on the surface roughness and color stability of polyether ether ketone (PEEK) dental materials was studied. Seventy disk-shaped (10 × 3 mm) specimens were fabricated and divided into seven groups ($n = 10$) according to the cleaning procedure. One of these groups subjected to distilled water was the control group. Other three groups were subjected to daily cleansing with denture cleaners (5% sodium hypochlorite, alkaline peroxide, chlorhexidine gluconate solution) and the other three groups were subjected to mechanical cleaning with a toothbrush with three different dentifrices (toothpaste, soap, and denture cleansing gel). The surface roughness values (R_a) were measured with a profilometer before (R_a0) and after cleaning procedures for 270 days (R_a1). CIELab color parameters of each specimen were measured with a spectrophotometer before and after 7 days of storage in a coffee solution. Color differences were calculated, and data were statistically analyzed with one-way ANOVA and the Tukey HSD test ($\alpha = .05$). For all test groups, R_a0 and R_a1 values were lower than the plaque accumulation threshold level (PATL) of 0.200 µm. For both R_a and ΔE_{00} values, the effect of the cleaning method was not statistically significant ($P > 0.05$). Also, no significant difference was observed for R_a0, R_a1, and ΔE_{00} values between the test groups ($P > .05$). It was concluded that considering the color stability and surface roughness, many cleaning procedures can be used safely for PEEK polymers.

Keywords PEEK · Denture cleaning · Surface roughness · Color stability · Surface morphology

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Introduction

Polyetheretherketone (PEEK) is a high-temperature-resistant semi-crystalline thermoplastic polymer within the polyaryletherketone (PAEK) family. PEEK polymer is considered one of the most efficient thermoplastic materials due to its unique properties such as abrasion resistance, superior strength and hardness, hydrolytic stability, and corrosion resistance. PEEK has been used as an alternative to metal alloys in many industrial applications since the late 1970s. Due to its stable physical properties, it has been increasingly used as a biomaterial in a wide range of applications, especially for orthopedic, trauma, and spinal implants [1–4].

The biological and physical properties of PEEK are suitable and compatible with the prosthetic requirements in dentistry. The elastic modulus of PEEK is close to that of dentine and bone. Therefore, when used as an implant material, PEEK may show less stress concentration than titanium and titanium alloys. Besides, PEEK material has similar tensile properties to enamel, dentin, and cortical bone properties [2, 5–7]. In this context, PEEK shows high potential as a candidate for use in dental applications [8, 9].

On the other hand, appropriate cleaning procedures are essentially required to protect the health of oral and perioral soft tissues and to prevent any discomfort such as prosthetic stomatitis [10–12]. Generally, two basic cleaning methods are used for the cleaning of a prosthesis; one is the mechanical method by brushing with soap or toothpaste and the other is the chemical method by using chemical solutions [13]. Short-term or long-term use of chemically active agents affects the surface properties of dental resins such as surface roughness, color, and gloss [14–16]. It is well known that dental prostheses with rough surfaces are more prone to bacterial adhesion, dental plaque accumulation, staining, and discoloration [17–20].

The main purpose of this in vitro study was to evaluate the effect of different denture cleaning methods on the surface roughness and color stability of PEEK dental materials. Many studies examining the effect of denture cleaning methods on the mechanical and physical properties of widely used dental acrylic resin prostheses were reported. However, rather limited studies have been reported on the effect of cleaning methods for the polymeric material of PEEKdental matrices.

Materials and methods

Specimen preparation

The materials used in this study are listed in Table 1. PEEK denture base material has been subjected to mechanical and chemical cleaning methods to determine the change of color and surface roughness.

For this study, seventy disk-shaped PEEK specimens, with a diameter of 10 mm and thickness of 3 mm, were designed by a universal CAD (Computer

Table 1 Materials used in the study

Product	Component	Manufacturer	Batch Number
CopraPeek	Polyetheretherketone (PEEK)	Whitepeaks, dental solution, Germany	E10205
Universal polishing Paste	Paste of aluminum oxide	Ivoclar Vivadent, Schaan/Liechtenstein	WL4113
Corega denture cleanser	Potassium monopersulfate, sodium bicarbonate, sodium lauryl sulfoacetate, sodium perborate monohydrate, sodium polyphosphate	GlaxoSmithKline, Ireland	7V8P
Clorhex	0.12% Chlorhexidine gluconate	Drogsan, Turkey	19L102811
Wizard sodium hypochlorite	NaHOCl (5%)	Rehber Kimya, Turkey	1704–10
Aktident gel	Sodium Laureth Sulfate, Aqua, Peg-4 Rapeseed Amide, Glycerol, Mentha Arvenis, Saccharin, Sodium Chloride	Aktif Dis Ticaret, Turkey	8,104,401
Colgate total	Calcium carbonate, sorbitol, sodium lauryl sulfate, sodium monoflorosulfate, magnesium aluminum silicate, sodium carbonate	Colgate-Palmolive Co., China	9239CN123G
Activex	Sodium laureth ether Sulfate, cocamidopropyl betaine, glycerine, sodium chloride, cocamide glyceryl cocoate, citric acid, tetrasodium EDTA, perfume	Evyap, Turkey	85409–9

Aided Design) software (inLab SW 4.2.1; Sirona Dental Systems, NY, USA) and were milled by using a CAM (Computer Aided Manufacturing) machine (inLab MC X5; Sirona Dental Systems, NY, USA) from PEEK. All specimens were ground-finished, respectively, with 400, 800, 1200, and 2500 grit silicon carbide abrasive paper (English Abrasives, English Abrasives & Chemicals Ltd, UK) on a sanding machine (Phoenix Beta, Buehler, Illinois, USA) and subjected to water cooling (300 revs/min, during 5 s) before polishing. Subsequently, the specimens were fine-polished with universal polishing paste (Ivoclar Vivadent, Schaan, Liechtenstein) and a lathe flannel wheel on a polishing lathe (P1000, Zubler, Germany) for 90 s at a rate of 1500 rpm. All specimens were ultrasonically cleaned (Hygosonic, Dürr Dental, Germany) in distilled water for 10 min, rinsed, and dried with air. The specimens were then randomly divided into seven groups ($n = 10$) the groups were arranged as; one control group, three groups for chemical cleaning, and three groups for mechanical cleaning (Table 2).

Cleaning procedures, surface roughness, and color stability assessments

The initial surface roughness (R_a0) of each PEEK specimen was measured using a contact profilometer (Perthometer M2, Mahr) before the application of cleaning procedures. The profilometers resolution was 0.01 µm, the interval (cutoff length) was 0.8 mm, the transverse length was 5.5 mm and the stylus speed was 1 mm/s. The mean value of R_a0 values measured from three directions for each specimen was calculated. A digital colorimeter (Minolta CR-321, Osaka, Japan) was used to measure the CIE (Commission International de l Eclairage) L*a*b* color parameters of each specimen. Measurements were repeated three times, and the mean values were recorded as L_0*, a_0*, and b_0*.

The control group (Cnt) was immersed into a container with 200 ml of distilled water at room temperature (25 °C). Three test groups that were subjected to chemical cleaning were immersed into three different containers; (1) with 200 ml

Table 2 One-way ANOVA results of R_a and ΔE_{00} values

Parameter		SS	df	MS	F	*P*
R_a0	Between groups	0.014	6	0.002	1.432	0.217
	In groups	0.101	63	0.002		
	Total	0.115	69			
R_a1	Between groups	0.026	6	0.004	2.066	0.070
	In groups	0.133	63	0.002		
	Total	0.159	69			
ΔE_{00}	Between groups	2.455	6	0.409	1.573	0.170
	In groups	16.390	63	0.260		
	Total	18.845	69			

*ΔE_{00}, color differences; R_a0, roughness average before cleaning procedure; R_a1, roughness average after cleaning procedure; SS, sum of squares; df, degrees of freedom; MS, mean square; $P < .05$, the significant difference

volume of 5% sodium hypochlorite (NaOCl) solution (NaOCl group); (2) with 200 ml distilled water and an alkaline peroxide tablet (Ap group); (3) with 200 ml volume of 0.12% chlorhexidine gluconate solution (Chx group). Immersions were made to simulate a daily hygiene routine for 3 months (90 days). All specimens were submerged in the surface cleaning agent three times with 8 h duration in a day to simulate the daily hygiene routine and the night immersion (overnight) for 3 months (90 days). Therefore, the cleaning solutions were changed three times a day throughout the test, and the specimens were washed for 5 s at each renewal step and dried before immersion in a new solution [21].

Mechanical cleaning procedures were examined with a toothbrushing simulation device (DentArge TB-6.1, Analitik Medikal, Turkey). Toothbrushes with a compact head and medium-bristles tips (Denta, Banat, Turkey) were used in the device and different cleaners were mixed with water with the ratio of 1:2 by volume as follows; (1) deionized water with toothpaste for toothbrush/toothpaste group (Tbp); (2) deionized water with soap for toothbrush/soap group (Tbs); (3) deionized water with denture cleansing gel for toothbrush/denture cleansing gel group (Tbg).

Each specimen was subjected to linear brushing action and kept in slurries at room temperature (25 °C) under a constant vertical force of 350 g (3.43 N) and a stroke length of 20 mm for 7500 cycles, to simulate 9 months of toothbrushing [22]. After toothbrushing, each specimen was rinsed under running water, sonicated in deionized water for 10 min and dried. All specimens were reassessed with the profilometer for R_a after being immersed and brushed, and the mean values of measurements were obtained using the same device settings and recorded as R_a1.

A staining solution was prepared by dissolving 7.5 g of coffee (Nescafé Classic; Nestle Company) in 500 ml of boiled distilled water for the staining procedures of specimens. The specimens were embedded in wax plates to cover the unpolished surface and stored in the solution at 37 °C in a dark environment to simulate intraoral conditions for 7 days. At the end of the staining procedure, the specimens were washed for 5 min and air-spray-dried. The color parameters were remeasured and recorded as L_1*, a_1*, and b_1*. The color change of the specimens is determined by using Eq. (1); [23].

$$\Delta E_{00} = \left[\left(\frac{\Delta L'}{K_L S_L} \right)^2 + \left(\frac{\Delta G'}{K_c S_c} \right)^2 + \left(\frac{\Delta H'}{K_H S_H} \right)^2 + R_T \left(\frac{\Delta G'}{K_c S_c} \right) \left(\frac{\Delta H'}{K_H S_H} \right) \right]^{1/2} \tag{1}$$

where ΔL′, ΔC′, and ΔH′ are the differences in lightness (L), chroma (C), and hue (H) for a pair of specimens in CIEDE2000 and R_T was the rotation factor that accounts for the interaction between chroma and hue differences in the blue region. Weighting factors S_L, S_C, and S_H adjusted the total color difference for variations in the location of the color difference pair in the L*, a*, b* coordinates and the parametric factors. K_L, $K_{C,}$ and K_H are the terms for the experimental conditions. The parametric factors of Eq. (1) were set to 1. Also, the visual perceptibility threshold level (VPTL) was set as $\Delta E_{00} \leq 0.8$ and the clinical acceptability threshold level (CATL) as $\Delta E_{00} \leq 1.8$ units [24].

Surface morphology

The surfaces of all resin materials after dynamic loading were examined with the scanning electron microscope (SEM) (Nova Nano SEM 450, FEI Co.). The acceleration voltage of the cathode was set to 14 kV. The images were obtained at × 1000 magnifications.

Statistical analysis

The Levene test of homogeneity was used to evaluate the normal distribution of the variables. The test showed normal distribution of variables. The one-way analysis of variance test (ANOVA) was performed to evaluate the effects of cleansing procedures on the R_a and ΔE_{00} values and to achieve descriptive statistics. The mean R_a and ΔE_{00} values were multiplied compared with Tukeys HSD test ($\alpha = 0.05$). The pairwise comparisons between R_a0 and R_a1 values and also with plaque accumulation threshold level of 0.200 µm (PATL) were performed with independent samples t test. The pairwise comparisons of ΔE_{00} values with VPTL and CATL were also performed with independent samples t test. Statistical software (SPSS 20.0 V; SPSS, Inc., Chicago, IL) was used for statistical analyses, and significance was evaluated at $P < 0.05$ for all tests.

Results

One-way ANOVA results of R_a and ΔE_{00} values are given in Table 2. The mean R_a0 and R_a1 values, standard deviations (SD), and multiple and pairwise comparison results of test groups are shown in Table 3. It was seen that the cleaning method was not statistically significant on R_a0, R_a1, and ΔE_{00} values ($P > 0.05$).

Table 3 Mean ± SD of Ra0 and Ra1 for test groups

Cleaning Procedure	R_a0		R_a1		*t*-Test***
	Mean/SD	*t*-Test with PATL**	Mean/SD	*t*-Test with PATL**	
Cnt	0.137 ± 0.032[a*]	$P < .001$	0.124 ± 0.021[a]	$P < .001$	$P = .325$
Ap	0.146 ± 0.033[a]	$P = .001$	0.152 ± 0.024[a]	$P < .001$	$P = .622$
Chx	0.140 ± 0.053[a]	$P = .006$	0.153 ± 0.060[a]	$P = .037$	$P = .611$
NaOCl	0.114 ± 0.023[a]	$P < .001$	0.126 ± 0.024[a]	$P < .001$	$P = .262$
Tbp	0.156 ± 0.047[a]	$P = .018$	0.169 ± 0.048[a]	$P = .073$	$P = .560$
Tbs	0.151 ± 0.041[a]	$P = .005$	0.172 ± 0.044[a]	$P = .079$	$P = .284$
Tbg	0.158 ± 0.040[a]	$P = .011$	0.175 ± 0.071[a]	$P = .305$	$P = .531$

*Tukey HSD test results are shown as letters and values having the same letters are not statistically different ($P > 0.05$. **Pairwise comparison results of the mean Ra0 and Ra1 values of the test groups with PATL, according to the independent sample t-Test ($P < 0.05$.*** Pairwise comparison results of the mean Ra0 and Ra1 values for each test group

The mean (±SD) R_a0 values of test groups were in the range of 0.114±0.023 µm and 0.158±0.040 µm, and R_a1 values were 0.124±0.021 µm and 0.175±0.071 µm. All detected R_a0 (Fig. 1) values and the R_a1 values of Cnt (0.124±0.021), Ap (0.152±0,024), Chx (0.153±0,060) and NaOCI (0,126±0,024) groups were significantly lower than PATL of 0.200 µm, according to the pairwise comparisons with independent samples t test ($P<0.05$) as shown in Fig. 2. Tukeys multiple comparison results showed that there was no significant difference between the test groups not only for R_a0 but also for R_a1 values ($P>0.05$). According to the pairwise comparisons of R_a0 and R_a1 values of each test group, no statistically significant difference was detected between the groups ($P>0.05$).

The mean (±SD) ΔE_{00} values, and multiple and pairwise comparison results of test groups are shown in Table 4. The ΔE_{00} values of test groups were in the range of 1.01±0.73 and 1.51±0.47, which are visually perceptible but clinically acceptable. However, only the mean ΔE_{00} values of Cnt (1.30±0.28), Chx (1.51±0.47), Tbt (1.47±0.21), and Tbg (1.42±0.64) test groups were significantly higher than VPTL, according to the pairwise comparisons with independent samples t test ($P<0.05$). According to the pairwise comparisons with CATL, the mean ΔE_{00} values of Cnt (1.30±0.28), Ap (1.09±0.48), NaOCI (1.11±0.56), and Tbg (1.01±0.73) were significantly lower ($P<0.05$) (Fig. 3). Tukeys multiple comparisons showed that there was no significant difference between the ΔE_{00} values of test groups ($P>0.05$).

SEM images of PEEK specimens surfaces with a 1000 magnification ratio are given in Fig. 4 where (A) is the Control group, (B) is Ap, (C) is Chx, (D) is

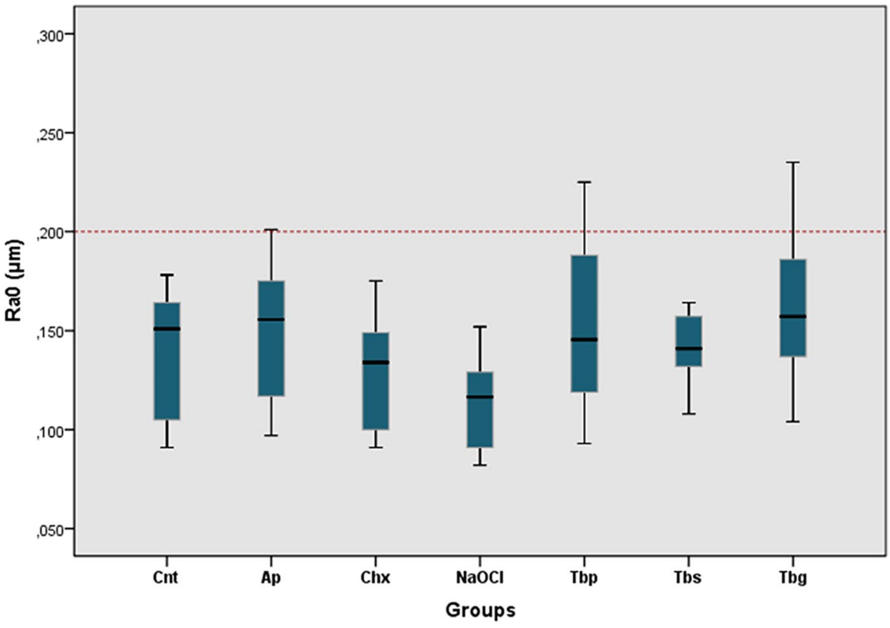

Fig. 1 Mean Ra (±SD) R_a0 values of test groups. Plaque accumulation threshold levels ($R_a=0.2$ mm) are indicated in the red line

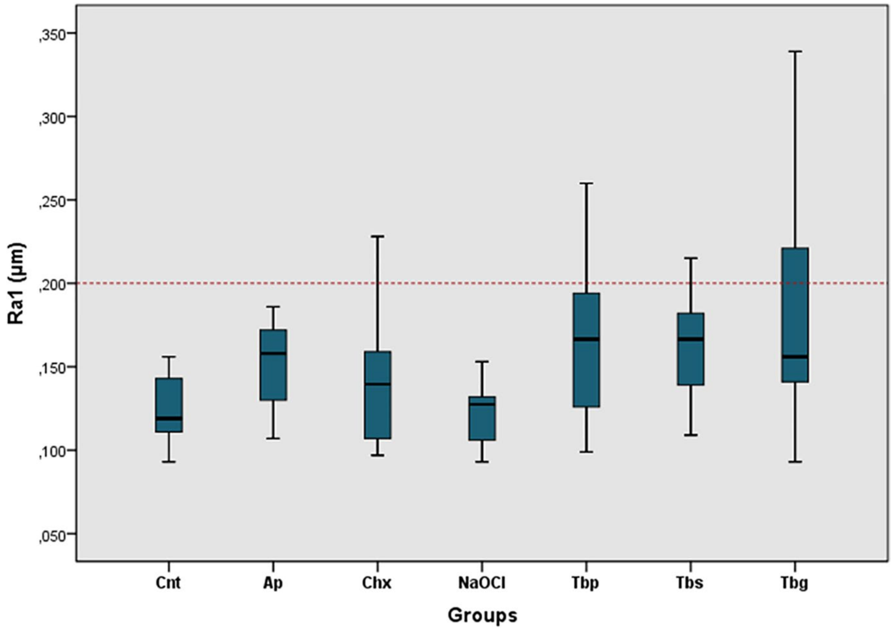

Fig. 2 Mean Ra (±SD) R_a1 values of test groups. Plaque accumulation threshold levels ($R_a = 0.2$ mm) are indicated as the red line

Table 4 Mean ± SD of ΔE_{00} for test groups

Cleaning procedure	ΔE_{00}	*t*-Test**	
	Mean/SD	VPTL (≤0.8)	CATL (≤1.8)
Cnt	1.30 ± 0.28[a*]	$P < .001$	$P < .001$
Ap	1.09 ± 0.48[a]	$P = .084$	$P = .001$
Chx	1.51 ± 0.47[a]	$P = .001$	$P = .077$
NaOCl	1.11 ± 0.56[a]	$P < = .117$	$P = .004$
Tbp	1.47 ± 0.21[a]	$P < .001$	$P = .001$
Tbs	1.01 ± 0.73[a]	$P = .385$	$P = .007$
Tbg	1.42 ± 0.64[a]	$P = .014$	$P = .089$

*Results of Tukey honest significant differences post hoc comparisons are shown as letters, values having the same letters are not statistically different ($P > 0.05$). **Pairwise comparison results of the mean ΔE_{00} values of the test groups with VPTL ($\Delta E_{00} \leq 0.8$) and CATL ($\Delta E_{00} \leq 1.8$) according to the independent sample *t*-Test ($P < 0.05$)

NaOCl, (E) is Tbp, (F) is Tbs and (G) is Tbg.The SEM images show similar surface morphologies to each other and the control group. It was seen that the surface roughness has not been changed.

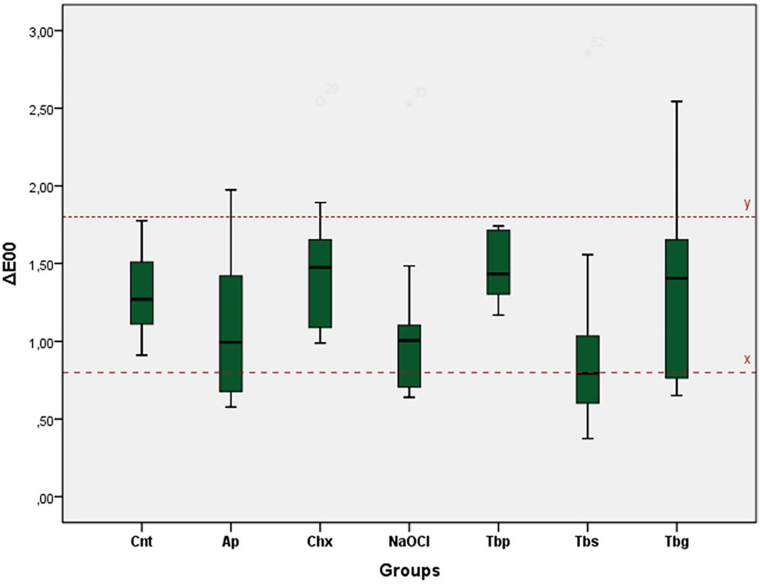

Fig. 3 Mean (±SD) ΔE_{00} values of test groups. The perceptibility threshold of color differences ($\Delta E_{00}=1.30$) is indicated as X line values and the acceptability threshold level ($\Delta E_{00}=2.25$) is indicated as Y line values

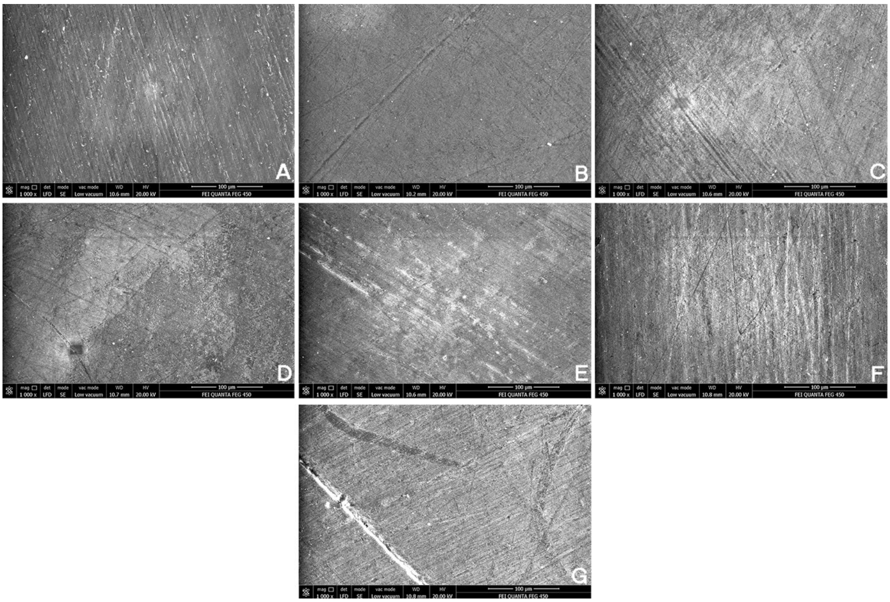

Fig. 4 SEM images of PEEK specimes surfaces (1000×). (**A**) Control, (**B**) Ap, (**C**) Chx, (**D**) NaOCl, (**E**) Tbp, (**F**) Tbs, (**G**) Tbg

Discussions

PEEK is one of the most popular high-performance polymers and is used in medical applications since the 1990s [1, 2, 25]. The material is also very new in dental applications and thus literature studies about the color and the surface properties of the PEEK as dental material inadequate. Therefore, in the present in vitro study, the surface roughness and color change of the PEEK material have been investigated by applying different surface cleaning processes.

The esthetics, biocompatibility, and long-term clinical life of dental restoratives depend on the surface finishing and polishing process [11]. In the present study, all specimens were fine-polished using universal polishing paste. In a study evaluating the surface roughness of PEEK polymer, it was stated that the lowest R_a values were obtained with the application of polishing paste [8]. Sturz et al. [15] measured the R_a of the PEEK material as about 0.277 µm after grinding with 1000 grid silicon carbide abrasive paper and reported that the R_a value decreased by an average of 0.073 µm when polishing paste was applied to these samples. Based on this result, the polishing paste was recommended for the surface finishing process of PEEK. Attached et al. [7] evaluated the effect of various polishing protocols on PEEK materials and concluded that the polishing paste applied groups significantly reduced surface roughness compared to those that have not been applied. Kurashi et al. [26] determined the R_a values of PEEK with rubber and various polishing pastes. The lowest surface roughness was reported to be 0.015 µm in the specimens where the polishing paste was applied after a rubber brush. In the current study, all test groups were fine-polished with universal polishing paste to provide standardization between the specimen surfaces.

The prostheses can be cleaned by mechanical and chemical methods and also by a combination of these two methods to remove the coloration and bacterial colonization of the denture base materials. However, cleaning procedures can lead to deterioration of denture bases by increasing the surface irregularities, whitening in color, blackening of metal elements, and corrosion. The most common method of routine denture cleaning is to brush with tap water and soap/toothpaste [27]. Brushing the PMMA with soap [28] and paste [29] is a frequently applied, cheap, and practical method. However, while cleaning with brushing methods is effective on the plaque in acrylic resin prostheses, it may distort color and surface properties. Approximately 10,000 cycles in the brushing simulator correspond to a one-year toothbrushing equivalent period, according to the reported data by Goldstein & Lerner [22]. In the current study, 7500 cycles were applied to specimens that correspond to a nine-month toothbrushing period. Toothbrushing abrasion test may be affected by factors such as toothbrush type, force applied during brushing, cycle speed, stroke length, and the cleaning agent used with brushing. Therefore, these parameters were standardized for each test group. 350 g (3.43 N) of brass weights were placed on each toothbrush holder arm in the simulator to mimic the force applied by patients when brushing their teeth [29]. Similar to a previous study [17], an equal amount of paste and distilled water mixture was used for brushing.

Chemical denture cleaning agents such as effervescent tablets generally contain sodium perborate or sodium bicarbonate. By dissolving these tablets in water, the sodium perborate in its structure is broken down to form an alkaline peroxide solution. This peroxide solution releases oxygen and mechanically removes residues on the surface of the prosthesis. It has been reported that this could cause a color change, especially in the structure of PMMA acrylic resins [30]. NaOCl cleaning solutions used in this study are a powerful disinfectant for microorganisms. The antimicrobial activity of NaOCl is because of hydroxyl ions and high pH [12]. 0.12% chlorhexidine solution is frequently used as a denture-cleaning agent to prevent prosthetic stomatitis and creates a strong color change in acrylic prostheses [31]. As mentioned, there are many studies reported on widely used dental acrylic PMMA resin types, while there are limited studies reported on abrasion resistance, surface structure, and color change of PEEK materials after mechanical and chemical surface cleaning. The PEEK polymers have an excellent chemical, physical stability, and inert structure with low surface energy, low surface modification characteristics, and superior abrasion resistance to many types of acidic-basic solutions or abrasives. Therefore, various chemical and/or mechanical surface treatment techniques have been tested on PEEK polymers, and better results reported for the sulfuric acid solution applications, especially at the concentration of 98% [1, 4, 32]. The effects of artificial saliva solutions with pH values of 3, 7, and 10 had been evaluated on the nanomechanical surface properties (friction performance, nano-hardness, elastic modulus, and viscoelasticity) of unreinforced and carbon fiber-reinforced PEEK, composite resin and PMMA materials at physiological temperatures over 30 days. It has been indicated that the aging resistance of the unfilled PEEK was higher than those of other materials and the PEEK matrix without filler was more stable than with filler in the nanoscale [32]. In the current study, while the alkaline peroxide solution group (Corega) was prepared according to the manufacturers instructions, 5% solution of sodium hypochlorite and 0.12% chlorhexidine gluconate were used considering the previous studies [12].

The surface roughness (R_a) of a material used for prosthetic rehabilitation is important and directly or indirectly affects the resistance to staining, plaque accumulation, the health of oral tissues, and patient comfort [21]. Surface roughness is associated with increased initial biofilm adhesion. Previous studies have confirmed that surfaces with low roughness and free energy show less bacterial growth and plaque accumulation and a smoother and brighter appearance [33, 34]. In the present study, the mean R_a0 value was determined as 0.137 µm for the Control group. Although the surface roughness values obtained are below the PATL (<0.200 µm), it is also higher compared to the other studies [7, 8, 15, 26] probably due to the polishing methods and the different content of PEEK materials.

The surface roughness of dental materials may be evaluated using many types of devices, such as conventional profilometers, laser-tipped profilometers, atomic force microscopes, and scanning electron microscopy (SEM) [35]. It has been reported in related studies that contact profilometer devices are effective to detect the surface roughness, caused by polishing techniques [35, 36]. In the present study, to evaluate the surface roughness of the PEEK material after polishing and also after applying the surface cleaning protocols, the contact profilometer and SEM have been used.

Özyilmaz et al. [16] investigated the effect of surface cleaning agents on the properties of three different denture base materials including PEEK and detected that all agents improved the surface roughness of all test groups. Unlike this studys findings, in the present study, the absence of difference between R_a0 and R_a1 values in all test groups may depend on the fact that the PEEK used did not contain fillers and had a high purity stable structure [16, 26, 35].

Benli et al. [37] evaluated the surface roughness and the wear behavior of PMMA, polycarbonate, PEEK, and polyethyleneterephthalate (PETG) using a simulated chewing test, and the lowest surface roughness value was determined in PEEK specimens. They ascribed this finding to the composition, characterization, and wear resistance of the material having different chemical structures. Similarly, in the present study, the lack of a statistically significant difference in the surface roughness values of PEEK specimens before and after brushing may be explained by the fact that PEEK is a more stable material due to its chemical structure.

It is important that an ideal denture base material is in harmony with the color of oral tissues and protects its color throughout the mouth [38]. Depending on the intrinsic factors of the base material and the adsorption and absorption of the colorants from extrinsic sources, the color change may occur in the material. Coffee is one of the most frequently used drinks in daily life and is used as a colorant agent in many studies [19, 20]. In the present study, test specimens were stored in a coffee solution. In order to simulate intraoral conditions, the coffee solution was changed for 7 days and stored at 37 °C in a dark environment [18]. Also, in the study, CIEDE 2000 color system and the $\Delta E_{00} \leq 0.8$ perceptibility threshold and the $\Delta E_{00} \leq 1.8$ acceptability threshold values are in parallel with the study reported by Paravina et al. [24]. The discoloration of PEEK and polyoxymethylene (POM) denture bases after immersing in a coffee solution were evaluated by Polychronakis et al. [30] and reported that higher color change values were obtained for POM. This result has been associated with higher surface roughness values and more water absorption of POM since it contains 20% ceramic filler. Heimer et al. [8] reported that they applied cleaning procedures to PEEK, PMMA-based and composite materials (COMP) after immersions in different environments such as distilled water, wine, curry, and chlorhexidine for 7 days, the least color change was seen in PEEK material. In the current study following the application of chemical and mechanical cleaning procedures, no statistically significant color change was observed in PEEK materials.

In previous studies, although it was found that the color change of the materials increased with the increasing surface roughness [8, 39–41], there was not always a correlation between the color change and the surface roughness [42, 43]. In the current study, similar to the studies [8, 30, 40, 41], no significant difference was detected in surface roughness values and color changes after surface cleaning processes. This situation may be attributed to the correlation between surface roughness and color change.

The brushing and immersing in cleaning solutions procedures were carried out for a limited time and only coffee was used to simulate intraoral conditions. Other factors such as nutritional habits and saliva should also be taken into consideration. Candida or bacterial adhesion, wear resistance, and optical properties in the long-term performance should be investigated and compared with different laboratory and chairside polishing techniques.

Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The R_a values of all test groups before and after the surface cleaning procedures were determined below the PATL of 0.200 µm.
2. No statistically significant difference was found between control and other test groups, in terms of both R_a and ΔE_{00} values.
3. Considering the color stability and surface roughness, many cleaning procedures can be used safely for PEEK polymers used for dental applications.

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Declarations

Conflict of interest The authors declare that they have no financial support or relationships that may represent a conflict of interest.

References

1. Simsiriwong J, Shrestha R, Shamsaei N, Lugo M, Moser RD (2015) Effects of microstructural inclusions on fatigue life of polyether ether ketone (PEEK). J Mech Behav Biomed Mater 51:388–397. https://doi.org/10.1016/j.jmbbm.2015.07.020
2. Kurtz SM, Devine JN (2007) PEEK biomaterials in trauma, orthopedic, and spinal implants. Biomaterials 28(32):4845–4869. https://doi.org/10.1016/j.biomaterials.2007.07.013
3. SM Kurtz 2012 Synthesis and processing of PEEK for surgical implants In: PEEK biomaterials handbook Elsevier, pp 9 22
4. Heimer S, Schmidlin PR, Roos M, Stawarczyk B (2017) Surface properties of polyetheretherketone after different laboratory and chairside polishing protocols. J Prosthet Dent 117(3):419–425. https://doi.org/10.1016/j.prosdent.2016.06.016
5. Najeeb S, Zafar MS, Khurshid Z, Siddiqui F (2016) Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. J Prosthodont Res 60(1):12–19. https://doi.org/10.1016/j.jpor.2015.10.001
6. Stawarczyk B, Ender A, Trottmann A, Özcan M, Fischer J, Hämmerle CH (2012) Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: effect of aging regimens. Clin Oral Investig 16(6):1669–1677. https://doi.org/10.1007/s00784-011-0670-4
7. Attayeb R, Elgamal M, Elwaseefy N, El Mekawy N (2019) Influence of various polishing protocols on polyether-ether-ketone removable partial frameworks fabricated by cad/cam (scanning electron microscope study). IOSR-JDMS 18:34–39
8. Heimer S, Schmidlin PR, Stawarczyk B (2017) Discoloration of PMMA, composite, and PEEK. Clin Oral Investig 21(4):1191–1200. https://doi.org/10.1007/s00784-016-1892-2
9. Costa-Palau S, Torrents-Nicolas J, Brufau-de Barberà M, Cabratosa-Termes J (2014) Use of polyetheretherketone in the fabrication of a maxillary obturator prosthesis: a clinical report. J Prosthet Dent 112(3):680–682. https://doi.org/10.1016/j.prosdent.2013.10.026

10. Işeri U, Uludamar A, Ozkan YK (2011) Effectiveness of different cleaning agents on the adherence of Candida albicans to acrylic denture base resin. Gerodontology 28(4):271–276. https://doi.org/10.1111/j.1741-2358.2010.00379.x
11. Scheibe KGBA, Almeida KGB, Medeiros IS, Costa JF, Alves CMC (2009) Effect of different polishing systems on the surface roughness of microhybrid composites. J Appl Oral Sci 17(1):21–26. https://doi.org/10.1590/S1678-77572009000100005
12. Kürkcüoğlu I, Özkir SE, Köroğlu A, Sahin O, Yilmaz B (2016) Effect of denture cleansing solutions on different retentive attachments. J Prosthet Dent 115(5):606–610. https://doi.org/10.1016/j.prosdent.2015.11.012
13. de Freitas Fernandes FS, Pereira-Cenci T, Da Silva WJ, RicominiFilho AP, Straioto FG, Cury AADB (2011) Efficacy of denture cleansers on Candida spp. biofilm formed on polyamide and polymethyl methacrylate resins. J Prosthet Dent 105(1):51–58. https://doi.org/10.1016/S0022-3913(10)60192-8
14. Campanha NH, Pavarina AC, Jorge JH, Vergani CE, Machado AL, Giampaolo ET (2012) The effect of long-term disinfection procedures on hardness property of resin denture teeth. Gerodontology 29(2):571–576. https://doi.org/10.1111/j.1741-2358.2011.00520.x
15. Sturz CR, Faber F-J, Scheer M, Rothamel D, Neugebauer J (2015) Effects of various chair-side surface treatment methods on dental restorative materials with respect to contact angles and surface roughness. Dent Mater J 34(6):796–813. https://doi.org/10.4012/dmj.2014-098
16. Ozyilmaz OY, Akin C (2019) Effect of cleansers on denture base resins structural properties. J Appl Biomater Funct Mater 17(1):2280800019827797. https://doi.org/10.1177/2280800019827797
17. Kuhar M, Funduk N (2005) Effects of polishing techniques on the surface roughness of acrylic denture base resins. J Prosthet Dent 93(1):76–85. https://doi.org/10.1016/j.prosdent.2004.10.002
18. Şahin O, Dede DÖ, Köroğlu A, Yılmaz B (2015) Influence of surface sealant agents on the surface roughness and color stability of artificial teeth. J Prosthet Dent 114(1):130–137. https://doi.org/10.1016/j.prosdent.2015.02.009
19. Dede DÖ, Şahin O, Koroglu A, Yilmaz B (2016) Effect of sealant agents on the color stability and surface roughness of nanohybrid composite resins. J Prosthet Dent 116(1):119–128. https://doi.org/10.1016/j.prosdent.2015.11.024
20. Sahin O, Koroglu A, Dede DÖ, Yilmaz B (2016) Effect of surface sealant agents on the surface roughness and color stability of denture base materials. J Prosthet Dent 116(4):610–616. https://doi.org/10.1016/j.prosdent.2016.03.007
21. Köroğlu A, Şahin O, Dede DÖ, Deniz ŞT, Sever NK, Özkan S (2016) Efficacy of denture cleaners on the surface roughness and Candida albicans adherence of sealant agent coupled denture base materials. Dent Mater J 35(5):810–816. https://doi.org/10.4012/dmj.2016-103
22. Goldstein GR, Lerner T (1991) The effect of toothbrushing on a hybrid composite resin. J Prosthet Dent 66(4):498–500. https://doi.org/10.1016/0022-3913(91)90511-T
23. Commission Internationale de l Éclairage (CIE) (2004) Technical report 15 Colorimetry 3rd ed. CIE Central Bureau, Vienna
24. Paravina RD, Ghinea R, Herrera LJ, Bona AD, Igiel C, Linninger M et al (2015) Color difference thresholds in dentistry. J Esthet Restor Dent 27:1–9. https://doi.org/10.1111/jerd.12149
25. Zoidis P, Papathanasiou I, Polyzois G (2016) The use of a modified poly-ether-ether-ketone (PEEK) as an alternative framework material for removable dental prostheses. A Clin Rep J Prosthodont 25(7):580–584. https://doi.org/10.1111/jopr.12325
26. Kurahashi K, Matsuda T, Ishida Y, Ichikawa T (2020) Effect of polishing protocols on the surface roughness of polyetheretherketone. J Oral Sci 62(1):40–42. https://doi.org/10.2334/josnusd.18-0473
27. Brill N, Tryde G, Stoltze K, El Ghamrawy E (1977) Ecologic changes in the oral cavity caused by removable partial dentures. J Prosthet Dent 38(2):138–148. https://doi.org/10.1016/0022-3913(77)90278-5
28. Axe AS, Varghese R, Bosma M, Kitson N, Bradshaw DJ (2016) Dental health professional recommendation and consumer habits in denture cleansing. J Prosthet Dent1 15(2):183–188. https://doi.org/10.1016/j.prosdent.2015.08.007
29. Heintze S, Forjanic M, Ohmiti K, Rousson V (2010) Surface deterioration of dental materials after simulated toothbrushing in relation to brushing time and load. Dent Mater 26(4):306–319. https://doi.org/10.1016/j.dental.2009.11.152
30. Polychronakis N, Lagouvardos P, Polyzois G, Sykaras N, Zoidis P (2020) Color changes of polyetheretherketone (PEEK) and polyoxymethelene (POM) denture resins on single and combined

staining/cleansing action by CIELab and CIEDE2000 formulas. J Prosthodont Res 4(2):159–166. https://doi.org/10.1016/j.jpor.2019.06.005
31. Budtz-Jorgensen E (1979) Materials and methods for cleaning dentures. J Prosthet Dent 42:619–623. https://doi.org/10.1016/0022-3913(79)90190-2
32. Gao S, Gao S, Xu B, Yu H (2015) Effects of Different pH-Values on the Nanomechanical Surface Properties of PEEK and CFR-PEEK Compared to Dental Resin-Based Materials. Materials (Basel) 8(8):4751–4767. https://doi.org/10.3390/ma8084751
33. Bollenl CM, Lambrechts P, Quirynen M (1997) Comparison of surface roughness of oral hard materials to the threshold surface roughness for bacterial plaque retention: a review of the literature. Dent Mater 13(4):258–269. https://doi.org/10.1016/S0109-5641(97)80038-3
34. Sipahi C, Anil N, Bayramli E (2001) The effect of acquired salivary pellicle on the surface free energy and wettability of different denture base materials. J Dent 29(3):197–204. https://doi.org/10.1016/S0300-5712(01)00011-2
35. Kakaboura A, Fragouli M, Rahiotis C, Silikas N (2007) Evaluation of surface characteristics of dental composites using profilometry, scanning electron, atomic force microscopy and gloss-meter. J Mater Sci Mater Med 18(1):155–163. https://doi.org/10.1007/s10856-006-0675-8
36. Joniot S, Gregoire G, Auther A, Roques Y (2000) Three-dimensional optical profilometry analysis of surface states obtained after finishing sequences for three composite resins. Oper Dent 25(4):311–315
37. Benli M, Gümüş BE, Kahraman Y, Gökçen-Rohlig B, Evlioğlu G, Huck O et al (2019) Surface roughness and wear behavior of occlusal splint materials made of contemporary and high-performance polymers. Odontology. https://doi.org/10.1007/s10266-019-00463-1
38. Craig R (1989) Restorative dental materials, eight. Mosby, St. Louis, pp 18–53
39. Sharma G, Wu W, Dalal EN (2005) The CIEDE2000 color-difference formula: Implementation notes, supplementary test data and mathematical observations. Color Res Appl: Endorsed by Inter-Society Color Council, The Colour Group (Great Britain), Canadian Society for Color, Color Science Association of Japan, Dutch Society for the Study of Color, The Swedish Colour Centre Foundation, Colour Society of Australia, Centre Français de la Couleur 30(1):21–30. https://doi.org/10.1002/col.20070.
40. Paranhos HdFO, Peracini A, Pisani MX, Oliveira VdC, Souza RFd, Silva-Lovato CH (2013) Color stability, surface roughness and flexural strength of an acrylic resin submitted to simulated overnight immersion in denture cleansers. Braz Dent J 24(2):152–156. https://doi.org/10.1590/0103-6440201302151
41. Topcu FT, Sahinkesen G, Yamanel K, Erdemir U, Oktay EA, Ersahan S (2009) Influence of different drinks on the colour stability of dental resin composites. Eur J Dent 3(01):50–56
42. Smales R, Gerke D (1992) Clinical evaluation of light-cured anterior resin composites over periods of up to 4 years. Am J Dent 5(4):208–212
43. Lima AF, Soares GP, Vasconcellos PH, Ambrosano G, Marchi GM, Lovadino JR et al (2011) Effect of surface sealants on microleakage of Class II restorations after thermocycling and long-term water storage. J Adhes Dent 13(3):249–254. https://doi.org/10.3290/j.jad.a19242

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