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Polierbarkeit und Reinigungsmethoden des Hochleistungswerkstoffes Polyetheretherketon (PEEK)

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Berichterstatterin: PD Dr. Dipl. Ing (FH), Bogna Stawarczyk, MSc

Mitberichterstatter: Prof. Dr. Dr. Franz-Xaver Reichl

Prof. Dr. Andrea Wichelhaus

PD Dr. Dr. Gerson Mast

Dekan: Prof. Dr. med. dent. R. Hickel

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1 Einleitung und Zielsetzung

Zur Stoffgruppe der Polyaryletherketone gehörend erregt Polyetheretherketon (PEEK) als teilkristalliner, thermoplastischer Kunststoff seit geraumer Zeit Aufsehen in der Medizintechnik. Es gilt als metallfreie Alternative zum festsitzenden und herausnehmbaren Zahnersatz. So wird die Anwendung von PEEK neben Gerüstkonstruktionen für den herausnehmbaren Zahnersatz auch zunehmend in der Implantatprothetik erwogen. Im Vergleich zu Metallen, Keramiken und Legierungen zeichnet sich PEEK durch ein geringes spezifisches Gewicht, eine leichte Verarbeitbarkeit und fehlende Korrosionsanfälligkeit aus. Desweiteren ist es röntgentransparent, wodurch die Entstehung von Artefakten bei bildgebenden Diagnoseverfahren verhindert werden kann. Ein weiterer Vorteil von PEEK (E-Modul: 4 GPa) ist die geringere Übertragung eingeleiteter Kaukräfte auf das Nachbargewebe. Dadurch können Überbelastungen von Nachbarzähnen und Kieferknochen, was bei Verwendung von steiferen Materialien wie Titan (E-Modul: 110 GPa) oder Zirkoniumdioxid (E-Modul: 210 GPa) oftmals auftritt, vermieden werden [1].

Auf Grund fehlender klinischer, prospektiver Langzeistudien hinsichtlich des Verhaltens von PEEK in Bezug auf Wasseraufnahme, Verfärbungstendenz und Langzeitstabilität ist dessen standardmäßiger Einsatz im klinischen Alltag jedoch kontrovers diskutiert. Zum gegenwärtigen Zeitpunkt besteht die Möglichkeit, durch Anreicherung des Grundmaterials PEEK mit verschiedenen Oxiden (Titaniumoxid, Zirkoniumoxid) gezielten Einfluss auf seine Materialfestigkeit zu nehmen [2, 3]. PEEK-gefertigte Restaurationen können mittels Pressen oder der CAD/CAM Technologie hergestellt werden.

Sowohl Zahntechniker als auch Zahnärzte sollten dafür sorgen, dass einzugliedernde Restaurationen vor dem Einsetzen eine glatte Oberfläche aufweisen. Hierbei kann eine Aufteilung der Methoden in Lab- und Chairside-Verfahren erfolgen. Auch die Reinigung frisch gefertigter bzw. bereits eingesetzter Restaurationen spielt eine wichtige Rolle. So kann der Patient neben Zahntechniker und Zahnarzt selbst durch individuelle Prophylaxe Einfluss auf die Langlebigkeit seines Zahnersatzes nehmen. Neben einer glatten Materialoberfläche zur Verhinderung der Biofilmanlagerung spielt auch das Verfärbungspotential eines Restaurationsmaterials eine wichtige Rolle für das ästhetische Empfinden. Durch den täglichen Konsum an Speisen bzw. Getränken wie z.B. Rotwein und Currygerichte unterliegt das eingebrachte Zahnersatzmaterial einer kontinuierlichen Farbveränderung. Diese kann als störend empfunden werden, so dass Reinigungsverfahren evaluiert werden müssen, welche einer potentiellen Verfärbung entgegenwirken. Dabei ist die Materialoberfläche durch die Anwendung von verschiedenen Politur- und Reinigungsverfahren zwangsläufig dem Verschleiß unterworfen.

Um die Effizienz bzw. die entstehenden Oberflächenveränderungen eines Politur- bzw. Reinigungsverfahrens zu ermitteln, stehen verschiedene Vorgehensweisen zur Verfügung. Dazu zählen neben der Messung der Oberflächenrauhigkeit und -benetzbarkeit die Detektion entstandener Farbveränderungen und die rasterelektronenmikroskopische Analyse der Materialoberfläche. Auf diese Weise kann eine objektive Aussage über die mittels der einzelnen Verfahren erzielten Ergebnisse gemacht und Vergleiche zwischen verschiedenen Materialgruppen gezogen werden.

Als Voraussetzung für eine funktionell langlebige, ästhetisch ansprechende Restauration spielen eine gute Polierbarkeit, ein angemessenes Reinigungsverhalten und die damit verbundene geringe Plaqueanlagerungstendenz eines zahnärztlichen Werkstoffes eine entscheidende Rolle. Nur auf diese Weise können Langzeitprobleme wie Sekundärkaries und parodontale Schädigungen verhindert werden. Auf Grund der vielfältigen Angebote an Polier- und Reinigungsgeräten auf dem dentalen Markt bereitet es zunehmend Schwierigkeiten, die für das Werkstück geeigneten Methoden herauszufiltern. Dies gilt in besonderem Maße für Werkstoffe, dessen Materialeigenschaften hinsichtlich bestimmter Verfahrenstechniken noch nicht ausreichend analysiert wurden. Aus diesem Grund war es das Ziel vorliegender Studie, das Politur- und Reinigungsverhalten von PEEK zu untersuchen und dieses mit dem eines herkömmlichen Polymethylmethacrylats und eines Verblendkomposits zu vergleichen. Zu diesem Zweck wurden zusammenfassend in vorliegender Arbeit folgende Punkte untersucht:

1. Oberflächeneigenschaften von PEEK nach verschiedenen Politurprotokollen im Lab- und Chairside-Verfahren
2. Oberflächeneigenschaften von PEEK nach verschiedenen Reinigungsverfahren im Labside-Verfahren und bei individueller und professioneller Prophylaxebehandlung
3. Reinigungsmethoden für PEEK zur Entfernung von Farbveränderungen nach Lagerung in ausgewählten Medien

2 Eigene Arbeiten

Nachfolgend werden drei Originalarbeiten in englischer Sprache vorgestellt und zusammengefasst.

2.1 Originalarbeit: Heimer S, Schmidlin PR, Roos M, Stawarczyk B. Surface properties of polyetheretherketone after different laboratory-based and chairside polishing protocols. Journal of Prosthetic Dentistry 2017;117(3):419-25 (IF: 1.515)

Zusammenfassung

Problemstellung: Der Hochleistungskunststoff Polyetheretherketon (PEEK) kann als Gerüstmaterial für den festsitzenden Zahnersatz verwendet werden. Die Informationen bezüglich der Politurmöglichkeiten im Lab- und Chairside-Verfahren sind jedoch zum gegenwärtigen Zeitpunkt nicht ausreichend.

Ziel: Das Ziel der vorliegenden in-vitro Studie war es zu testen, welche Auswirkungen die angewandten Lab- und Chairside-Politurmethoden auf die Oberflächenrauhigkeit und -benetzbarkeit haben und diese mit einem konventionellen Kaltpolymerisat (PMMA) und einem Verblendkunststoff (COMP) zu vergleichen.

Material und Methode: Aus Polyetheretherketon (PEEK), Polymethylmethacrylat (PMMA) und einem Verblendkomposit (COMP) wurden je 80 scheibenförmige Prüfkörper hergestellt (n=240). Diese wurden in sieben verschiedene Politurgruppen unterteilt, von denen vier einem Labside- und drei einem Chairside-Politurprotokoll untergeordnet wurden. Das Labside-Politurprotokoll beinhaltete die Verwendung von Abraso (Hochglanzpoliturpaste), Opal L (eine weitere Hochglanzpoliturpaste), Ceragum (Silikonpolierer) und Diagen-Turbo-Grinder (Diamantpoliersystem). Das Chairside-Politurprotokoll umfasste das Super-snap rainbow Politursystem, Prisma gloss (eine feinkörnige Aluminium-Polierpaste) und das Enhance Finier- und Poliersystem. Als Kontrollgruppe dienten maschinell hochglanzpolierte Prüfkörper. Gemessen wurden die durchschnittliche Oberflächenrauhigkeit und -benetzbarkeit, außerdem wurde die Oberflächenbeschaffenheit mittels rasterelektronenmikroskopischen Bildern untersucht. Zur Analyse der logarhythmisch erfassten Daten wurden die Kovarianzanalyse, die zweifaktorielle ANOVA, die einfaktorielle ANOVA und die partielle Korrelation ($\alpha = 0{,}05$) verwendet.

Ergebnisse: Es konnte gezeigt werden, dass das Politurprotokoll den höchsten Einfluss auf Oberflächenrauhigkeit und -benetzbarkeit ($P < 0{,}001$; SR: partial eta squared ηP^2

= 0,970; SFE: ηP^2 = 0,450) hatte gefolgt von der Materialgruppe ($P < 0{,}001$, SR: ηP^2 = 0,319; SFE: ηP^2 = 0,429). Der Interaktionseffekt der beiden unabhängigen Parameter (Politurprotokoll und Materialgruppe) zeigte des Weiteren signifikante Werte ($P < 0{,}001$, SR: ηP^2 = 0,681; SFE: ηP^2 = 0,365).

Schlussfolgerung: Chairside-Politurmethoden zeigten niedrigere Oberflächenrauhigkeitswerte als Labside-Politurmethoden. Bei der Verwendung von Zweikörperverschleißpoliturmethoden zeigten sich höhere Oberflächenrauhigkeitswerte als bei der Anwendung von Dreikörperverschleißmethoden.

Klinische Relevanz: Unter Berücksichtigung der erzielten Oberflächenrauhigkeits- und Oberflächenbenetzbarkeitswerte sollten zur Politur des Hochleistungskunststoffes PEEK vorwiegend Politurpasten wie Abraso, Opal L und Prisma gloss zur Anwendung kommen.

THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Surface properties of polyetheretherketone after different laboratory and chairside polishing protocols

Sina Heimer, Dr Med, Med Dent,[a] Patrick R. Schmidlin, Prof Dr Med Dent,[b] Malgorzata Roos, PD Dr Phil,[c] and Bogna Stawarczyk, PD Dr Rer Biol Hum, Dipl Ing (FH), MSc[d]

ABSTRACT

Statement of problem. Polyetheretherketone (PEEK) can be used as a framework material for fixed dental prostheses. However, information about laboratory and chairside polishing methods is still scarce.

Purpose. The purpose of this in vitro study was to determine the effects of laboratory and chairside polishing methods on the surface roughness (SR) and surface free energy (SFE) of PEEK, an autopolymerizing poly(methyl methacrylate), and a veneering composite resin.

Material and methods. For each of the 3 materials, 80 specimens were prepared (N=240) and divided into 7 polishing groups and 1 control group (n=10). The 7 groups were split into 4 laboratory protocols: polishing paste (Abraso), a second polishing paste (Opal L), silicone polisher (Ceragum), and diamond grinder (Diagen-Turbo grinder). The other 3 groups were chairside protocols: rainbow technique (Super-Snap kit), polishing paste (Prisma gloss), and a polishing system (Enhance finishing). Machine polishing with SiC P4000 served as the control treatment. The protocols' average SRs and SFEs were measured, and their surface topographies were evaluated with scanning electron microscopy (SEM). The logarithmically transformed data were analyzed using covariance analysis, 2-way and 1-way ANOVA, and partial correlation (α=.05).

Results. The polishing protocol exerted the highest influence on SR and SFE values (*P*<.001; SR: partial eta squared η_P^2=.970; SFE: η_P^2=.450), followed by material group (*P*<.001, SR: η_P^2=.319; SFE: η_P^2=.429). The interaction effect of the binary combinations of the 2 independent parameters (polishing protocol and material group) was also significant (*P*<.001, SR: η_P^2=.681; SFE: η_P^2=.365).

Conclusions. Chairside methods presented lower SR values than laboratory methods, and specimens polished using the 2-body mode showed higher SR than did specimens polished using the 3-body mode. (J Prosthet Dent 2017;117:419-425)

Polyetheretherketone (PEEK) is a synthetically produced polymeric material belonging to the polyacryletherketone family. Because of its excellent chemical, thermal, and mechanical properties and its excellent biocompatibility,[1] PEEK is used in various areas of dentistry.[2-4] Because the material possesses a grayish-brown or pearl-white opaque color, a veneering composite resin (COMP) material is also needed for esthetics.[5,6] Relevant parameters for evaluating the clinical longevity of dental restorations include water absorption, polymerization shrinkage, dimension stability, and polishing ability. PEEK has been shown to absorb less water than poly(methyl methacrylate) (PMMA), even after an immersion period of 10 days at 121°C.[7,8] Although PMMA and COMP show a polymerization shrinkage of approximately 2% to 4%, PEEK does not shrink during the polymerization process and remains chemically inert.[4,9] Furthermore, PEEK offers high stability with regard to hardness, rigidity, and strength, even over that of a wide range of temperatures; this results in less deformation than other thermoplastic materials.[4]

Obtaining a polished surface is not only crucial for esthetics, it is also a key factor in bacterial plaque

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[a]Medical Doctor and Dentist, Department of Prosthodontics, Ludwig-Maximilians-University, Munich, Germany.
[b]Head, Discipline of Periodontology and Peri-Implant Diseases, Clinic of Preventive Dentistry, Periodontology and Cariology, Center of Dental Medicine, University of Zurich, Switzerland.
[c]Senior Statistician, Department of Biostatistics, Epidemiology, Biostatistics and Prevention Institute, University of Zurich, Switzerland.
[d]Head, Dental Materials Unit, Department of Prosthodontics, Ludwig-Maximilians-University, Munich, Germany.

Clinical Implications

According to the surface roughness and surface free energy values, polishing pastes (Abraso, Opal L, and Prisma gloss) should be used when polishing polyetheretherketone (PEEK) restorations.

accumulation,[10,11] as a direct correlation exists between surface topography and biofilm formation.[12-19] Polishing should result in a final surface roughness (SR) below a threshold value of 0.2 μm in addition to a low surface free energy (SFE); if necessary, this can be accomplished by using different polishing devices.[20] The surface quality depends on several parameters (type of polisher, velocity, contact pressure, surrounding media, and surface quality) and on how much abrasive wear of the dental restorative material surfaces is intended.[21] Available polishing methods include 2-body abrasion (including grinding burs and both bonded and coated abrasives) and 3-body abrasion (consisting of polishing pastes such as aluminum oxide or diamond particles).[22] The correct material performance and the relationships between the material's hardness and its wear characteristics, light reflectiveness, surface topography, and roughness need to be considered.[23,24]

Dental technicians and dentists are facing the challenge of identifying an adequate polishing method because of the plethora of different methods and lack of precise guidelines. Data for the optimal method of polishing PEEK and its impact on SR and SFE is lacking. Therefore, this study investigated PEEK's polishing characteristics relative to those of PMMA and COMP. The null hypothesis tested was that the polishing protocol would not affect the tested materials' SR or SFE.

MATERIAL AND METHODS

The impact of 7 polishing protocols, with an unpolished group as a control, was investigated. Four laboratory and 3 chairside methods of PEEK processing (bioHPP; bredent GmbH & Co KG) were assessed with regard to SR, SFE, and surface topography. Additionally, PEEK values were compared with those of 2 conventional polymers: autopolymerizing denture PMMA (uni.lign PF 20; bredent GmbH & Co KG) and a veneering COMP (crea.lign; bredent GmbH & Co KG) (Table 1, Fig. 1). To minimize the outcome variability, all preparations, polishing procedures, and evaluations were conducted by the same investigator (S.H.).

The manufacturer provided 80 disks made of PEEK (3 mm high, 15 mm in diameter). Individually fabricated silicone molds with standardized geometries of 15×15×3 mm were used as templates to produce the PMMA (n=80) and COMP (n=80) specimens. PMMA powder (13 g) was mixed with the liquid (9 mL), used to

Table 1. Manufacturer, composition properties, and lot numbers of test materials

Material	Brand	Manufacturer	Lot No.	Composition	Method of Polymerization
PEEK	BioHPP	bredent GmbH & Co KG	410240	Ceramic filled (20%) PEEK	Press mode
PMMA	Uni.lign PF 20	bredent GmbH & Co KG	396617, 401822	99% PMMA polymer	Pressure pot (Heraeus Kulzer GmbH), 20 min, 55°C, 0.45 MPa
COMP	Crea.lign	bredent GmbH & Co KG	N141331	bis-GMA composite with microfillers	Visible light
	Incisal E2		123765		bre.Lux Power Unit (bredent GmbH & Co KG)

COMP, composite resin; bis-GMA; bisphenol A-glycidyl methacrylate PEEK, polyetheretherketone; PMMA, poly(methyl methacrylate).

fill the silicone molds, and polymerized in a pressure vessel (Palamat Elite; Heraeus Kulzer GmbH) for 20 minutes at 0.45 MPa, using warm (55°C) water. To prepare the COMP specimens, the molds were filled with a veneering COMP layer applied at a thickness of approximately 1 mm per increment. A light-polymerizing unit (bre.Lux Power Unit; bredent GmbH & Co KG) was used to polymerize each layer for 180 seconds at a wavelength between 370 nm and 500 nm. The specimens were ground with silicon carbide abrasive papers (SiC P500; Struers GmbH) for 2 minutes at a contact pressure of 0.3 MPa under constant water cooling. All specimens were prepolished with a fine pumice stone (Ernst Hinrichs Dental GmbH) and goat hair brushes (bredent GmbH & Co KG) for 2 minutes (Table 2).

The 4 laboratory and 3 chairside polishing methods tested are specified in Table 2. To determine SR and SFE, the same specimens (n=10) were used. The surface quality was analyzed using SR measurements from a contact profilometer (Mahr Perthometer SD 26; Mahr GmbH) and was measured with a diamond-tipped stylus that applied a measuring force of 0.7 mN using 6 readings with a track length of 6 mm. The distance between the lines was set at 0.25 mm. SR was analyzed directly after specimen preparation, after prepolishing with a fine pumice stone (Ernst Hinrichs Dental GmbH) and after final polishing. The accuracy of the profilometer was checked periodically with a calibration block. The profile length was 1.75 mm with a resolution of 0.01 μm. SFE is a measurement for quantifying the disruption of intermolecular bonds that occur while a surface is generated. After measuring the contact angles (Kruess Easy Pearl; Kruess GmbH) of the substrate with water (polar) and diiodomethane (dipolar), the SFE (in J/m^2) was calculated using software (DSA4; Kruess), which uses the Owens, Wendt, Rabel, and Kaelble method based on the Young equation and the Fowkes method.[25,26] The measurements were made on every second specimen and at different locations. In all, the SFE was measured on

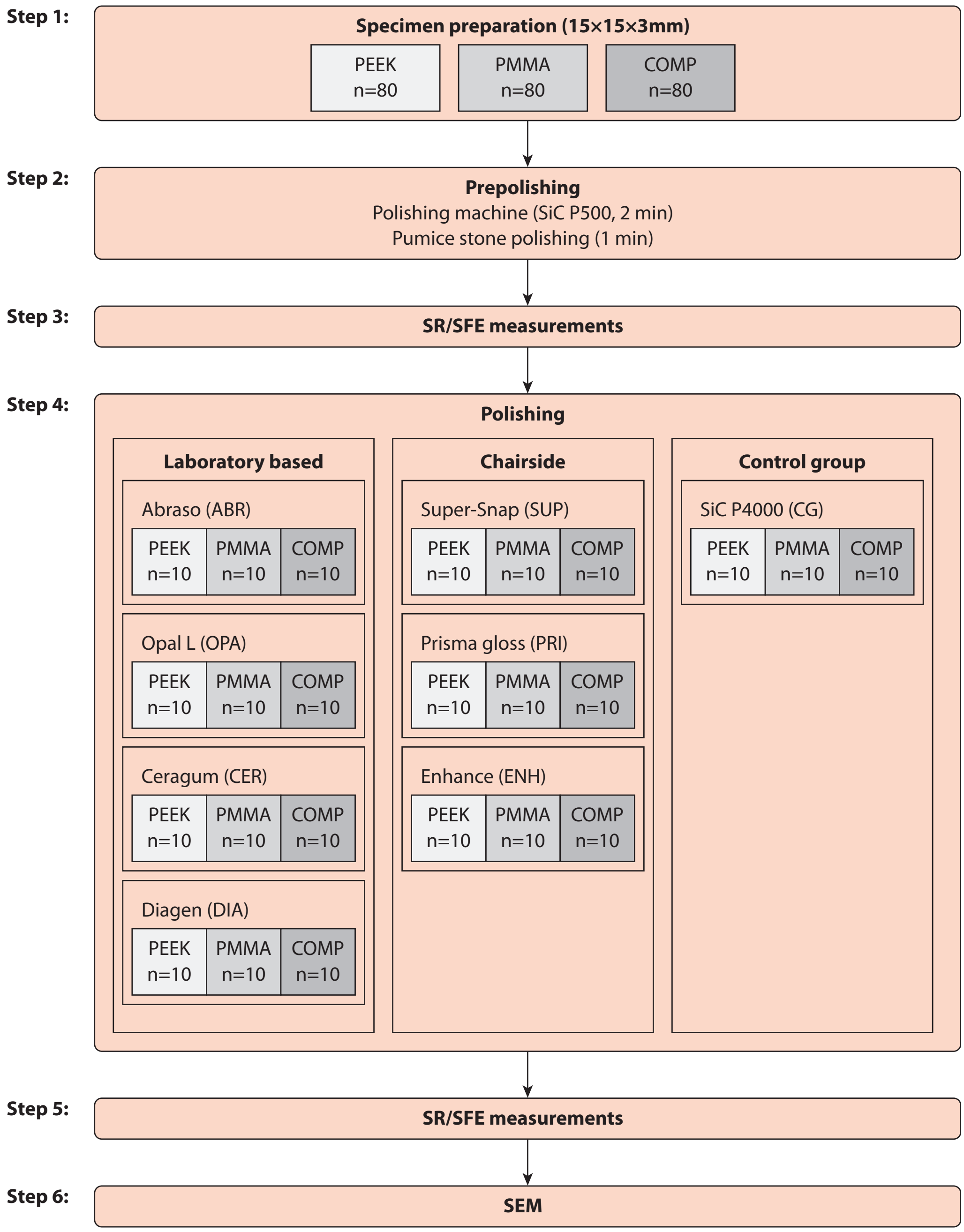

Figure 1. Study design, divided into different steps of preparation, prepolishing, clinical polishing, and SR/SFE measurements. COMP, composite resin; PEEK, polyetheretherketone; PMMA, poly(methyl methacrylate); SR/SFE, surface roughness/surface free energy; SEM, scanning electron microscopy.

240 specimens (5 in each group). One specimen of each material and polishing group was selected and gold-sputtered (SC7620 Sputter Coater; Quorum Technologies). The surface topography was evaluated using scanning electron microscopy (SEM; Supra 55VP; Carl Zeiss AG) at 10 kV, with a working distance of 6 mm and using original magnifications of ×15, ×300, and ×600.

The assumption of normality was tested using the Kolmogorov-Smirnov test, applied to the residuals of a 2-way ANOVA for SR and SFE. Both of the primary outcomes (SR and SFE) were logarithmically transformed to stabilize the variance and obtain an approximate normality. A 2-way ANOVA was used to assess, first, the effect of the independent parameters of the polishing protocol and material group and, second, the effect of their interaction on SR and SFE results (the dependent parameter). The significant differences between the materials and polishing protocols were indicated using a 1-way ANOVA followed by a Scheffé post hoc test. A global covariance analysis was applied to investigate the impact of laboratory-based versus chairside methods and of 2- versus 3-body modes, adjusted for material and polishing protocol. A partial

Table 2. Polishing protocols, products, and manufacturers used

Polishing Protocol	Manufacturer	Polishing Method (Manufacturer)
ABR	Abraso polishing paste (bredent GmbH & Co KG)	Polishing motor (Kavo Dental GmbH); Polishing mops (high-lustre buffs) (bredent GmbH & Co.KG); Duration: 1 min, 3000 U/min
OPA	Opal L polishing paste (Renfert GmbH)	Straight handpiece (KaVo Dental GmbH); Polishing mops (fabric buffs) (bredent GmbH & Co.KG); Duration: 1 min, 10 000 U/min
CER	Ceragum silicone polisher (bredent GmbH & Co KG)	Straight handpiece (Kavo Dental GmbH); Duration: 1 min, 12 000 U/min
DIA	Diagen-Turbo grinder (bredent GmbH & Co KG)	Straight handpiece (KaVo Dental GmbH); Duration: 1 min, 12 000 U/min
SUP	Super-snap polishing disks (Shofu Dental GmbH)	Contrangle handpiece (KaVo Dental GmbH); Duration: violet: 30 s; green: 30 s; pink: 30 s; 11000 U/min
PRI	Prisma-gloss polishing paste (Dentsply De Trey GmbH)	Contrangle handpiece (KaVo Dental GmbH); Duration: dry (40 s), wet (20 s), 8000 U/min
ENH	Enhance polishing system (Dentsply De Trey GmbH)	Contrangle handpiece (KaVo Dental GmbH); Duration: dry (1 min), 5000 U/min
CG	Polishing machine (Struers GmbH)	Polishing protocol for each material group; polishing materia used, silicon carbide abrasive papers; PEEK: P1200 (0.3 MPa, 1 min), P4000 (0.3 MPa, 4 min), P4000 (0.5 MPa, 4 min); PMMA: P2000 (0.3 MPa, 2 min), P4000 (0.3 MPa, 2 min); COMP: P500 (0.5 MPa, 4 min), P1200 (0.5 Mpa, 4 min), P2000 (0.5 MPa, 6 min), P4000 (0.5 MPa, 8 min)

COMP, composite resin; PEEK, polyetheretherketone; PMMA, poly(methyl methacrylate).

correlation between SR and SFE, adjusted for material and polishing protocol, was computed with software (IBM SPSS Statistics v23.0, IBM Corp) (α=.05).

RESULTS

The polishing protocol exerted the highest influence on the SR and SFE values (*P*<.001; SR: η_P^2=.970; SFE: η_P^2=.450), followed by material group (*P*<.001; SR: η_P^2=.319; SFE: η_P^2=.429). The interaction effect of the binary combinations of the 2 independent parameters (protocol and material group) was also significant (*P*<.001; SR: η_P^2=.681; SFE: η_P^2=.365).

For all materials, the protocols affected the SR and SFE values (*P*<.001 to *P*=.001) (Table 3). The PEEK specimens that were polished using protocol DIA (Diagen-Turbo grinder [bredent GmbH & Co KG]) had higher SR values than the specimens polished using the control or the other protocols, which had SR values in descending order: ABR (Abraso polishing paste [bredent GmbH & Co KG]), OPA (Opal L polishing paste [Renfert GmbH]), PRI (Prisma-gloss polishing paste [Dentsply De Trey GmbH]), SUP (Super-snap polishing discs [Shofu Dental GmbH]), CER (Ceragum Silicone polisher [bredent GmbH & Co KG]), ENH (Enhance polishing system [Dentsply De Trey GmbH]) (P<.001). PEEK polished using protocol ENH presented lower SFE than did specimens polished with protocols ABR, DIA, SUP, and PRI or the control (*P*<.001). The PMMA specimens polished using protocols OPA, PRI, SUP, and the control showed significantly lower SR values than those polished using protocols ABR, CER, and ENH. The highest SR was measured for PMMA specimens polished using protocol DIA (*P*<.001). With respect to the SFE values, PMMA specimens polished using protocols OPA and ENH showed lower values than those polished using protocol ABR (*P*=.001). The COMP specimens polished using protocols DIA and ENH showed higher SR than any of the other protocols (*P*<.001). With respect to the SFE values, the following differences were observed (*P*<.001): The COMP specimens polished using protocol OPA showed lower values than those using protocols DIA and ENH, and those polished using protocol CER presented lower values than those using protocol DIA (Table 3).

All protocols were observed to affect the SR values of the material groups (*P*<.001 to *P*=.022). For protocol ABR, SR was lowest for PEEK, followed by COMP; PMMA had the highest SR (*P*<.001). Protocol OPA presented lower SR for PEEK than for PMMA (*P*=.001). For specimens polished according to protocol CER, the highest SR was for PEEK, followed by PMMA; COMP had the lowest SR (*P*<.001). Protocol DIA resulted in a higher SR for PEEK than for COMP (*P*=.011). Within specimens polished using protocols SUP (*P*<.001) and PRI (*P*=.022), PEEK presented higher SR values than either PMMA or COMP. Among groups polished using protocol ENH (*P*=.001) and the control protocol (*P*<.001), PMMA had higher SR values than either COMP or PEEK (Table 3).

Within groups polished using protocols OPA, PRI, and control, no impact on SFE values was determined (with *P* between .061 and .438). The remaining protocols showed an impact of the material group (*P*<.001 to *P*=.025). Protocol ABR provided higher SFE for PMMA than for either PEEK or COMP (*P*<.001). Specimens polished using protocol CER showed higher SFE for PMMA than for PEEK (*P*=.025). Protocol DIA provided higher SFE for COMP than for either PEEK or PMMA (*P*=.001). The PEEK specimens polished using protocol SUP had lower SFE values than did either the COMP or the PMMA specimens (*P*<.001). For specimens polished using protocol ENH, COMP specimens showed higher SFE than did PEEK specimens (*P*=.001). A global covariance analysis revealed that chairside methods led to significantly lower SR values (*P*<.001, η_P^2=.196) than did laboratory-based methods and that specimens polished using the 2-body mode led to higher SR than did specimens polished using the 3-body mode (*P*<.001,

Table 3. Analysis after clinical polishing and measurements

Material	Polishing Protocol	SR (μm)*		SFE (J/m^2)*	
		Mean ±SD	95% CI	Mean ±SD	95% CI
PEEK					
Laboratory based	ABR	0.034 ±0.010^{aA}	0.025-0.042	44.9 ±2.0^{bA}	42.3-47.5
	OPA	0.046 ±0.008^{aA}	0.039-0.052	39.9 ±4.0^{abA}	34.8-44.9
	CER	0.424 ±0.117^{dC}	0.339-0.508	39.0 ±3.4^{abA}	34.7-43.3
	DIA	1.337 ±0.265^{eB}	1.146-1.528	45.4 ±1.0^{bA}	44.0-46.7
Chairside	SUP	0.118 ±0.027^{cB}	0.097-0.137	43.6 ±2.1^{bA}	40.8-46.2
	PRI	0.072 ±0.009^{bB}	0.025-0.042	46.7 ±5.3^{bA}	39.9-53.3
	ENH	0.5670 ±0.103^{dA}	0.495-0.644	34.3 ±4.1^{aA}	29.1-39.4
CG	CG	0.032 ±0.003^{aA}	0.028-0.035	45.9 ±1.8^{bA}	43.5-48.1
PMMA					
Laboratory based	ABR	0.103 ±0.021^{bC}	0.087-0.119	56.5 ±2.9^{bB}	52.8-60.1
	OPA	0.064 ±0.012^{aB}	0.054-0.074	43.0 ±7.3^{aA}	33.8-52.1
	CER	0.268 ±0.055^{cB}	0.227-0.308	45.4 ±4.7^{abA}	39.4-51.3
	DIA	1.127 ±0.273^{eAB}	0.930-1.323	47.2 ±2.2^{abA}	44.3-50.0
Chairside	SUP	0.063 ±0.015^{aA}	0.051-0.074	52.2 ±3.4^{abB}	47.9-56.4
	PRI	0.062 ±0.007^{aA}	0.056-0.068	48.6 ±2.3^{abA}	45.6-51.6
	ENH	0.684 ±0.078^{dB}	0.627-0.741	42.9 ±6.5^{aA}	34.6-51.0
CG	CG	0.072 ±0.004^{aB}	0.067-0.076	48.5 ±2.3^{abA}	45.4-51.4
COMP					
Laboratory based	ABR	0.059 ±0.017^{bB}	0.045-0.071	47.9 ±3.1^{abcA}	43.9-51.7
	OPA	0.055 ±0.011^{abAB}	0.046-0.063	43.9 ±2.0^{aA}	41.3-46.4
	CER	0.099 ±0.041^{cA}	0.068-0.128	45.0 ±2.6^{abA}	41.6-48.3
	DIA	0.989 ±0.097^{eA}	0.918-1.059	52.9 ±3.7^{cB}	48.2-57.5
Chairside	SUP	0.074 ±0.018^{bcA}	0.060-0.088	49.5 ±1.8^{abcB}	47.2-51.7
	PRI	0.062 ±0.008^{bcA}	0.055-0.069	50.2 ±2.7^{abcA}	46.8-53.6
	ENH	0.517 ±0.067^{dA}	0.468-0.566	51.8 ±4.0^{bcB}	46.7-56.7
CG	CG	0.038 ±0.014^{aA}	0.027-0.048	48.8 ±1.6^{abcA}	46.6-50.9

ABR, Abraso polishing paste (bredent GmbH & Co KG); CER, Ceragum silicone polisher (bredent GmbH & Co KG); CG, polishing machine (Struers GmbH); COMP, composite resin; ENH, enhance polishing system (Dentsply De Trey GmbH); OPA, Opal L polishing paste (Renfert GmbH);PEEK, polyetheretherketone; PMMA, poly(methyl methacrylate); PRI, Prisma-gloss polishing paste (Dentsply De Trey GmbH); SR/SFE, surface roughness/surface free energy; SUP, Super-snap polishing discs (Shofu Dental GmbH). Overview of mean values, standard deviations, and 95% confidence intervals (CI) after clinical polishing and SR/SFE measurements divided into different materials (PEEK, PMMA, COMP). Average SR values are listed in μm, mean SFE values are measured in J/m^2. *Different superscript lowercase letters represent significant differences between polishing protocols within one material group. Different superscript uppercase letters represent significant differences between materials within one polishing protocol.

η_P^2=.720). By contrast, the type of method had no impact on SFE (P>.600).

For laboratory-based methods, protocols DIA and CER caused higher SR values than did protocols ABR and OPA (P<.001). With respect to the SFE, polishing using protocols OPA and CER led to lower values than did using protocols ABR and DIA (P<.001). In general, the PEEK specimens after polishing showed higher SR than PMMA, and the lowest SR values were observed for COMP material (P<.001). In both laboratory-based and chairside methods, PEEK led to lower SFE values than did either COMP or PMMA (P<.001). Among the chairside methods, protocols SUP and PRI resulted in lower SR values than did protocol ENH (P<.001). Protocol ENH led to lower SFE values than did protocols DIA and SUP (P<.001). COMP specimens, after polishing, showed lower SR than did PEEK and PMMA specimens (P=.001). No partial correlation was found between SR and SFE after adjusting for material and protocol (P=.225). The SEM pictures of all polished surfaces are presented in Figure 2.

DISCUSSION

The null hypothesis of this study was that the examined materials and the different polishing protocols would affect neither SR nor SFE values. For both parameters, the null hypothesis was rejected. In this study, the polishing ability of PEEK specimens were comparable to those of PMMA and COMP specimens; this was followed by efficiency tests for the 7 different protocols.

The authors are unaware of data concerning polishing methods using PEEK restoration material, despite this material's potential for restoration due to its outstanding mechanical, thermal, and chemical properties.[1] These considerations justify this study's selection of PEEK for the evaluation of its surface properties and polishing ability. Previous plaque formation studies have also found that PEEK can serve as a suitable dental restoration material.[10-12] The initial period of plaque formation, known as the critical or adhesion phase, has a decisive influence on plaque increase, ending in the formation of a manifest incipient carious lesion on neighboring teeth.

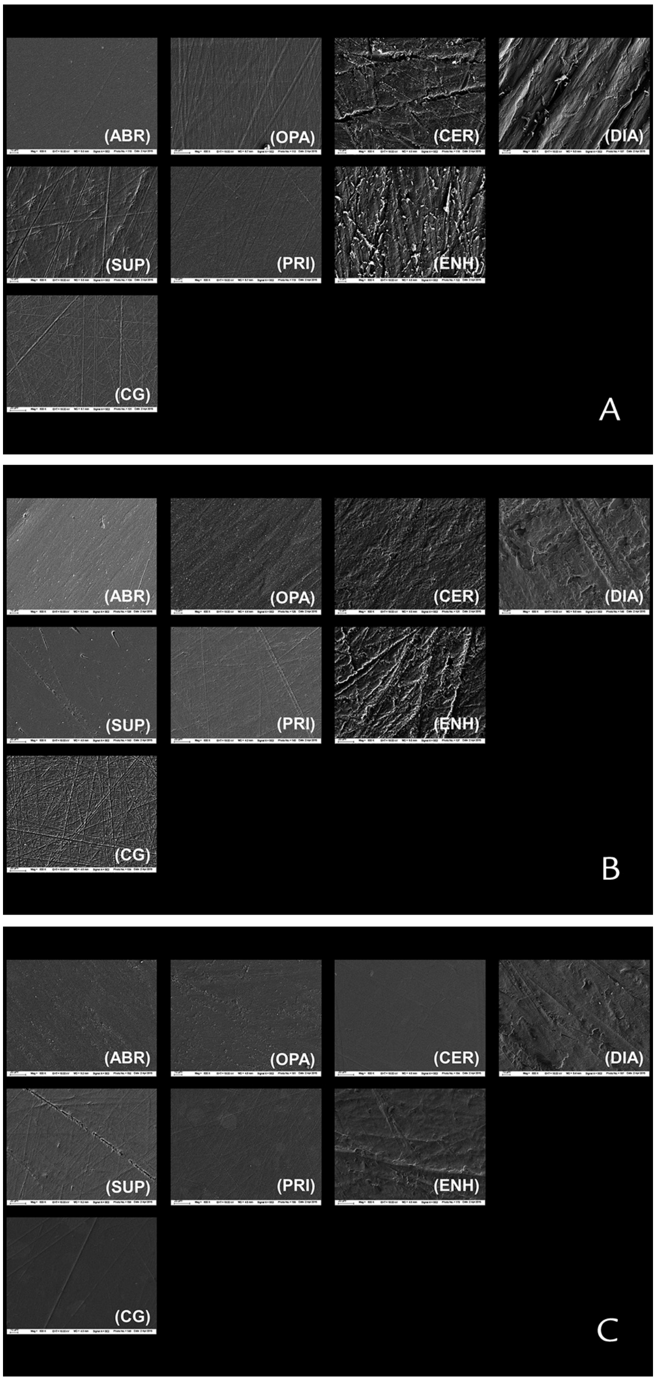

Figure 2. Representative scanning electron micrographs of materials evaluated, divided into different polishing protocols (I-VII, CG; original magnification ×600). A, PEEK. B, PMMA. C, COMP. COMP, composite resin; PEEK, polyetheretherketone; PMMA, poly(methyl methacrylate).

To counteract this development, it is essential to obtain a high luster, smooth restoration surface with low SR and SFE values to prevent early settling bacteria from attaching. Even chemical surface properties show crucial impacts on plaque formation.[27]

In previous studies, SR was shown to influence plaque accumulation on titanium implant surfaces. SR values above 0.2 μm led to an increased rate of biofilm formation, whereas SR values less than 0.2 μm had less effect on plaque adhesion.[15,16] Studies have also confirmed increased dental plaque formation on rough surfaces.[17-19] Furthermore, Buergers et al,[14] regarding the correlation between surface properties and the adhesion of *Streptococcus mutans*, concluded that there were correlations both between bacterial adhesion and SFE values and between SFE and SR values; otherwise, they found no correlation between SR and fluorescent bacterial biofilm. Thus, whether SR values or SFE values are the more essential factors in evaluating a polishing protocol for bacterial adhesion is unclear.

Further clinical studies are needed to test PEEK in terms of its surface properties and bacterial formation. Particularly within the first 20 hours, PEEK shows a significantly lower formation of viable biomass than do other abutment materials (zirconia and titanium). This may be because even glazed ceramics do not reach SR values below 0.3 μm.[28] In a study by Hahnel et al,[12] PEEK was polished using an automated polishing machine with SiC P4000 grinding paper, comparable to the method used in the control group of the present study. Concerning the impact of the protocol on PEEK, the control group and protocols ABR, OPA, SUP, and PRI showed a lower SR than the other groups did. Protocol ENH achieved the lowest SFE values, and these differences were significant, but this protocol's SR values were still above 0.2 μm. A key issue in the present study is the distinction between laboratory-based and chairside protocols. Dental restorations should display a smooth surface before being inserted in the oral cavity. In restorations where occlusal adjustment is required, the restoration surface must be adequately repolished. Therefore, both the 2-body and the 3-body modes are available.[22] The 2-body mode includes abrading burs and coated abrasives (comparable to those used in laboratory-based protocols CER and DIA and chairside protocols SUP and ENH). Laboratory-based protocols ABR and OPA and chairside protocol PRI represent 3-body wear using high-gloss polishing pastes. The benefit of using polishing pastes is that the combination of the paste with water leads to a fine abrasive action and a high-gloss, light-reflective surface.[21]

In contrast, the dry version acts in a more aggressive way, causing a higher amount of wear and potentially producing deep notches. The drawback of polishing with pastes is the need to use polishing brushes. Concerning laboratory-based protocols, methods ABR and OPA showed lower SR values than the other methods for all materials. Polishing OPA and CER resulted in lower SFE values than did the other laboratory-based protocols. Among chairside protocols, groups SUP and PRI showed lower SR values across all materials; however, the lowest SFE values were found in group ENH. The Enhance polishing system in protocol ENH led to high SR values (>0.5 μm) across all material groups. These results are comparable to those seen in the PEEK material group. This outcome could be confirmed by testing polishing methods (measure by SR) using different types of COMPs.[29]

In the current study, PEEK showed tangentially lower SFE but higher SR than did either COMP or PMMA. A correlation between the SR and SFE values could not be found, which is conspicuous in that the 3-body wear methods (in particular) reached the best results with regard to low SR and SFE values for all protocols, except for the chairside protocol SUP. Potentially decisive aspects that cannot be disregarded include surface properties like hardness, filler degree, and the matrix texture of the polished materials. PEEK shows a hardness of approximately 110 Vickers hardness number (VHN), which is comparable to that of established PMMA materials. COMP is a considerably harder material, with a hardness value of approximately 600 VHN.[1] Filler loading could be proven to determine the mechanical properties of composites, depending on their filler morphologies. In this context, a straight proportionality between filler loading and hardness can be assumed.[23,24] The current examinations seem to show that COMP achieved the lowest SR for all the protocols. However, the PEEK specimens achieved lower SR than did either the PMMA or COMP specimens. The assumption is that materials with a high hardness can reach lower SR after polishing than can smoother materials, which end up with lower SFE. Future studies should investigate this correlative thesis.

CONCLUSIONS

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

1. For the laboratory-based protocols, polishing pastes (protocols ABR and OPA) created PEEK surfaces with lower SR than those produced by protocols CER and DIA. The lowest SFE were achieved using protocols OPA and CER.
2. For the chairside protocols, both the protocols SUP and PRI led to PEEK surfaces with lower SR than were produced with protocol ENH. The lowest SFE was achieved using the protocol ENH.
3. Chairside polishing methods resulted in lower SR than did laboratory-based methods.
4. Specimens polished using 2-body mode showed higher SR than did specimens polished using 3-body mode.

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Corresponding author:
Dr Bogna Stawarczyk
Department of Prosthodontics
Dental School
Ludwig-Maximilians University Munich
Goethestrasse 70, 80336 Munich
GERMANY
Email: bogna.stawarczyk@med.uni-muenchen.de

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Zusammenfassung

Ziel: Vorliegende Studie untersucht den Effekt verschiedener Reinigungsmethoden auf Oberflächenrauhigkeit und -benetzbarkeit des Hochleistungswerkstoffes Polyetheretherketon (PEEK), des Kaltpolymerisats Polymethylmethacrylat (PMMA) und eines konventionellen Verblendkunststoffes (COMP) aus der Sicht des Patienten, des Zahntechnikers und des Zahnarztes.

Material und Methode: Nach der Fertigung von insgesamt 990 scheibenförmigen Prüfkörpern aus den Materialien Polyetheretherketon (PEEK), Polymethylmethacrylat (PMMA) und einem konventionellen Verblendkunststoff (COMP) erfolgte deren Einteilung in folgende Gruppen (n=30/Gruppe): (i) Individualprophylaxe mit den Untergruppen (ST) weiche, (MT) mittelharte und (SOT) Ultraschallzahnbürsten, (ii) labortechnische Reinigungsmöglichkeiten unterteilt in das (SY) Sympro Reinigungssystem, (SS) SunSparkle, (UB) Ultraschallbad und (AP) Korund und (iii) professionelle Prophylaxe, bei welcher (PS) Perio Soft-Scaler, (SO) Sonicsys, (AFC) Air Flow Comfort und (AFP) Air Flow Plus verwendet wurden. Vor Beginn und nach Abschluss der Reinigungsdurchgänge wurden die Oberflächenrauhigkeit mittels Profilometer, die Oberflächenbenetzbarkeit mit Hilfe der Kontaktwinkelmessung und deren Beschaffenheit mittels rasterelektronenmiskroskopischen Aufnahmen untersucht. Zur Auswertung der Daten wurden multivariate Analysemethoden, der Kruskal-Wallis-H und der Mann-Whitney-U Test angewendet ($p < 0{,}05$).

Ergebnisse: Die verwendeten Materialien zeigten keinen Einfluss auf die Oberflächenrauhigkeit ($p = 0{,}443$). Die Anwendung von Korund (AP) und Air Flow Plus (AFP) führte zu signifikant höheren Oberflächenrauhigkeiten als bei den verbliebenen Reinigungsmethoden ($p < 0{,}001$). Bezüglich der Oberflächenbenetzbarkeit erzielte die jeweils verwendete Reinigungsmethode den höchsten Einfluss ($p < 0{,}001$, $\eta P2 = 0{,}246$), direkt gefolgt vom Material ($p < 0{,}001$, $\eta P2 = 0{,}136$). Nach der Durchführung der einzelnen Reinigungsmethoden zeigten PMMA und PEEK niedrigere Werte hinsichtlich der Oberflächenbenetzbarkeit als COMP. Die Reinigung mittels Perio Soft-Scaler, Ultraschallbad und Sonicsys führte zu niedrigeren Oberflächenbenetzbarkeitswerten als eine solche mittels SunSparkle, weicher Zahnbürste und Sympro. Dabei zeigte die Reinigung mit Hilfe von Sympro die höchsten Oberflächenbenetzbarkeitswerte.

Schlussfolgerung: Unter Berücksichtigung der erzielten Oberflächenrauhigkeitswerte können mit Ausnahme von Korundstrahlen alle Methoden zur Reinigung von PEEK empfohlen werden. Auf Grund der durchgängig niedrigen Oberflächenbenetzbarkeitswerte von PEEK kann geschlussfolgert werden, dass daraus im Vergleich zu COMP eine niedrigere Plaqueanlagerungsrate resultiert. Zur Stützung vorliegender Erbenisse müssen weitere Untersuchungen folgen.

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ORIGINAL ARTICLE

Effect of different cleaning methods of polyetherether-ketone on surface roughness and surface free energy properties

Sina Heimer[1], Patrick R. Schmidlin[2], Bogna Stawarczyk[1]

[1] Department of Prosthodontics, Ludwig-Maximilians-University, Munich - Germany
[2] Clinic of Preventive Dentistry, Periodontology and Cariology, Center of Dental Medicine, University of Zurich, Zurich - Switzerland

ABSTRACT

Purpose: To determine the effect of different individual, laboratory and professional cleaning methods on the surface-roughness (SR) and surface free energy (SFE) of polyetheretherketone (PEEK), PMMA-based (PMMA) and composite (COMP) materials.

Methods: 330 specimens of PEEK, PMMA and COMP (N = 990) were prepared and divided into the following cleaning protocols (n = 30/group): (i) individual prophylaxis using (ST) soft, (MT) medium-hard and (SOT) sonic toothbrushes, (ii) in-lab cleaning protocols consisting of (SY) Sympro cleaning system, (SS) SunSparkle, (UB) ultrasonic bath and (AP) Al_2O_3-powder device and (iii) professional prophylaxis applying (PS) Perio Soft-Scaler, (SO) Sonicsys, (AFC) Air Flow Comfort, and (AFP) Air Flow Plus. After each protocol SR (profilometer), SFE (contact angle devise) and surface topography (SEM) were measured. Data were analyzed using multivariate analysis, Kruskal-Wallis-H- and Mann-Whitney-*U*-test (p<0.05).

Results: No impact of material on SR was observed (p = 0.443). Cleaning using conventional air-abrasion and powders (AP), followed by AFC produced higher SR values than the remaining methods (p<0.001). Within SFE, the cleaning method exerted the highest influence on SFE values (p<0.001, ηP^2 = 0.246), closely followed by the polymer material (p<0.001, ηP^2 = 0.136). PMMA and PEEK presented after cleaning lower SFE than COMP. PS, UB and SO showed lower SFE than specimens cleaned using SS, ST and SY. Cleaning using SY led to the highest SFE.

Conclusions: With regard to SR, all methods – with exception of conventional air-abrasion – can be recommended to clean PEEK. According to the SFE, PEEK may be an acceptable material providing even lower plaque accumulation rates than COMP. The field for more research is now open for scrutiny.

Keywords: Cleaning, Surface roughness, Surface free energy, Polyetheretherketone

Introduction

After a long search for substitutes of dental restoration materials such as ceramics or composites, polyetheretherketone (PEEK) has gained significant attention as a suitable alternative in recent years (1). Belonging to the family of high-temperature thermoplastic polymers, PEEK unites various positive aspects: it works as a tooth-colored and biocompatible restoration material (2) and is free of residual monomer, which is a great advantage when compared to other denture resins. PEEK is dimensionally stable and consists of connected aromatic benzene molecules by alternating functional ether or ketone groups (3-4). Early studies examined the influence of different media on the surface properties of PEEK like artificial saliva (5), but investigations regarding surface changes after laboratory and patient/dentist specific cleaning protocols are still scarce.

A prerequisite for the long-term clinical success of any dental restoration with minimal susceptibility to secondary caries formation and onset of periodontal problems is to incorporate adequately finished and polished work pieces and to ensure the initial quality by using effective cleaning methods later on, based on individual and professional prophylaxis tools. Concerning laboratory cleaning methods, technicians have the choice between 2 main cleaning versions: dry cleaning, like corundum blasting, or the wet version, like ultrasonic bath or needle cleaning devices in combination with either tap water or specially created cleaning liquids.

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Corresponding author:
Bogna Stawarczyk
Department of Prosthodontics
Dental School
Ludwig-Maximilians University Munich
Goethestrasse 70
80336 Munich, Germany
bogna.stawarczyk@med.uni-muenchen.de

The individual prophylaxis can be divided into 3 main groups: mechanical cleaning methods, chemical cleaning methods, or a combination of both (6). Along with the usual use of commercially available manual toothbrushes, there are various other methods for cleaning teeth, like electric toothbrushes or the use of floss and interdental brushes. In combination with a suitable toothpaste, patients are encouraged to brush their teeth twice a day according to several clinical trials (7-8). The advantage of electric toothbrushes compared to manual ones has been shown in various studies. They are more effective in removing plaque and thus in preventing periodontal disease (9-10). Although dentists are in favor of more efficient cleaning methods than patients are, there is the problem of solely intraoral use compared with labside cleaning methods. The professional cleaning spectrum of dentists includes both hand instruments (e.g., scalers and curettes) and mechanical ones like ultrasonic scalers and powder jet devices (air-abrasion).

To the best of our knowledge, to date there are no studies available comparing the cleaning properties of PEEK. Changes in surface properties like surface roughness (SR) and surface free energy (SFE) seem to be ideal surrogate parameters to study the consequential scratch damage and surface roughening potential of any given cleaning method. Previous studies showed that both SR and SFE have an influence on supragingival plaque formation and that the restoration material itself represented a predilection for bacterial adherence (11-13). It was determined that a high SR will lead to biofilm formation and growth, while a high SFE supports strongly and densely packed plaque with a certain bacterial selection (14). In this context, it can be hypothesized that more invasive cleaning methods probably exceed the SR threshold value of 0.2 µm, which was correlated with a higher adhesion of bacteria (15). In principle, Hahnel et al were able to demonstrate that there are nonfavorable conditions for biofilm transformation on PEEK compared with other implant materials, such as titanium (16). However, the dependence of material sensitivities and their surface properties, such as hardness, water absorption and filler degree, should be revised. Materials with low hardness surface profiles in particular, like PEEK, are more vulnerable for cleaning methods using high force and pressure, resulting in surface changes and mechanical fatigue (17).

This investigation examined the impact of 11 different cleaning protocols (3 individual prophylaxes, 4 laboratory cleaning and 4 professional prophylaxes) on the surface roughness (SR) and surface free energy (SFE) of PEEK and compared these results with 2 conventional polymer materials, namely a cold-curing denture polymethylmethacrylate (PMMA) and a veneering resin composite (COMP). The null hypothesis tested was therefore that PEEK shows similar SR and SFE values compared to the conventional PMMA-based and composite materials and that all tested cleaning methods indicate similar surface properties.

Material and methods

The following materials were used in this study: PEEK (bioHPP; Bredent), a cold-curing denture polymethylmethacrylate (PMMA) (uni.lign PF 20; Bredent) and a veneering resin composite (COMP) (crea.lign; Bredent). Details of the 3 materials are presented in Table I.

TABLE I - Summary of used products, compositions and manufacturer

Abbrev.	Material	Composition	Manufacturer (Lot No.)
PEEK	bioHPP	Ceramic filled (20%) PEEK	Bredent, Senden, Germany (410240)
PMMA	uni.lign PF 20	99% PMMA polymer	Bredent, Senden, Germany (396617/401822)
COMP	Crea.lign Incisal E2	Bis-GMA composite with microfillers	Bredent, Senden, Germany (N141331/123765)

Specimen preparation

A total of 330 disc-shaped specimens with a diameter of 15 mm and a thickness of 3 mm were made from PEEK and were directly provided by the manufacturer. This standardized specimen size ensured that there was enough space for subsequent surface measurements. Standardized silicone models were individually fabricated (15 × 3 mm) and used as templates for the production of PMMA (n = 330) and COMP (n = 330) specimens.

A PMMA mixture consisting of powder (13 g) and liquid (9 mL) was filled in the molds of the silicone model and polymerized in a pressure pot (Palamat Elite®; Heraeus Kulzer) for 20 minutes, 4.5 bar and at 55°C according to the manufacturer`s instructions. COMP specimens were prepared by filling the veneering resin composite material into the molds with a layer thickness of approximately 1 mm per increment. Each layer was light cured for 180 seconds as recommended by the manufacturer at a wavelength of 370 to 500 nm (bre.Lux Power Unit; Bredent).

Before grinding specimens with a series of silicone carbide abrasive papers up to P4000, they were checked for the same thickness (± 0.05 mm). All specimens were polished with a laboratory polishing machine (Abramin; Struers) in the following order: P1200 (3 bar) for 1 minute, P4000 (3 bar) for 4 minutes and P4000 (5 bar) for 4 minutes under constant water cooling.

Cleaning protocols

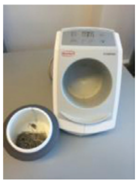
Individual prophylaxis (PPx)

A toothpaste slurry was made using toothpaste (Blend a Med Complete; Procter & Gamble) mixed with tap water at a ratio of 1:2. The pH values were set and controlled by pH measuring (Voltcraft PH-100 ATC; Conrad Electronic) at a pH value of 7.58. The specimens were cleaned for 4 minutes with rotary movements.

The following brushes were used:

(ST) A soft toothbrush (Dr. Best, GlaxoSmithKline)
(MT) A medium-hard toothbrush (Dr. Best, GlaxoSmithKline)
(SOT) A sonic toothbrush (Oral-B Pulsonic, Procter & Gamble)

TABLE II - Manufacturers and cleaning products used

	Abbrev.		Cleaning method
Individual PPx	ST		Soft toothbrush (Dr. Best; GlaxoSmithKline) Duration: 4 min
	MT		Medium-hard toothbrush (Dr. Best; GlaxoSmithKline) Duration: 4 min
	SOT		Sonic toothbrush (Oral-B Pulsonic; Procter & Gamble) Duration: 4 min
Laboratory protocols	SY		Sympro (Renfert): 75 g needles, 200 mL fluid Duration: 20 min, 2000 U/min
	SS		SunSparkle (Sun Dental Laboratories): tap water, half a teaspoon of cleaning powder Duration: 15 min
	UB		Ultrasonic bath (Dema): tap water Duration: 380 s
	AP		Al_2O_3 (Renfert): 50 µm, Distance: 4 mm Duration: 15 s
Professional PPx	PS		Perio-Soft Scaler (Kerr) Duration: 15 s
	SO		Sonicsys (KaVo) Duration: 15 s
	AFC		Air Flow Comfort (EMS): 40 µm, Distance: 4 mm Duration: 15 s
	AFP		Air Flow Plus (EMS): 14 µm, Distance: 4 mm Duration: 15 s

In order to standardize contact pressure and surface distance, 6 sonic toothbrushes were connected in series. Specimens were fixed in special devices (custom-made device at the Ludwig-Maximilians University of Munich) and cleaned by vibrating toothbrush heads.

Laboratory protocols

(SY) Sympro (Renfert): A high-performance cleaning unit for dentures and orthodontic appliances was used with 75 g of needles and 200 mL Symprofluid (Renfert) for 20 minutes at a rotation speed of 2,000 U/min.

(SS) SunSparkle (Sun Dental Laboratories): A dental cleaning system, was tested with tap water and half a teaspoon of SunSparkle cleaning powder (Sun Dental Laboratories) for 15 minutes, respectively.

(UB) An ultrasonic bath (USR2200; Dema) was filled with tap water and specimens were cleaned for 380 seconds.

(AP) Aluminum oxide blasting (50 µm) (Renfert): Specimens were cleaned for 15 seconds at a distance of 4 mm.

Professional prophylaxis (PPx)

(PS) Perio Soft-Scaler (Kerr): Specimens were cleaned for 15 seconds, applying a reaming motion.

(SO) Sonicsys (KaVo Sonicflex): A contra-angle piece (KaVo) was used for 15 seconds with rotary movements.

(AFC) Air Flow Comfort (EMS): The powder was applied in a PROPHYflex 3 (KaVo). The supragingival sodium bicarbonate air polishing powder (40 µm) was used for 15 seconds at a distance of 4 mm in moving circles.

(AFP) Air Flow Plus (EMS): The powder was applied in a PROPHYflex 3 (KaVo). The powder, which is suitable for supra- and subgingival polishing (14 µm), was tested similarly to AFC.

To reduce the outcome variability to a minimum, all preparations, cleaning methods and evaluations were performed by the same person (SH).

Surface roughness measurements

The surface quality surface roughness (SR) was measured for each specimen by a contact profilometer, applying a load of 0.7 mN (Perthometer SD 26; Mahr). Six readings with a track length of 6 mm were recorded with a distance of 0.25 mm between the lines. SR was analyzed twice: before storage in the different media and after final cleaning. The performance of the profilometer was periodically controlled using a calibration block (length of the profiles 1.75 mm, resolution of 0.01 µm).

Surface free energy measurements

SFE was investigated after cleaning by measuring the contact angle (Easy Pearl; Kruess) of water (polar) and diiodomethane (dipolar) at different locations. Data were analyzed by DSA4 software (Kruess). The surface free energy was calculated.

Surface topography

For scanning electron microscopy (SEM), a representative PEEK specimen of each cleaning group was selected. Specimens were gold-sputtered (SC7620 Sputter Coater; Quorum technologies) and visualized (SUPRA 55VP; Carl Zeiss) operating at 10 kV with a working distance of 6 mm using 68-, 300- and 600-x magnifications.

Statistical methods

Multivariate analysis was used to assess the effects of the independent parameters of each cleaning protocol and material group and the effect of their interaction on SR and SFE results (dependent parameter). Normality of data distribution was tested using the Kolmogorov-Smirnov test. Nonparametric descriptive statistics, such as minimum, median and maximum, for all cleaning and material groups were calculated. Kruskal-Wallis-H and Mann-Whitney-U tests were used to analyze the effect of the cleaning protocols and materials. The results of statistical analyses with p values less than 0.05 were interpreted as statistically significant. Data were analyzed using the statistical software SPSS Version 23.

Results

The Kolmogorov-Smirnov test indicated a violation of the assumption of normality. Therefore, nonparametric tests were used. After cleaning, a statistically significant impact of the different cleaning protocols on the SR values was observed ($p<0.001$). Cleaning using conventional air-abrasion and powders (AP), followed by AFC produced higher SR than the remaining cleaning methods. In contrast, the different materials showed no effect on the SR values ($p = 0.443$). The descriptive statistics are presented in Table III. When considering the differences of SR values (Fig. 1) between the cleaning procedure and polishing, the significant differences in the values mentioned above regarding SR after cleaning could be confirmed (Tab. III).

With respect to the SFE values, the cleaning method exerted the highest influence on the SFE values ($p<0.001$, partial eta squared $\eta P^2 = 0.246$), closely followed by polymer material ($p<0.001$, $\eta P^2 = 0.136$). PMMA and PEEK presented after cleaning significantly lower SFE values than COMP (Fig. 2). Comparing the cleaning methods, PS, UB and SO showed significantly lower SFE than specimens cleaned using SS, ST and SY. In general, cleaning using SY led to the highest SFE (Tab. IV).

Figure 3 presents representative SEM images of differently cleaned PEEK surfaces for visualizing particular surface topographies. As can be seen, PEEK surfaces cleaned by SY and AP show clear dents caused by needles as well as by Al_2O_3 powder. Surface impressions of AFC and AFP are also clearly observable when seen through SEM.

Discussion

This study was motivated by the fact that there are currently no reliable data regarding the cleaning methods of PEEK and their impact on surface properties like SR and SFE. Each intraoral inserted dental restoration material was subjected to wear and biofilm formation. The speed of plaque development depends on the initial quality of the polished surface, the material properties of a given restoration and the patients' compliance. Patients usually brush their teeth

TABLE III - Overview of median, minimum and maximum SR/ΔSR values after different cleaning procedures divided into the different materials (PEEK, PMMA, COMP)

	Cleaning method	SR Median (Min;Max)	ΔSR Median (Min;Max)
PEEK			
individual PPx	ST	0.043 (0.034;0.063)	0.021 (0.011;0.041)
	MT	0.043 (0.033;0.074)*	0.024 (0.010;0.053)*
	SOT	0.078 (0.044;0.207)	0.055 (0.017;0.187)
laboratory protocols	SY	0.067 (0.050;0.129)	0.050 (0.023;0.112)
	SS	0.035 (0.021;0.070)	0.010 (0.002;0.046)
	UB	0.033 (0.020;0.052)	0.012 (-0.003;0.029)
	AP	0.331 (0.068;1.070)*	0.311 (0.051;1.048)*
professional PPx	PS	0.046 (0.026;0.069)	0.024 (0.003;0.047)
	SO	0.037 (0.020;0.063)	0.015 (-0.011;0.031)
	AFC	0.486 (0.268;0.744)	0.464 (0.121;1.647)*
	AFP	0.101 (0.040;0.235)	0.078 (0.011;0.208)
PMMA			
individual PPx	ST	0.055 (0.042;0.073)	0.001 (-0.013;0.017)
	MT	0.050 (0.038;0.079)*	-0.005 (-0.016;0.027)*
	SOT	0.132 (0.062;0.572)*	0.087 (0.007;0.512)*
laboratory protocols	SY	0.068 (0.049;0.120)*	0.012 (-0.007;0.067)*
	SS	0.065 (0.050;0.089)	0.009 (-0.007;0.040)
	UB	0.066 (0.049;0.106)	0.011 (-0.003;0.054)*
	AP	0.248 (0.070;1.444)*	0.185 (0.006;1.391)*
professional PPx	PS	0.063 (0.049;0.100)*	0.007 (-0.007;0.046)*
	SO	0.073 (0.055;0.098)	0.018 (0.001;0.038)
	AFC	0.246 (0.151;0.563)*	0.193 (0.090;0.501)*
	AFP	0.116 (0.070;0.424)*	0.064 (0.008;0.346)*
COMP			
individual PPx	ST	0.045 (0.025;0.123)	0.017 (0.009;0.056)*
	MT	0.046 (0.025;0.074)	0.017 (0.000;0.044)
	SOT	0.149 (0.027;0.296)	0.113 (0.007;0.269)
laboratory protocols	SY	0.035 (0.022;0.057)*	0.007 (-0.009;0.026)
	SS	0.030 (0.019;0.057)	0.001 (-0.032;0.015)
	UB	0.034 (0.021;0.061)	0.003 (-0.014;0.034)*
	AP	0.489 (0.033;2.472)*	0.463 (0.008;2-440)*
professional PPx	PS	0.031 (0.021;0.126)*	0.005 (-0.011;0.063)*
	SO	0.041 (0.020;0.082)	0.008 (-0.028;0.030)
	AFC	0.043 (0.021;0.094)*	0.015 (0.001;0.074)*
	AFP	0.041 (0.022;0.124)	0.011 (-0.025;0.074)

* not normally distributed data. Median SR and ΔSR values are listed in µm.

twice a day using a toothpaste; thus, they are thought to be able to reduce the newly build plaque to a minimum. Numerous studies have examined the differences between manual and electric toothbrushes. Zimmer and coworkers showed that after a period of 8 weeks, plaque (PI) and gingivitis (PBI) could be significantly reduced by the use of sonic toothbrushes compared to manual ones (18). On the other hand, it was shown that the use of electric toothbrushes leads to significantly higher abrasion of enamel than brushing with manual toothbrushes (19). In particular, patients who have a high consumption of erosive foods or acid indigestion should not use electric cleaning devices. As far as individual prophylaxis protocols are concerned, there are no significant differences in SR between manual and electric brushing, although SR

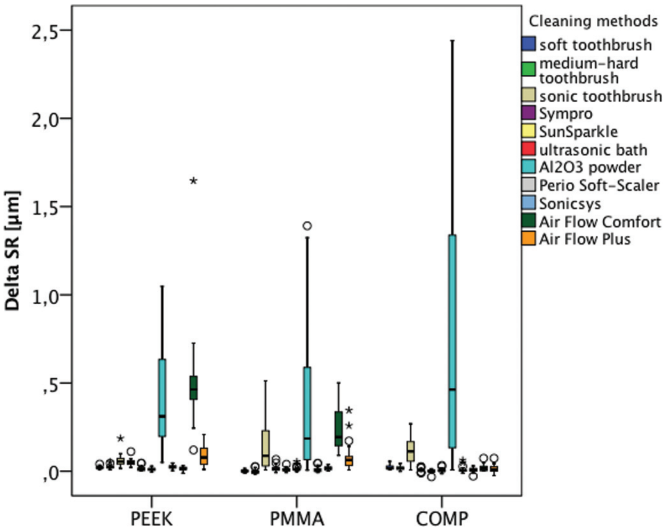


Fig. 1 - Boxplots for the SR differences between the cleaning procedure and polishing for each cleaning method and material separately.

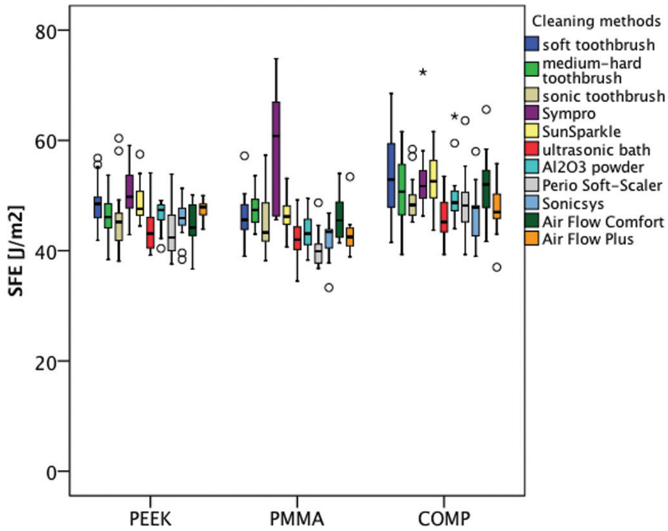


Fig. 2 - Boxplots for the SFE values for each cleaning method and material separately.

TABLE IV - Median, minimum and maximum SFE values after different cleaning protocols

	Cleaning method	PEEK	PMMA	COMP
		SFE Median (Min;Max)		
individual PPx	ST	48.5 (41.9;56.8)	45.6 (39.0;57.2)	52.9 (41.5;68.5)
	MT	46.1 (38.4;53.7)	47.4 (43.0;53.6)	50.7 (39.3;61.6)
	SOT	45.2 (38.1;60.4)*	43.3 (38.2;57.3)	48.3 (45.2;58.4)
laboratory protocols	SY	49.8 (42.9;59.1)	60.8 (45.6;74.8)*	51.7 (46.3;72.4)
	SS	47.6 (44.5;57.5)	46.2 (40.7;53.1)	52.6 (43.7;61.6)
	UB	43.1 (39.2;54.1)	42.0 (34.5;49.2)	45.2 (39.3;53.5)
	AP	47.4 (40.4;49.1)*	43.1 (38.3;49.5)	48.7 (44.0;64.4)*
professional PPx	PS	42.4 (37.6;53.9)	39.9 (36.8;48.7)	48.2 (39.3;63.6)
	SO	45.9 (38.4;51.3)	43.4 (33.3;46.8)	47.8 (39.0;58.0)
	AFC	44.2 (36.7;50.1)	45.5 (41.4;54.0)	52.0 (41.7;65.6)
	AFP	47.9 (43.9;50.0)	42.5 (38.9;53.4)*	47.0 (37.0;55.8)

* not normally distributed data. Median SFE values are measured in J/m^2.

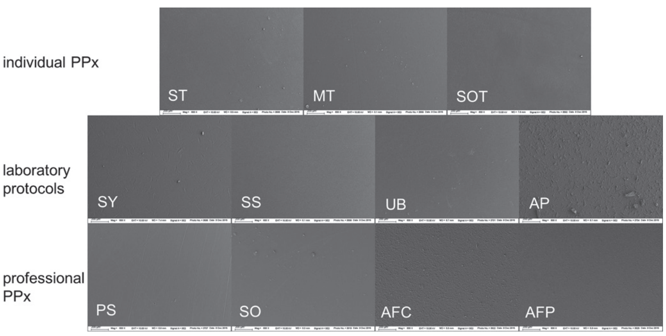


Fig. 3 - Representative SEM images of the cleaned PEEK surface at a magnification of 600:1: (1) individual prophylaxis (ST), (MT), (SOT), (2) laboratory protocols (SY), (SS), (UB) and (3) (AP); and professional prophylaxis (PS), (SO), (AFC), (AFP).

values of sonic toothbrushes were higher. Because of the short investigation period it is difficult to say whether the SR values of power devices develop proportionally to the period of their application or not. Therefore, additional studies need to be conducted to give clear guidelines and clarify the question of why SFE values go in the opposite direction to SR values.

The laboratory protocols are comparing wet cleaning options with dry ones. In the present study it was noticeable that the wet cleaning methods like Sympro, SunSparkle and ultrasonic bath lead to significantly lower SR values than the dry method (Al_2O_3 powder). The main application of alumina air-abrasion is to condition restoration materials to reach a high bonding strength (20). Highly sharpened corundum particles are accelerated and hit the material surface, where they cause a release of energy. Dents formed like grain impacts could be seen on the surfaces of cleaned PEEK specimens. According to this, surface roughening is higher than when using wet cleaning methods, which do not affect material surfaces directly. In the latter case, water or liquid serve as a protective barrier helping to prevent deep scratches and notches. The Sympro cleaning method contains needles beside cleaning liquid, whereas SunSparkle and ultrasonic bath require no additional cleaning devices. Surfaces of treated PEEK specimens examined with SEM showed needle-shaped dents.

A final look at the professional prophylaxis protocols reveals that using AFC leads to significantly higher SR values than the other cleaning protocols. The average grain size of AFC is 40 µm and according to the manufacturer, it is suitable exclusively for supra-gingival application. In this way, periodontal damages should be avoided. To allow a subgingival application, the manufacturer reduces the average grain size to 14 µm (AFP). Thus, SR values could be significantly decreased, but are nevertheless more comparable to the other chairside methods. This effect of prophylactic powders of increasing SR on the enamel was also observed in another study (21). SEM analysis in the present study gives credence to this hypothesis.

The study of Eliades et al (22) also confirmed that remaining and attaching bicarbonate particles could be found on specimen surfaces. It has not yet been definitively determined if the resting bicarbonate influences surfaces negatively or has an antibacterial effect by neutralizing bacterial metabolism products. Using sodium bicarbonate as a toothpaste ingredient showed positive clinical results in terms of plaque building and dental health (23), but further studies have to follow. It has to be mentioned that after using air-abrasion devices, a final polishing is recommended by the manufacturer, which is a current clinical standard to prevent the problems listed above and current clinical standards to prevent the problems listed above.

In general, all cleaning methods showed the same impact on the tested materials. Therefore, the hypothesis that PEEK shows similar SR values compared to the conventional PMMA-based and composite materials can be accepted, while the hypothesis that all tested cleaning methods indicate similar surface properties was rejected. These statements concerning similar surface conditions of polymethylmethacrylate denture base materials in terms of surface roughness were demonstrated by Zafar and coworkers (24). In conclusion, over all the highest changes in SR were detected in AFC, AP and AFP, which can be explained with surface roughening by grains used in wet and dry conditions.

Regarding SFE values, SY showed the highest ones followed by ST, SS, AFP and AP. This can be explained by the fact that impacting needles combined with cleaning liquid affect the material surface by its increase, which correlates with higher surface free energy. In terms of AP and AFP, a similar effect is detectable. A previous study investigating different chairside cleaning methods confirmed this fact according to air-polishing protocols (25). In contrast, material behavior in terms of SFE and cleaning by ST and SS has to be discussed. The unique ingredients of SunSparkle cleaning system powder remain a company secret. It may be concluded that liquid used in combination with vibrations causes surface changes leading to an increase in SFE.

A noteworthy aspect is that patients usually use individual prophylaxis devices twice a day for an average time of 2 to 4 minutes, whereas professional prophylaxis is applied 1 up to 4 times per year. Therefore, it can be assumed that the postcleaning surface changes with regard to individual prophylaxis are more pronounced than for professional or laboratory cleaning devices.

As mentioned at the beginning, both SR and SFE influence bacterial adhesion and biofilm formation on dental restoration materials. On PEEK surfaces, a reproducible growth of plaque pellicle was achieved in various studies (26). Quyrinen et al showed that surfaces with lower SFE values accumulate less bacterial colonies than high-energy ones (14), which was confirmed in further studies (27). Therefore it can be concluded that the use of cleaning methods strongly impacting surface properties (SR and SFE) should be avoided in daily clinical practice. Due to the fact that the present study was a laboratory study, limitations concerning the correlation between plaque formation and surface properties are fulfilled. Further studies need to be conducted in order to evaluate the cleaning efficacy of different methods and a proper balance needs to be struck between surface roughening and removing plaque and discolorations.

Conclusions

Within the limitations of this in vitro study, we conclude that PEEK showed lower SFE values compared to COMP and thus lower biofilm formation (27). Concerning individual prophylaxis methods, all tested toothbrushes can be recommended depending on the patient's intraoral starting conditions, such as tooth abrasion. According to laboratory protocols, Al_2O_3 powder should be avoided because it causes high SR and SFE values. For dentists, instruments like PS and SS should be preferred, whereas air-abrasion devices like AFC and AFP should be avoided without final polishing.

Disclosures

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Conflict of interest: The authors declare no conflict of interest.

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2.3 Originalarbeit: Heimer S, Schmidlin PR, Stwawarczyk B. Discoloration of PMMA, composite and PEEK. Clinical Oral Investigations 2017;21(4):1191-1200 (IF: 2.308)

Zusammenfassung

Ziel: Das Bestreben vorliegender Studie lag in der Untersuchung der Effizienz verschiedener Reinigungsmethoden hinsichtlich der Entfernung von Verfärbungen und Auflagerungen am Hochleistungskunststoff Polyetheretherketon (PEEK) nach einer einwöchigen Einlagerung in verschiedenen Medien. Die mittels individueller/professioneller Prophylaxe und labortechnischen Methoden erzielten Reinigungsergebnisse wurden mit denen eines Kaltpolymerisats (PMMA) und eines Verblendkunststoffes (COMP) verglichen.

Material und Methode: Insgesamt wurden 1320 zylindrische Prüfkörper aus den Materialien PEEK, PMMA und COMP gefertigt und für eine Dauer von sieben Tagen zur Erzeugung von Verfärbungen in Rotwein, Currysuspension, Chlorhexidin und destilliertem Wasser (Kontrollgruppe) eingelagert. Im Anschluss wurden die Prüfkörper in drei verschiedene Reinigungsgruppen eingeteilt (n=10): (i) Individualprophylaxe mit den Untergruppen (ST) weiche, (MT) mittelharte und (SOT) Ultraschallzahnbürsten, (ii) labortechnische Reinigungsmöglichkeiten unterteilt in das (SY) Sympro Reinigungssystem, (SS) SunSparkle, (UB) Ultraschallbad und (AP) Korundstrahlen und (iii) professionelle Prophylaxe, bei welcher (PS) Perio Soft-Scaler, (SO) Sonicsys, (AFC) Air Flow Comfort und (AFP) Air Flow Plus verwendet wurden. Mit Hilfe eines Spectrophotometers konnten die entstandenen Farbveränderungen (ΔE) detektiert werden. Zur Auswertung der Daten wurden multivariate Analysemethoden, der Kruskal-Wallis-H und der Mann-Whitney-U-Test ($p < 0{,}05$) verwendet.

Ergebnisse: Die Einlagerung in destilliertem Wasser und Chlorhexidin (CHX) führte zu den geringsten Verfärbungsraten gefolgt von Rotwein ($p < 0{,}001$). Die Currylösung verursachte die höchsten Verfärbungsraten ($p < 0{,}001$). PEEK zeigte die signifikant geringsten Verfärbungsraten ($p < 0{,}001$), während COMP die höchsten Farbveränderungen aufwies. Zu den signifikant effektivsten Reinigungsergebnissen führte die Verwendung des Ultraschallbades (UB) und Air Flow Plus (AFP) ($p < 0{,}001$). Unter dem Gebrauch der weichen und mittelharten Zahnbürste sowie der Anwendung von SunSparkle konnten die geringsten Entfärbungserfolge erzielt werden ($p < 0{,}001$).

Schlussfolgerung: PEEK zeigte sich im Vergleich zu den weiteren untersuchten Materialien stabiler hinsichtlich auftretender Verfärbungstendenzen. Unter Berücksichtigung des Reinigungspotenzials kann in der Individualprophylaxe jede Zahnbürstenform verwendet werden. Für die professionelle Prophylaxe sollten Pulverstrahlgeräte mit schonendem

Prophylaxepulver zur Anwendung kommen. Hinsichtlich der labortechnischen Reinigungsmöglichkeiten sollte auf schonende Reinigungsmethoden (Ultraschallbad) zurückgegriffen werden.

Klinische Relevanz: Zahnärzte und Zahntechniker sollten ihre Patienten über das Verfärbungspotenzial bestimmter Speisen bzw. Getränke aufklären. Des Weiteren sollten sie auf Reinigungsmethoden zurückgreifen, welche eine effiziente Verfärbungsentfernung gewährleisten ohne das Restaurationsmaterial nachhaltig zu schädigen.

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ORIGINAL ARTICLE

Discoloration of PMMA, composite, and PEEK

Sina Heimer[1] · Patrick R. Schmidlin[2] · Bogna Stawarczyk[1]

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Abstract
Introduction To assess the discoloration and stain removal potential of different cleaning methods relevant to individual/professional prophylaxis and laboratory cleaning on polyetheretherketone (PEEK), poly(methyl methacrylate) (PMMA)-based, and composite (COMP) materials after storage in different media for 7 days.
Methods One thousand three hundred twenty specimens of PEEK, PMMA, and COMP ($N = 440$ of each group) were prepared and stored in four different media for 7 days to cause stain. Samples were divided into three cleaning groups ($n = 10$): (i) individual prophylaxis, (ii) laboratory protocols, and (iii) professional prophylaxis. Color was determined by a portable spectrophotometer and calculated between different time points (ΔE). The data was statistically evaluated using univariate analyses, Kruskal–Wallis *H* and Mann–Whitney *U* tests ($p < 0.05$).
Results The significantly ($p < 0.001$) lowest discoloration was found when specimens were stored in distilled water and chlorhexidine (CHX), followed by red wine. Curry solution caused the highest discoloration. PEEK showed the significantly ($p < 0.001$) lowest color changes, while COMP showed the highest changes. Ultrasonic bath and Air Flow Plus (AFP) were the significantly ($p < 0.001$) most effective methods to remove staining. The least cleaning effect was found using a soft toothbrush (ST), a medium-hard toothbrush (MT), and SunSparkle (SS) cleaning system.
Conclusions PEEK seems more stable against discolorations than other denture resin materials. Regarding the cleaning potential, individual prophylaxis can be conducted with toothbrushes. For professional prophylaxis, air-abrasion devices using gentle powders are effective. Laboratory protocols should include gentle cleaning methods like ultrasonic bath.
Clinical relevance Clinicians and dental technicians should inform their patients about the discoloration potential of certain foods/beverages and recommend the most efficient cleaning, but preventive methods.

Keywords Cleaning · Surface roughness · Surface free energy · Discoloration · Polyetheretherketone

✉ Bogna Stawarczyk
bogna.stawarczyk@med.uni-muenchen.de

[1] Department of Prosthodontics, Ludwig-Maximilians-University, Munich, Germany

[2] Clinic of Preventive Dentistry, Periodontology and Cariology, Center of Dental Medicine, University of Zurich, Zurich, Switzerland

Introduction

Polyetheretherketone (PEEK) was developed for space travel and introduced to the dental market as a high-performance, chemically inert biomaterial known for its bioinert characteristics [1]. With its extremely low potential to trigger an allergy, PEEK is known to cause very few reported or no systemic immune responses after intraoral insertion [2].

Used in oral rehabilitation, PEEK-based materials are applied in addition to other polymers like poly(methyl methacrylate) (PMMA) and composite resin materials upon other terms in removable dental prosthesis (RDP) and fixed dental prosthesis (FDP) technology. PEEK has become an alternative to conventional and well-investigated veneering and denture base resin materials with low discolorations and improved mechanical properties [3–5]. There are various possibilities of compounding PEEK [6]. In addition to unfilled versions, PEEK is available containing fibers or powder in differing

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combinations, e.g., carbon or glass fibers in short or endless chain structures reducing wear and improving flexural strength or hardness [7]. High-quality restoration materials are characterized by good polishing ability, low water sorption, minimal polymerization shrinkage, low residual monomer content, and color stability [8–10]. Polishing ability and material composition but also patient's dietary and cleaning habits are key parameters achieving color stability mainly over a longer period of time [11, 12]. Patients and dentists expect tooth-colored fillings and natural dental prostheses, which represent important parameters for patient satisfaction and compliance. In order to achieve a lighter or more tooth-colored appearance of the grayish-brown or pearl-white opaque PEEK restorations, several manufacturers of dental materials added titanium oxide [6, 13, 14]. Another possibility would be veneering with composite resins after different surface modifications [15–17].

Discoloration of dental prostheses developing over a certain period of time is measured as value over time by a spectrophotometer [18] and is determined by two essential factors [5, 19]: extrinsic factors derive primarily from colorants of food products like caffeine-containing beverages or mouth rinses, which cause staining by chemical adhesion [20], but also from smoking; intrinsic factors are chemical reactions within the restoration material triggered by heredity, age, and processing modes of placed restorations [21]. The processes which lead to discoloration of PEEK still remain to be elucidated. Color stability significantly depends on surface roughness and surface free energy [22]. Several studies showed that there is a positive correlation between high surface roughness and discoloration of denture resins, which is explained by the large surface with various predilection sites for agglomerating colorants [23, 24]. Combined with bacterial adhesion and formation of biofilm, this cannot only result in development of caries and periodontal disease but also in further discoloration caused by metabolic products of bacteria [25, 26].

Therefore, effective cleaning methods are required. Besides individual and professional prophylaxis measures, laboratory cleaning protocols are available. Two types of cleaning alternatives can be distinguished: dry cleaning methods like manual instruments (curettes) or corundum blasting, or wet cleaning methods containing manual or electric tooth brushing using toothpaste and air-abrasion using powder devices [27–32]. The use of abrasion powders and manual cleaning instruments over a certain period of time results in surface damage of natural teeth and inserted restorations [33, 34]. Practicability, time requirements, and potential damage to the inserted restoration materials by using different cleaning methods need to be considered carefully. At the present time, there are no studies available assessing the cleaning protocols of PEEK and its discoloration or cleaning opportunity.

This study therefore aimed to assess the discoloration and the stain removal potential of different cleaning methods relevant to individual/professional prophylaxis and laboratory cleaning on PEEK, PMMA-based, and composite (COMP) materials after storage in different media for 7 days. The null hypothesis tested was that PEEK shows similar discolorations after storage in different media and after the use of various cleaning devices as compared to PMMA- and COMP-based materials.

Material and methods

This study examined the influence of 11 different cleaning protocols (three individual prophylaxis, four professional prophylaxis, and four laboratory protocols) on the surface discoloration of PEEK (bioHPP, bredent, Senden, Germany). The results were compared with two denture resin-based materials, i.e., a cold-curing denture PMMA (uni.lign PF 20, bredent) and a veneering resin COMP (crea.lign, bredent). Materials are listed in Table 1.

Specimen preparation

Cylindric PEEK blanks were provided by the manufacturer, which were prepared in a disc form with a diameter of 15 mm and a thickness of 3 mm (n = 440). Corresponding silicone models were used as templates for the PMMA (n = 440) and COMP (n = 440) specimen fabrication. For the fabrication of the standardized PMMA discs, molds were filled with a PMMA mixture consisting of powder (13 g) and liquid (9 mL) and were polymerized in a pressure pot (Palamat elite, Heraeus Kulzer, Hanau, Germany) for 20 min at 4.5 bar in 55 °C warm water. In order to prepare COMP specimens, the veneering resin composite was filled into the molds with a layer thickness of approximately 1 mm in increments. Each layer was light cured for 180 s at a wavelength of 370–500 nm using bre.Lux Power Unit (bredent). After checking the dimensions using a caliper (±0.05 mm), they were grinded with a series of silicone carbide abrasive papers up to P4000 using a laboratory polishing machine (Abramin, Struers, Ballerup, Denmark). All specimens were polished in the following order: P1200 (3 bar) for 1 min, P4000 (3 bar) for 4 min, and P4000 (5 bar) for 4 min with a pressure of 3 bar under constant water-cooling.

Media storage

The specimens of each group were randomly divided into three subgroups (n = 110) consisting of different storage media: (a) red wine (Cepa Lebrel 2013, Lidl GmbH & Co.KG), (b) curry (Ostmann GmbH), and (c) chlorhexidine (Orbi-CHX; Orbis Dental GmbH). Ten control samples of each

Table 1 Used products, manufacturer, and compositions

Material	Abbrev.	Lot no.	Manufacturer	Composition
bioHPP	PEEK	410240	bredent, Senden, Germany	Ceramic-filled (20 %) PEEK
Uni.lign PF 20	PMMA	396617/ 401822	bredent, Senden, Germany	99 % PMMA polymer
crea.lign Incisal E2	COMP	N141331/ 123765	bredent, Senden, Germany	Bis-GMA composite with microfillers

material (n = 10) were stored in distilled water (Aqua Bidest, Kerndl, pH = 6.7). While red wine and chlorhexidine were not diluted, 40 g of curry powder was suspended in 1 L of distilled water, which was boiled for 10 min. Specimens were then stored at 37 °C for 7 days.

Cleaning methods

Individual prophylaxis

Specimens were brushed for 4 min with rotary instruments and an average contact pressure of 80 g using a toothpaste slurry (Blend-a-med complete, Procter & Gamble GmbH), which was a mixture of a high-abrasive toothpaste (RDA = 100, 1450 ppm NaF) and tap water (pH value of 7.58) in a ratio of 1:2. The following commercially available toothbrushes were used:

A **s**oft **t**oothbrush (ST) (Dr.Best, GlaxoSmithKline, Munich, Germany) with rounded bristles and a special suspension avoiding on teeth and surrounding gum.
A **m**edium-hard **t**oothbrush (MT) (Dr.Best, GlaxoSmithKline) with the same configuration like the soft one but different in the hardness of bristles.
A **so**nic **t**oothbrush (SOT) (Oral-B Pulsonic, Procter & Gamble, OH, USA) with 31,000 vibrations per minute. The brushes were fixed in special devices (custom-made device at the Ludwig-Maximilians University of Munich), whereby six toothbrushes were serially connected in order to ensure a standardized contact pressure and surface distance.

Laboratory protocols

Sympro (SY) (Renfert, Uhldingen-Mühlhofen, Germany): A high-performance cleaning unit for dentures and orthodontic appliances was used with 75 g of needles and 200 mL fluid for 20 min at a rotation speed of 2000 U/min. The specimens were rinsed with cold tap water after cleaning procedure immediately.

Sun**S**parkle (SS) (Sun Dental Laboratories, Düsseldorf, Germany): An ultrasonic battery-operated cleaning unit was tested with tap water and 2.5 g of SunSparkle concentrated disinfecting cleaning powder (Sun Dental Laboratories) for 15 min, respectively. For removal of powder residues, specimens were rinsed with cold tap water.

An **u**ltrasonic **b**ath (UB) (USR2200, Dema, Mannheim, Germany) was filled with tap water, and specimens were cleaned for 380 s according to the manufacturer's instructions. Technical data are as follows: power, 170 W; cleaning frequency, 42 kHz; capacity, 2600 mL.

Aluminum oxide (AP) blasting (50 μm) (Renfert): Using the Basic quattro IS (Renfert), specimens were cleaned for 15 s with aluminum oxide (50 μm) at a distance of 4 mm with the following operating parameters: working pressure, 14.5–87 psi; connecting pressure, 87–116 psi. **A**luminum oxide **p**-articles (Cobra white, Renfert) were applied in sharp-edged and extremely pure form (approx. 99.7 % Al_2O_3).

Professional prophylaxis

Perio **S**oft-Scaler (PS) (Kerr, Karlsruhe, Germany): Specimens were cleaned for 15 s applying a reaming motion with an average contact pressure of 80 g.

Sonicflex (SO) 2003/L (KaVo Sonicflex, Biberach, Germany): An air scaler with a cellular optic glass rod (SONICflex 2003L, KaVo) and the Sonicflex tip no. 7 were used for 15 s with rotary movements at sound frequency. Operating parameters are as follows: operating pressure, 36 psi; performance level 1; the average contact pressure was 80 g, and the water setting at 15 psi.

Air **F**low **C**omfort (AFC) (EMS, Nyon, Switzerland): The powder was applied in a PROPHYflex 3 (KaVo) with a handle sleeve, which can be rotated by 360°. The construction of the cannula guaranteed a concentrated powder jet. The following operating parameters were used: drive pressure, 46–73 psi; air consumption, 10–13 Nl/min; nozzle angle, 60°, and the nozzle-surface distance, 4 mm. The supragingival sodium bicarbonate air polishing powder (40 μm) was used for 15 s in moving circles.

Air **F**low **P**lus (AFP) (EMS): The powder was applied in a PROPHYflex 3 (KaVo) too. The powder, which is suitable for supra- and subgingival polishing (14 μm), was tested in analogy to AFC.

For reducing the outcome variability to a minimum, all preparations, cleaning methods, and evaluations were performed by the same person (SH).

Color measurements

The color measurements were performed by a portable spectrophotometer SP60 (X-rite GmbH, MI, USA) before and after storage in different media and after final cleaning. The following operating parameters were used: standard illuminant D65, illuminating geometry d/8°, and standard observer 10°. Reflectance and transmission measurements were combined formulating translucency. After calibration of the colorimeter according to the manufacturer's recommendations, the target window was directly applied on the specimen surface at three different areas. Measurements were started under daylight conditions on the same time of three consecutive days. Light source and samples were at a 90° angle to each other.

A formulation Master FM 2 software (X-rite GmbH) was used to calculate/evaluate L^* (degree of lightness), a^* (degree of greenness or redness), and b^* values (degree of blueness or yellowness) according to the CIELAB color system (Commission Internationale de l'Eclairage, CIE). From L^*, a^*, and b^* data, the discoloration (ΔE^*) was calculated using the formula [35]:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Individual ΔE^* represents the following: ΔE1: before and after media storage, ΔE2: before and after cleaning procedures, and ΔE3: before media storage and after cleaning.

Statistical methods

The effect of the independent parameters of storage medium, cleaning protocol, and material group and the effect of their interaction on discoloration were assessed using multivariate analyses. Normality of data distribution was tested using the Kolmogorov–Smirnov test. Kruskal–Wallis H and Mann–Whitney U tests were used to analyze the effect of the storage media, cleaning protocols, and materials ($p < 0.05$). Statistical analyses were performed using the software SPSS Version 23.0 (SPSSINC, Chicago, IL, USA).

Results

Discoloration after 7 days storage in different media (ΔE1)

Data regarding the discoloration after 7 days storage in different media is presented in Fig. 1.

The storage medium and polymer material showed a significant ($p < 0.001$) impact on the discoloration values. Storage media exerted higher partial eta squared values ($\eta P^2 = 0.599$) than the polymer materials ($\eta P^2 = 0.036$).

The significantly ($p < 0.001$) lowest discolorations were observed for specimens that were stored in distilled water and chlorhexidine, followed by red wine. The significantly ($p < 0.001$) highest color change was observed after storage in curry solution. The discoloration by specimens stored in

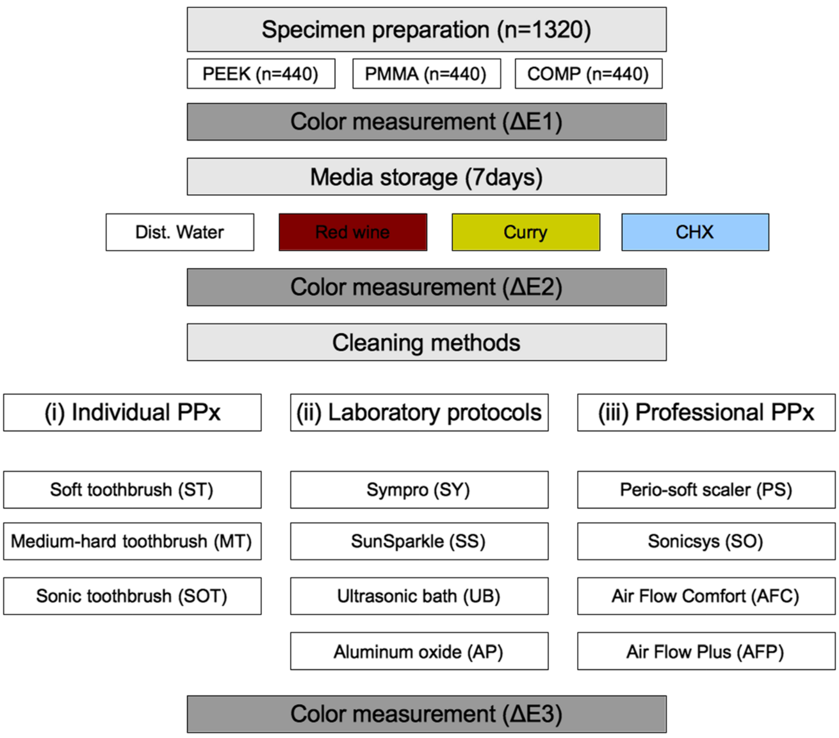

Fig. 1 Study design illustrating the different steps of specimen preparation, media storage, cleaning methods, and color measurements

distilled water could not be assessed in further measurements after cleaning procedures.

In general, PEEK showed significantly ($p < 0.001$) lower discolorations as compared to PMMA and COMP. COMP showed the highest discoloration.

Discoloration after different cleaning procedures (ΔE2)

Discoloration after different cleaning procedures is presented in Fig. 2.

Storage medium, polymer material, and cleaning procedure showed a significant ($p < 0.001$) impact on the discoloration values after cleaning procedure. The storage medium exerted the highest influence on the discoloration ($\eta P^2 = 0.519$), followed by the cleaning procedure ($\eta P^2 = 0.151$) and the polymer material ($\eta P^2 = 0.020$) (Table 2).

Storage in chlorhexidine led to a significantly ($p < 0.001$) lower discoloration than storage in red wine. Specimens stored in curry solution showed the highest discoloration. Ultrasonic bath and Air Flow Plus were the significantly ($p < 0.001$) more effective in removing extrinsic staining. The weakest discoloration removal potential was shown for the soft and medium-hard toothbrushes as well as for Sympro ($p < 0.001$). After cleaning, PEEK and PMMA showed significantly ($p = 0.008$) lower discoloration as compared to COMP.

Discoloration differences between before and after storage and cleaning procedure (ΔE3)

Discoloration differences before and after storage and the different cleaning procedures is presented in Table 3.

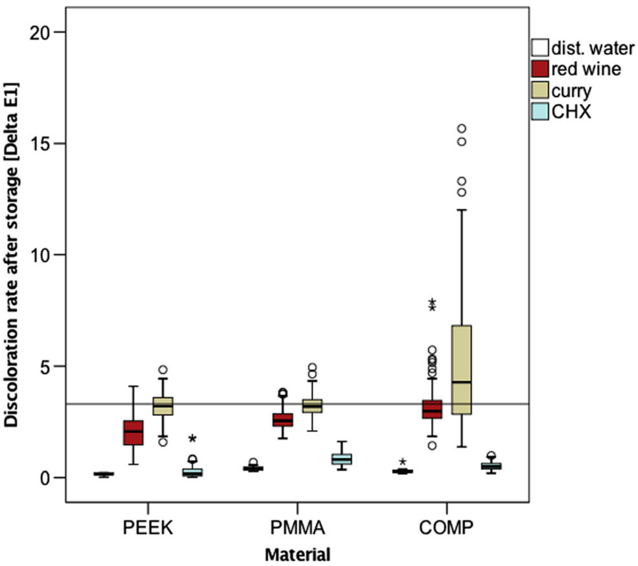

Fig. 2 Discoloration rate after 7 days storage in different media (ΔE1)

Storage medium, polymer material, and cleaning procedure showed a significant ($p < 0.001$) impact on the ΔE values. The storage medium exerted the highest influence on the discoloration ($\eta P^2 = 0.381$), followed by the polymer material ($\eta P^2 = 0.375$) and the cleaning procedure ($\eta P^2 = 0.099$).

Specimens stored in chlorhexidine showed significantly ($p < 0.001$) lower ΔE values than specimens stored in red wine or curry solution. No significant ($p = 0.064$) differences were observed between specimens stored in the two latter solutions. Specimens cleaned with Sympro, Air Flow Plus, SunSparkle, Air Flow Comfort and all the three toothbrush types showed significantly ($p < 0.001$) lower ΔE values than specimens cleaned with ultrasonic bath, Perio Soft-Scaler, and Al_2O_3 powder. PEEK showed significantly ($p < 0.001$) lower ΔE values than COMP and PMMA. No differences ($p = 0.980$) were observed between COMP and PMMA.

Discussion

The null hypothesis tested was that PEEK shows similar color changes compared to the conventional PMMA-based and composite materials after storage in different media and that all tested cleaning methods indicate similar cleaning properties.

Determination of discoloration

The overall appearance and perception of dental restorations depends on several factors: the color of the neighboring teeth or the remaining tooth substance, light scattering effects, and inherent material characteristics like opacity and translucency. Color differences detectable to the human eye are normally non-discernible below ΔE values of 1 and only change into an unacceptable color set when ΔE is more than 3.3 [36–38].

Since a subjective visual appraisal is rather difficult for routine application and quantification, instrument devices are the preferred method for objective evaluation, especially for color measurement [39].

Impact of storage media

In the present study, specimens were stored in media that are known to cause discoloration. Especially foods/drinks including pigments like curry and red wine cause accentuated staining by anionic polyphenols in interaction with cationic salivary pellicles [40, 41]. In this study, specimens were only stored in different media, without influence of natural or artificial saliva. Therefore, any discoloration resulted from interactions of food or drink ingredients with the respective materials tested.

There are three main factors causing extrinsic stain by supporting adhesion of colorant particles on restoration surfaces [42]: physical and chemical forces like electrostatic

Table 2 Overview of mean values and standard deviations of ΔE2 after different cleaning procedures divided into the different materials (PEEK, PMMA, COMP) and storage media (red wine, curry, CHX)

	Cleaning method	ΔE2		
		Mean ± SD		
		Red wine	Curry	CHX
PEEK				
Individual PPx	ST	2.21 ± 0.42^{bB1}	*3.61 ± 0.45*^{aC6}	0.70 ± 0.16^{bA1}
	MT	1.99 ± 0.78^{aB1}	*3.30 ± 0.34*^{aC56}	0.47 ± 0.11^{aA1}
	SOT	2.13 ± 0.56^{bB1}	2.51 ± 0.47*^{abB345}	0.45 ± 0.20^{aA1}
Laboratory protocols	SY	2.23 ± 0.44^{aB1}	2.69 ± 0.34^{aC456}	0.34 ± 0.33*^{aA1}
	SS	1.89 ± 0.44^{aB1}	1.62 ± 0.28^{aB123}	0.17 ± 0.11^{aA1}
	UB	2.00 ± 0.33^{cC1}	1.29 ± 0.26^{aB12}	0.28 ± 0.22^{aA1}
	AP	2.18 ± 0.73^{aC1}	1.11 ± 0.38^{aB1}	0.35 ± 0.48*^{aA1}
Professional PPx	PS	2.15 ± 0.73^{bB1}	1.98 ± 0.47^{abB1234}	0.40 ± 0.27^{aA1}
	SO	1.64 ± 0.73^{aB1}	1.63 ± 0.73^{aB123}	0.37 ± 0.38*^{aA1}
	AFC	1.24 ± 0.71^{aB1}	2.15 ± 0.81^{aC234}	0.37 ± 0.26^{aA1}
	AFP	1.18 ± 0.65^{aB1}	2.04 ± 0.51^{aC1234}	0.35 ± 0.22^{aA1}
PMMA				
Individual PPx	ST	2.22 ± 0.72^{bB12}	2.49 ± 0.38^{aB45}	0.69 ± 0.19^{bA12}
	MT	2.46 ± 1.33^{aB23}	2.58 ± 0.34^{aB5}	1.28 ± 0.49^{bA12}
	SOT	1.97 ± 0.61^{abB12}	1.54 ± 0.24^{aB12}	0.66 ± 0.39^{aA1}
Laboratory protocols	SY	2.14 ± 0.82^{aB2}	2.28 ± 0.42^{aB345}	0.84 ± 0.38^{bA12}
	SS	1.90 ± 0.35*^{aB12}	1.53 ± 0.45^{aB12}	0.71 ± 0.31^{cA12}
	UB	1.49 ± 0.40^{bA12}	1.26 ± 0.33^{aA1}	1.58 ± 1.08^{bA2}
	AP	**3.58 ± 0.77**^{bC3}	1.72 ± 0.45^{aB123}	0.62 ± 0.33^{aA1}
Professional PPx	PS	1.08 ± 0.35^{aA1}	1.35 ± 0.29^{aA12}	1.11 ± 0.40^{bA12}
	SO	1.53 ± 0.52^{aB12}	1.79 ± 0.28^{aB123}	0.77 ± 0.17^{bA12}
	AFC	1.46 ± 0.55^{aB12}	1.84 ± 0.24^{aB1234}	0.56 ± 0.27^{aA1}
	AFP	1.35 ± 0.50^{aB12}	1.97 ± 0.37^{aC2345}	0.64 ± 0.25^{bA1}
COMP				
Individual PPx	ST	1.42 ± 0.51^{aA123}	*5.89 ± 2.39*^{bB2}	0.36 ± 0.13^{aA1}
	MT	1.60 ± 0.24^{aA123}	*5.44 ± 3.16*^{bB12}	0.34 ± 0.17^{aA1}
	SOT	1.46 ± 0.52^{aA123}	*3.70 ± 2.03*^{bB12}	0.44 ± 0.23^{aA1}
Laboratory protocols	SY	2.12 ± 0.37^{aB3}	3.01 ± 1.63^{aB12}	0.43 ± 0.32*^{aA1}
	SS	1.84 ± 0.34^{aB23}	1.77 ± 0.65^{aB1}	0.44 ± 0.18^{bA1}
	UB	0.86 ± 0.40^{aA1}	2.05 ± 1.29^{aB12}	0.33 ± 0.18^{aA1}
	AP	1.94 ± 0.89^{aAB23}	3.08 ± 1.93*^{bB12}	0.53 ± 0.38*^{aA1}
Professional PPx	PS	0.77 ± 0.40^{aA1}	3.23 ± 2.72^{bB12}	0.67 ± 0.37^{aA1}
	SO	1.37 ± 0.38^{aA123}	3.26 ± 1.85^{bB12}	0.43 ± 0.15^{aA1}
	AFC	1.29 ± 0.43^{aA123}	3.16 ± 2.03^{aB12}	0.33 ± 0.20^{aA1}
	AFP	1.13 ± 0.43*^{aB12}	2.47 ± 0.91^{aC12}	0.25 ± 0.09^{aA1}

Values about ΔE2 3.3 are set in italic

^{abcd} Different superscript lowercase letters represent significant differences between media and cleaning protocols within one material group

^{ABC} Different superscript uppercase letters represent significant differences between materials and cleaning protocols within one medium

^{1234567} Different superscript numbers represent significant differences between materials and media within one cleaning protocol

*Not normally distributed data

Table 3 Overview of mean values and standard deviations of ΔE3 after different cleaning procedures divided into the different materials (PEEK, PMMA, COMP) and storage media (red wine, curry, CHX)

	Cleaning method	ΔE3		
		Mean ± SD		
		Red wine	Curry	CHX
PEEK				
Individual PPx	ST	0.55 ± 0.13^{aA12}	0.38 ± 0.09^{aA12}	0.67 ± 0.21^{aA1}
	MT	0.60 ± 0.14^{aB2}	1.20 ± 0.28^{aA1}	0.45 ± 0.11^{aA1}
	SOT	0.31 ± 0.10^{aA12}	0.31 ± 0.09^{aB34}	$0.34 \pm 0.17{*}^{aA1}$
Laboratory protocols	SY	0.21 ± 0.12^{aA1}	1.70 ± 0.37^{aA1}	0.26 ± 0.26^{aA1}
	SS	0.44 ± 0.28^{aA12}	2.04 ± 0.41^{aB45}	0.24 ± 0.12^{aA1}
	UB	0.40 ± 0.13^{aA12}	1.67 ± 0.35^{abB5}	0.28 ± 0.18^{aA1}
	AP	1.19 ± 0.23^{aB3}	1.37 ± 0.19^{aC45}	$0.34 \pm 0.42{*}^{aA1}$
Professional PPx	PS	$0.30 \pm 0.23{*}^{aA12}$	1.38 ± 0.20^{aB34}	$0.39 \pm 0.29{*}^{aA1}$
	SO	0.30 ± 0.10^{aA12}	1.05 ± 0.48^{aB34}	0.24 ± 0.17^{aA1}
	AFC	0.32 ± 0.16^{aA12}	$1.40 \pm 0.29{*}^{aB23}$	0.39 ± 0.22^{aA1}
	AFP	0.25 ± 0.19^{aA1}	0.67 ± 0.21^{aB34}	0.27 ± 0.23^{aA1}
PMMA				
Individual PPx	ST	1.48 ± 0.39^{aB12}	1.11 ± 0.27^{aA1}	0.91 ± 0.25^{bA1}
	MT	$2.36 \pm 1.03{*}^{bB2}$	1.63 ± 0.31^{aA12}	1.43 ± 0.60^{bA1}
	SOT	1.66 ± 0.61^{bB12}	1.55 ± 0.37^{aB1234}	$0.81 \pm 0.29{*}^{bA1}$
Laboratory protocols	SY	1.13 ± 0.45^{abA1}	1.83 ± 0.29^{bA123}	1.14 ± 0.33^{bA1}
	SS	0.85 ± 1.31^{aA1}	2.22 ± 0.33^{aB3456}	0.94 ± 0.19^{cA1}
	UB	1.41 ± 0.22^{abA12}	$2.51 \pm 0.45{*}^{bB4567}$	1.57 ± 0.79^{bA1}
	AP	*4.49 ± 0.63^{bC3}*	2.31 ± 0.22^{baB7}	1.03 ± 0.56^{bA1}
Professional PPx	PS	2.22 ± 0.47^{bB2}	2.42 ± 0.40^{aB567}	1.16 ± 0.46^{bA1}
	SO	1.76 ± 0.38^{bB12}	1.70 ± 0.27^{bC67}	0.82 ± 0.22^{cA1}
	AFC	1.69 ± 0.36^{bB12}	$1.58 \pm 0.35{*}^{bB2345}$	0.88 ± 0.40^{bA1}
	AFP	1.48 ± 0.20^{bB12}	0.91 ± 0.25^{aB1234}	0.87 ± 0.32^{bA1}
COMP				
Individual PPx	ST	2.96 ± 1.92^{bB1}	2.12 ± 1.09^{bAB1}	0.53 ± 0.14^{aA1}
	MT	$2.02 \pm 1.09{*}^{bB1}$	2.41 ± 0.92^{bB1}	0.55 ± 0.05^{aA1}
	SOT	2.37 ± 0.95^{bB1}	2.12 ± 0.98^{bB1}	0.63 ± 0.22^{bA1}
Laboratory protocols	SY	$1.74 \pm 1.56{*}^{bAB1}$	1.64 ± 0.58^{bB1}	0.52 ± 0.19^{aA1}
	SS	2.04 ± 1.31^{bB1}	1.63 ± 0.57^{aB1}	0.56 ± 0.15^{bA1}
	UB	$2.52 \pm 1.98{*}^{bB1}$	1.48 ± 0.75^{aAB1}	$0.64 \pm 0.16{*}^{aA1}$
	AP	1.54 ± 0.48^{aB1}	2.39 ± 1.74^{aB1}	0.68 ± 0.26^{abA1}
Professional PPx	PS	2.89 ± 0.45^{cB1}	$2.14 \pm 0.84{*}^{aB1}$	$0.61 \pm 0.47{*}^{aA1}$
	SO	$1.95 \pm 0.46{*}^{bB1}$	$1.52 \pm 0.64{*}^{bB1}$	0.56 ± 0.16^{bA1}
	AFC	$2.33 \pm 0.65{*}^{cC1}$	1.37 ± 1.01^{abB1}	$0.48 \pm 0.12{*}^{aA1}$
	AFP	2.34 ± 0.43^{cC1}	$0.53 \pm 0.14{*}^{aB1}$	0.44 ± 0.14^{aA1}

Value about ΔE2 3.3 is set in italic

[abcd] Different superscript lowercase letters represent significant differences between media and cleaning protocols within one material group

[ABC] Different superscript uppercase letters represent significant differences between materials and cleaning protocols within one medium

[1234567] Different superscript numbers represent significant differences between materials and media within one cleaning protocol

*Not normally distributed data

forces (van der Waals) and hydrophobic interdependencies. Media with low pH values in the range of 3–6 lead to surface softening and removal of inorganic substances like Ca^{2+}, Al^{3+}, and Sr^{2+} and result in increased dye deposition [43, 44]. Red wine is more acidic than distilled water or chlorhexidine, with a pH of 5.5–7. Despite alkaline pH values, the curry suspension led to significantly higher color changes than red wine, followed by chlorhexidine and distilled water. This can be explained by the fact that curry includes more orange pigments in contrast to the other media used. Conjugated diarylhepnoids (e.g., curcumin) cause orange color staining and show a high affinity to the polymer phase [45].

Physiomechanical characteristics of the tested materials like water absorption, solubility, and Martens hardness (HM) must be considered. No correlation was found between these properties and the tendency to discoloration [46, 47]. PEEK showed the lowest water absorption, solubility, and HM values as compared to PMMA-based and composite resin materials. During a storage period of 180 days in saliva and distilled water, water absorption was independent of the storage medium, but showed dependency on storage duration and material properties [48]. The results can be explained by the fact that a higher amount of resin matrix in combination with a lower content of filler particles results in higher water absorption [49]. These materials are vulnerable to staining by hydrophilic colorants in aqueous solutions increasing over a longer period of storage time [50]. Water storage and thermal cycling had no influence on HM of tested composite resin materials at all [51].

Impact of tested cleaning devices

The question how color stain caused by different media can be effectively removed from PEEK restorations once they occur, however, still remains. First of all, a differentiation between three main user groups must be made: patients, who perform individual prophylaxis using manual or electric toothbrushes at home; dentists, who apply professional prophylaxis measures in their dental practice; and dental technicians, who use laboratory protocols in their laboratory. With regard to the discoloration, only some cleaning protocols showed an effect. Sonic toothbrush, Sympro, and Air Flow Plus represented the most widespread cleaning devices with respect to the individual user group related to stain removal capacity of PEEK. According to a laboratory study assessing extrinsic stain removal, a clear superiority of sonic toothbrushes could be demonstrated so far [52]. Particularly noticeable were the contradictory $\Delta E2$ and $\Delta E3$ values of tested PMMA after cleaning with aluminum oxide (AP). PMMA consists primarily of matrix components with a low filler degree. They are known for their vulnerability for color changes caused by certain beverages [53]. Red wine as a representative of a more acidic medium is able to attack the material's surface. When aluminum oxide particles impact a material's surface, a high amount of superficially situated red wine pigments can be removed, which is a possible explanation for the high $\Delta E2$ value. During aluminum oxide impact, energy is liberated in the form of heat. This process may also induce changes in the matrix opacity. The result is a strong deviation from the initially measured color, especially in combination with residual and embedded red wine pigments. Therefore, high $\Delta E3$ value can be observed.

The tested materials showed strong differences in baseline *L*, *a*, and *b* values: PEEK (mean *L* value 88.2) is darker than COMP (mean *L* value 66.3) and PMMA (mean *L* value 55.4). Therefore, it must be taken into consideration that brighter materials potentially show a higher tendency for discolorations than darker ones.

The high deviation of $\Delta E1$ values in the group COMP (Fig. 2) is striking. COMP shows an average filler content of approximately 40 %. Color particles are located between the connected surfaces of filler and matrix. The irregularity of distribution of inserted fillers and pigments correlates with a wider dispersion of the values.

An ongoing in-house study also evaluated the surface roughness and free energy after different cleaning protocols. The abovementioned cleaning methods resulted in severe surface changes like scratches and notches. Cleaning using conventional air-abrasion and powders (AP), followed by AFC, resulted in higher SR values, i.e., with higher values than the recommended threshold value of 0.2 μm, than the other devices (<0.2 μm) [54]. The latter threshold value is defined as a more or less arbitrarily derived value, from which a significant higher biofilm formation is notable [55]. As a consequence, the use of these cleaning methods should be avoided. With regard to professional prophylaxis, air-abrasion using sodium bicarbonate powder of specific size is known to cause substance damage on natural teeth. However, it displays outstanding abilities to remove extrinsic stains [56]. The overall degree of substance loss depends on particle size, instrumentation time, and working distance [57].

High surface roughness correlates with increased initial biofilm adhesion. It has to be investigated, which parameters predominantly influence bacterial adherence and growth. Previous studies corroborated that PEEK surfaces with a low surface roughness (<0.2 μm) and free energy showed significantly less bacterial growth [58]. Both unspecific plaque accumulation and the color transformation process of biofilms cause discoloration. However, the user has to strike a balance between damage and benefit of used cleaning devices.

Conclusion

Within the limitations of this study, it can be concluded that PEEK showed the significantly ($p < 0.001$) lowest discoloration after a 1-week storage over all coloring media as compared to PMMA and COMP. PEEK starts with higher *L* values and a lower tendency to discoloration than COMP and PMMA.

In order to reduce discoloration of PEEK restorations, patients should use sonic toothbrushes keeping in mind the application limitations, such as erosion, for individual prophylaxis. Dentists are able to remove discoloration on PEEK surfaces by utilizing powder air-abrasion, e.g., AFP within the scope of professional prophylaxis. For laboratory protocols, the use of Sympro or an ultrasonic bath is recommended.

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3 Diskussion

In diesem Abschnitt werden die jeweiligen Untersuchungen einzeln diskutiert.

3.1 Oberflächenbeschaffenheit von PEEK nach unterschiedlichen Politurmaßnahmen

Die Null-Hypothese vorliegender Studie, welche von keiner wechselseitigen Beeinflußung der untersuchten Materialien und der verschiedenen Politurmaßnahmen mit der Oberflächenrauhigkeit und -benetzbarkeit ausging, konnte zurüchgewiesen werden. Dabei wurde die Polierbarkeit des Werkstoffes PEEK mit der von PMMA und COMP verglichen und die Effizienz von sieben verschiedenen Politurprotokollen untersucht. Zum gegenwärtigen Zeitpunkt existieren keine vergleichbaren Daten bezüglich geeigneter Politurmaßnahmen des Werkstoffes PEEK ungeachtet seines großen Potentials als Restaurationsmaterial auf Grund seiner herausragenden mechanischen, thermischen und chemischen Eigenschaften [4]. Diese Aspekte rechtfertigen die Auswahl des Materials PEEK für die Untersuchung der Oberflächeneigenschaften und geeigneter Politurmethoden im Hinblick auf die Ergebnisse vorliegender Studie. Bereits durchgeführte Studien, welche die Plaqueanlagerungstendenz von PEEK untersuchten, konnten zeigen, dass PEEK als geeignetes Restaurationsmaterial fungiert [12, 13, 14]. Dabei spielt gerade die Initialperiode der Plaquebildung - bekannt als kritische bzw. Adhäsionsphase - eine entscheidende Rolle für das Plaquewachstum, was letztendlich zur Bildung einer manifesten Initialkaries im Nachbarzahngebiet führen kann. Um eine solche Entwicklung zu unterbinden ist es unabdingbar, für eine hochglanzpolierte und glatte Oberfläche des Restaurationsmaterials mit einer geringen Oberflächenrauhigkeit und -benetzbarkeit zu sorgen. Auf diese Weise soll die Anheftung von Frühbesiedlerbakterien vermieden werden. Einen entscheidenden Einfluß auf die Plaquebildung hat die chemische Zusammensetzung von Restaurationsmaterialoberflächen [27].

In einigen Untersuchungen konnte gezeigt werden, dass es einen signifikanten Zusammenhang zwischen der Oberflächenrauhigkeit von Titanimplantatoberflächen und der detektierten Plaqueakkumulation gab. Dabei führten Oberflächenrauhigkeitswerte von $> 0{,}2$ µm zu einer gesteigerten Biofilmbildung, wohingegen Oberflächenrauhigkeitswerte von $<$ 0,2 µm zu keiner nachweisbar erhöhten Plaqueadhäsion beitrugen [17, 18]. Weitere Studien konnten den Zusammenhang zwischen erhöhten Oberflächenrauhigkeitswerten und gesteigerter Plaquebildung bestätigen [19, 20, 21]. Desweiteren gelang es Bürgers et al. [16] nachzuweisen, dass eine signifikante Korrelation zwischen der Oberflächenbeschaffenheit von PEEK und der Adhäsion von Streptococcus mutans besteht. Dabei ergaben sich sowohl signifikante Zusammehänge zwischen der bakteriellen Adhäsion und den Oberflächenbenetzbarkeitswerten als auch zwischen den Oberflächenrauhigkeits- und Oberflächenbenetzbarkeitswerten. Dementgegen konnte keine signifikante Korrelation zwischen der Oberflächenrauhigeit und einem fluoreszierenden bakteriellen Biofilm detektiert werden. Auf Grund dieser Tatsache kann nicht sicher geschlussfolgert werden, ob die Oberflächenrauhigkeit oder -benetzbarkeit einer Materialoberläche einen wesentlicheren Bewertungsfaktor für eine Politurmaßnahme darstellt. Um diese These zu bestätigen müssen weitere klinische Untersuchungen folgen, welche sich dezidiert mit dem Zusammenhang zwischen der Oberflächenbeschaffenheit eines Restaurationsmaterials und der sich entwichelnden Plaquebildung auseinandersetzen.

Bei einer Untersuchung der Plaqueanlagerungsrate an verschiedenen Implantatabutmentmaterialien zeigte PEEK innerhalb der ersten 20 Stunden eine signifikant geringere Menge an gemessener Biomasse als Zirkon- und Titanoxid. Dies kann dadurch erklärt werden, dass selbst glasierte Keramikmaterialien keine Oberflächenrauhigkeitswerte unter 0,3 µm aufweisen [28]. In den Untersuchungen von Hahnel et al. [14] wurden die getesteten Prüfkörper mittels einer automatisierten Poliermaschine und einem Schleifpapier der Korngröße P4000 poliert, was mit der Politurmethodik der Kontrollgruppe vorliegender Studie zu vergleichen ist. Betrachtet man den Einfluss der Politurmethode auf den Werkstoff PEEK, so konnte gezeigt werden, dass neben der Kontrollgruppe die Gruppen Abraso, Opal L, Super-snap und Prisma gloss zu signifikant geringeren Oberflächenrauhigkeitswerten führten als die restlichen Versuchsgruppen. In Gruppe Enhance zeigten sich die signifikant geringsten Oberflächenbenetzbarkeitswerte, wohingegen die Rauhigkeitswerte stets oberhalb der 0,2 µm-Marke lagen.

Ein Kernpunkt vorliegender Studie war die strikte Aufteilung der Methoden in Labside- und Chairside-Verfahren. Sowohl Zahntechniker als auch Zahnärzte müssen sicherstellen, dass einzugliedernde Restaurationen vor dem Einsetzen eine glatte Oberfläche aufweisen. Das gilt auch nach intraoralen Einschleifmaßnahmen die statische und dynamische Okklusion betreffend. Dafür stehen verschiedene Möglichkeiten zur Verfügung, welche der Einfachheit halber in Zwei- und Dreikörperverschleiß eingeteilt werden können [24]. Zur Gruppe des Zweikörperverschleißes zählen Fräsen und beschichtete Schleifkörper (zu vergleichen mt den Labside-Politurmethoden Ceragum und Diagen und den Chairside-Verfahren Super-snap und Enhance). Der Dreikörperverschleiß beinhaltet unter anderem die Verwendung von Hochglanzpoliturpasten wie in den Labside-Verfahren Abraso und Opal-L und der Chairside-Variante Prisma gloss. Der Vorteil bei der Verwendung von Politurpasten besteht darin, dass deren Anwendung mit Wasser kombiniert werden kann, was zu einer geringeren Abrasivität (Nanometer-Bereich) mit einer hochglänzenden, lichtreflektierenden Oberfläche führt [23]. Demgegenüber steht die unverdünnte Anwendung der Politurpaste, was durch eine aggressivere Verfahrensweise mit einem erhöhten Abtrag und dem Risiko des Entstehens von tiefen Kratzern verbunden sein kann. Voraussetzung dafür, dass eine Politur mittels Pasten durchgeführt werden kann, ist der Gebrauch von Polierbürsten per Hand- oder Winkelstück.

Betrachtet man alle Labside-Politurmethoden, so zeigten die Verfahren Abraso und Opal L signifikant niedrigere Oberflächenrauhigkeitswerte als die restlichen Verfahren innerhalb aller getesteten Materialien. Die Polituren mittels Opal L und Ceragum führten im Vergleich zu den anderen Labside-Methoden zu den signifikant niedrigsten Oberflächenbenetzbarkeitswerten. Hinsichtlich der Chairside-Politurprotokolle zeigten die Gruppen Supersnap und Prisma gloss innerhalb aller getesteten Materialien signifikant niedrigere Rauhigkeitswerte. Die niedrigsten Benetzbarkeitswerte konnten in diesem Bereich in Gruppe Enhance detektiert werden. Jedoch führte die Anwendung des Enhance-Politursystems bei allen getesteten Materialien zu Rauhigkeitswerten $> 0{,}5$ µm, insbesondere beim untersuchten Material PEEK. Diese Ergebnisse konnten durch die Studie von Hassan et al. [29] verifiziert werden, welche sich mit der Untersuchung des Einflusses unterschiedlicher Politurverfahren auf die Oberflächenrauhigkeit verschiedener Kompositarten beschäftigte.

In vorliegender Studie zeigte PEEK sowohl in der Labside- als auch in der Chairside-Gruppe niedrigere Benetzbarkeitswerte als PMMA und COMP. Bezüglich der Rauhigkeitswerte waren bei PEEK signifikant höhere Werte zu konstatieren als bei PMMA und COMP. Dabei konnte keine Korrelation zwischen Oberflächenrauhigkeit und -benetzbarkeit gefunden werden, obwohl gerade mittels des Dreikörperverschleißes die besten Resultate hinsichtlich geringer Oberflächenrauhigkeit und -benetzbarkeit erzielt werden konnten. Ausgenommen hiervon war das Chairside-Politurverfahren Super-snap.

Entscheidende Parameter, welche ebenfalls eine wichtige Rolle für die Polierbarkeit eines Werkstoffes spielen wie z.B. Härte, Füllkörperanteil und Matrixbeschaffenheit, dürfen nicht außer Acht gelassen werden. Dabei weist PEEK eine Härte von ca. 110 HV auf und ist somit vergleichbar mit etablierten PMMA Materialien. Demgegenüber steht COMP als wesentlich härteres Material mit Werten von bis zu 600 HV [4]. Es konnte nachgewiesen werden, dass der Füllkörperanteil die mechanischen Eigenschaften von Kompositmaterialien determiniert abhängig von der Füllermorphologie. In diesem Zusammenhang kann von einer direkten Proportionalität zwischen Füllkörperanteil und Materialhärte ausgegangen werden [25, 26]. Die vorliegenden Untersuchungen konnten zeigen, dass COMP innerhalb aller untersuchten Politurmethoden die niedrigsten Oberflächenrauhigkeitswerte aufwies. So kann geschlussfolgert werden, dass Materialien mit einer höheren Härte niedrigere Rauhigkeitswerte nach der Politur aufweisen, was unter anderem in einer geringeren Benetzbarkeit resultiert. Um diese Korrelationsthese zu bestätigen, müssen jedoch noch weitere Studien folgen.

3.2 Oberflächenbeschaffenheit von PEEK nach unterschiedlichen Reinigungsverfahren

Der Anreiz für die vorliegende Studie war die Tatsache, dass zum gegenwärtigen Zeitpunkt keine aussagekräftigen Daten zum Thema Reinigungsmethoden von PEEK und deren Einfluss auf dessen Oberflächeneigenschaften wie Oberflächenrauhigkeit und -benetzbarkeit existieren. Jedes intraoral eingebrachte Restaurationsmaterial ist auf Dauer der Abnutzung und der Biofilmanlagerung unterworfen. Dabei sind unter anderem die anfängliche Oberflächenbeschaffenheit und die Materialeigenschaften eines Restaurationsmaterials in Kombination mit der Mitarbeit des Patienten ausschlaggebend für die Dauer der Plaqueanlagerung. Für gewöhnlich putzen sich Patienten zweimal am Tag die Zähne unter Verwendung von Zahnpaste. Man geht davon aus, die Plaqueneubildung auf diese Weise auf ein Minimum reduzieren zu können. Zahlreiche Studien untersuchten die Unterschiede zwischen Hand- und elektrischen Zahnbürsten. Dabei konnten Zimmer et al. [43] zeigen, dass Plaque und Gingivitiden, welche nach einem Beobachtungszeitraum von acht Wochen entstanden sind, durch den Gebrauch von Ultraschallzahnbürsten signifikanter reduziert werden konnten als im Vergleich zu Handzahnbürsten. Andererseits konnte nachgewiesen werden, dass die Anwendung elektrischer Zahnbürsten zu einer signifikant höheren Schmelzabrasion führt als bei Handzahnbürsten [44]. Patienten mit einem hohen Konsum an erosiven Nahrungsmitteln oder saurer Indigestion sollten den Gebrauch von elektrischen Reinigungsverfahren vermeiden. Betrachtet man die untersuchten, individuellen Prophylaxemethoden finden sich keine signifikanten Unterschiede bezüglich der Oberflächenrauhigkeit zwischen elektrischen und Handzahnbürsten, auch wenn die Rauhigkeitswerte der Schallzahnbürsten höhere Werte ergaben. Auf Grund des kurzen Untersuchungszeitraums ist es schwierig eine Aussage darüber zu treffen, ob eine Proportionalität zwischen den gemessenen Rauhigkeitswerten und der Geräteanwendungszeit besteht. Um dezidierte Gebrauchsrichtlinien zu geben und um die Frage zu klären, warum Oberflächenrauhigkeit und -benetzbarkeit gegenläufige Werte zeigen, müssen weitere Studien folgen.

Innerhalb der Labside-Reinigungsverfahren wurden feuchte mit trockenen Reinigungsmethoden verglichen. In der vorliegenden Studie konnte gezeigt werden, dass feuchte Reinigungsverfahren wie Sympro, SunSparkle und das Ultraschallbad zu signifikant niedrigeren Oberflächenrauhigkeitswerten führten als die trockenen Varianten (Korund). Der Hauptanwendungsbereich von Korund ist die Konditionierung von Restaurationsmaterialien zur Verbesserung des Haftverbundes [45]. Dabei werden scharfkantige Korundpartikel beschleunigt. Beim Auftreffen auf der Materialoberfläche wird Energie freigesetzt. Die dabei entstehenden Oberflächenvertiefungen konnten auf der Oberfläche korundgestrahlter PEEK-Prüfkörper nachgewiesen werden. Demzufolge entstehen auf diese Weise höhere Oberflächenrauhigkeitswerte als bei der Verwendung feuchter Reinigungsverfahren, welche die Materialoberfläche nicht direkt beeinflußen. Im letzteren Fall fungieren Wasser oder ein Reinigungsfluid als schützende Barriere, um die Entstehung tiefer Kratzer und Furchen zu vermeiden. Das Sympro Reinigungsverfahren beinhaltet neben der Reinigungsflüssigkeit Nadeln, wohingegen SunSparkle und das Ultraschallbad keine zusätzlichen Reinigungsobjekte enthalten. So war es auffällig, dass bei der elektronenmikroskopischen Auswertung von PEEK Prüfkörpern, welche mittels Sympro gereinigt wurden, nadelförmige Einschläge auf deren Oberfläche gefunden werden konnten.

Bei der Untersuchung der professionellen Prophylaxemethoden konnte gezeigt werden, dass die Verwendung von Air Flow Comfort zu signifikant höheren Oberflächenrauhigkeitswerten führte als die der anderen Verfahren. Bei der Verwendung von Air Flow Comfort beträgt die durchschnittliche Korngröße der enthaltenen Partikel 40 µm. Laut Herstellerangaben ist Air Flow Comfort ausschließlich für den supragingivalen Gebrauch geeignet, um parodontale Schäden zu vermeiden. Um eine subgingivale Anwendung zu ermöglichen, reduzierte der Hersteller die Korngröße auf 14 µm (Air Flow Plus). Auf diese Weise konnten die Rauhigkeitswerte zwar signifikant verringert werden, dennoch konnten bei Weitem nicht derart niedrige Werte wie bei den anderen Chairside-Verfahren erreicht werden. Dass die Anwendung von Pulverstrahlgeräten einen oberflächenrauhigkeitserhöhenden Effekt ausübt, konnte bereits in einer anderen Studie gezeigt werden [46]. Bei der elektronenmikroskopischen Analyse konnte dieser Effekt ebenfalls bestätigt werden. Desweiteren konnten in vorliegender Studie und bei den Untersuchungen von Eliades et al. [47] verbliebene und auf der Prüfkörperoberfläche anheftende Bikarbonatpartikel nachgewiesen werden. Es ist dabei noch nicht abschließend geklärt, ob die verbliebenen Bikarbonatpartikel einen eher negativen Effekt ausüben oder im positiven Sinne zur Neutralisation von bakteriellen Stoffwechselprodukten beitragen. Bei der Verwendung von bikarbonathaltigen Zahnpasten konnten positive klinische Ergebnisse hinsichtlich der Plaquebildung und der Mundgesundheit erzielt werden [48]. Um diese Ergebnisse zu fundieren, müssen jedoch noch weitere klinische Studien folgen. Dabei ist anzumerken, dass nach der Anwendung von Pulverstrahlgeräten eine abschließende Politur vom Hersteller empfohlen wird und dem klinischen Standard entspricht, um die genannten Probleme zu vermeiden.

Alle untersuchten Reinigungsverfahren beeinflussten die getesteten Materialien gleichermaßen. Daher kann die gestellte Hypothese, dass PEEK ähnliche Oberflächenrauhigkeitswerte nach dessen Reinigung aufweist wie PMMA und COMP, bestätigt werden. Dabei zeigten sich jedoch nach Reinigung keine ähnlichen Oberflächenbeschaffenheiten. Die ähnliche Oberflächenbeschaffenheit von PMMA hinsichtlich seiner Rauhigkeit nach Reinigung konnte durch die Untersuchungen von Zafar et al. [49] bestätigt werden. Die stärksten Veränderungen bezüglich der Oberflächenrauhigkeit konnten bei der Anwendung von Air Flow Comfort, Korund und Air Flow Plus beobachtet werden, was durch die kornartigen Bestandteile dieser Verfahren in trockenem und feuchtem Vorgehen erklärt werden kann.

Bezüglich der Oberflächenbenetzbarkeit konnten bei der Methode Sympro die höchsten Werte festgestellt werden gefolgt von der weichen Zahnbürste, SunSparkle, Air Flow Plus und Korund. Diese Tatsache kann dadurch erklärt werden, dass die auf der Oberfläche auftreffenden Nadeln in Kombination mit dem verwendeten Reinigungsfluid einen oberflächenvergrößernden Effekt ausüben, was mit höheren Oberflächenbenetbarkeitswerten korreliert. Bezüglich der Reinigungsverfahren Korund und Air Flow Plus kann ein ähnlicher Effekt beobachtet werden. Eine kürzlich durchgeführte Studie zur Untersuchung verschiedener Chairside-Reinigungsverfahren konnte vorliegende Ergebnisse hinsichtlich verwendeter Pulverstrahlgeräte bestätigen [50].

Die Veränderung der Oberflächenbenetzbarkeit bei der Anwendung der Schallzahnbürste und SunSparkle muss anderweitig versucht werden zu erklären. Die genauen Bestandteile des SunSparkle Reinigungssystems sind ein Firmengeheimnis, was einen Erklärungsansatz erschwert. Es wird vermutet, dass die Kombination aus dem verwendeten Reinigungsfluid und den vom Gerät induzierten, vibrierenden Bewegungen zu einer Veränderung der Materialoberfläche in Form eines Anstiegs der Oberflächenbenetzbarkeit führt. Des Weiteren muss darauf hingewiesen werden, dass sich Patienten durchschnittlich zweimal am Tag die Zähne mit einer Dauer von zwei bis vier Minuten putzen. Professionelle Prophylaxemethoden kommen allerdings nur zwischen einem und vier Malen im Jahr zur Anwendung. Folglich kann geschlussfolgert werden, dass die Oberflächenveränderungen hinsichtlich individueller Prophylaxemethoden ausgeprägter auftreten als bei den anderen Reinigungsverfahren. Wie bereits anfänglich erwähnt haben sowohl die Oberflächenrauhigkeit als auch -benetzbarkeit einen entscheidenden Einfluß auf die Bakterienadhäsion und die Biofilmbildung auf zahnärztlichen Restaurationsmaterialien. Ein reproduzierbares Wachstum von Plaquepellikeln konnte dabei auf PEEK Oberflächen gezeigt werden [51]. Quyrinen et al. [40] konnten nachweisen, dass Materialoberflächen mit geringeren Oberflächenbenetzbarkeitswerten zu einer geringeren Akkumulation von Bakterienkolonien neigen als solche mit hohen Benetzbarkeitswerten, was durch eine weitere Studie bestätigt werden konnte [52]. Daher kann geschlussfolgert werden, dass die Verwendung von Reinigungsmethoden, welche zu einer starken Veränderung der Oberflächeneigenschaften wie deren Rauhigkeit und Benetzbarkeit führen, im klinischen Alltag umgangen werden sollten. Da es sich bei der vorliegenden Studie um eine in-vitro Untersuchung handelt, ergeben sich Grenzen hinsichtlich der zu untersuchenden Korrelation zwischen der Plaquebildung und der Oberflächenbeschaffenheit des untersuchten Materials. Dabei müssen weitere Studien folgen, um die Effizienz verschiedener Reinigungsmethoden abschließend zu prüfen. Ein ausgewogenes Gleichgewicht zwischen der Aufrauhung der zu reinigenden Oberfläche und der Entfernung von Plaque und Verfärbungen ist in diesem Zusammenhang anzustreben.

3.3 Reinigungsmethoden für PEEK nach Lagerung in ausgewählten Medien

Bei der getesteten Null-Hypothese der vorliegenden Studie ging man davon aus, dass PEEK ähnliche Farbveränderungen nach einer Lagerung in verschiedenen Medien zeigt wie PMMA und COMP. Außerdem wurde die These aufgestellt, dass alle getesteten Reinigungsverfahren ein ähnliches Reinigungspotential aufweisen.

Das ästhetische Empfinden zahnärztlicher Restaurationen und deren farbliche Erscheinung hängt von verschiedenen Faktoren ab: die natürliche Zahnfarbe der Nachbarzähne oder der verbliebenen Zahnhartsubstanz, der Lichteinfall und die inhärenten Materialcharakteristika wie die Opaziät und die Transluzenz des verwendeten Restaurationsmaterials. Farbveränderungen mit ΔE Werten < 1 sind normalerweise nicht für das menschliche Auge wahrnehmbar. Ab ΔE $>$ 3,3 kann von für die menschliche Wahrnehmung nicht mehr akzeptablen Farbveränderungen das Restaurationsmaterial betreffend die Rede sein [62, 63, 64]. Da sich die visuelle Bewertung einer Verfärbung im klinischen Alltag schwierig gestaltet und schwer quantifizierbar ist, werden vornehmlich instrumentelle Methoden verwendet. Auf diese Weise soll eine objektive Evaluation bezüglich der Messung von Farbveränderungen gewährleistet werden [65].

In vorliegender Studie wurden die Prüfkörper in verschiedenen Medien gelagert. Dabei wurden Lagerungsflüssigkeiten verwendet, welche für ihr Verfärbungspotential nach einer bestimmten Zeit der Lagerung bekannt sind. Vorgängerstudien konnten zeigen, dass es vor allem die Bestandteile stark pigmenthaltiger Speisen/Getränke wie Curry und Rotwein sind, welche zu starken Verfärbungen führen. Dies kann durch die Wechselwirkung anionischer Polyphenole mit kationischen Speichelbestandteilen erklärt werden [66, 67]. In dieser Studie wurden die Prüfkörper ausschließlich in Medien ohne Einfluß von natürlichem bzw. künstlichem Speichel gelagert. Folglich können die in diesem Falle entstandenen Verfärbungen auf eine direkte Interaktion zwischen Speise- bzw. Getränkeinhaltsstoffen und Materialbestandteilen zurückgeführt werden.

Es gibt drei wesentliche Hauptfaktoren, welche die Entstehung extrinsischer Verfärbungen durch die Begünstigung der Anlagerung von Farbstoffpartikeln an Restaurationsmaterialien begünstigen [68]: physikalische Vorgänge, chemische Prozesse wie z.B. elektrostatische Wechselwirkungen (van der Waals) und hydrophobe Wechselbeziehungen. Lagerungsmedien mit niedrigen pH-Werten (pH 3-6) führen nachhaltig zu einer Oberflächenerweichung und zu einem Herauslösen anorganischer Substanzen wie z.B. Ca2+, Al3+ und Sr2+ in Verbindung mit einer erhöhten Farbstoffausfällung [69, 70]. Rotwein weist einen saureren pH-Wert auf als destilliertes Wasser oder Chlorhexidin (pH 5,5-7,0). Es konnte nachgewiesen werden, dass das Lagerungsmedium Curry trotz seines eher alkalischen pH-Wertes zu signifikant stärkeren Verfärbungen führte als Rotwein gefolgt von Chlorhexidin und dem Kontrollmedium destilliertes Wasser. Vorgängerstudien erklären diese Beobachtung durch den höheren Anteil an gelben Pigmenten im Medium Curry. Konjugierte Diarylheptanoide (Curcuma) verursachen orange Verfärbungen und weisen eine hohe Affinität zur Polymerphase der Materialien auf [71].

Des Weiteren müssen physiomechanische Charakteristika wie die Wasserabsorption, Löslichkeit und die Härte (Martenshärte) der getesteten Materialien näher betrachtet werden. Es konnte keine Korrelation zwischen den genannten Eigenschaften und der Verfärbungstendenz der untersuchten Materialien festgestellt werden [72, 73]. PEEK zeigte die geringste Wasserabsorption, Löslichkeit und Martenshärte im Vergleich zu PMMA und COMP. Während einer Einlagerungsperiode von 180 Tagen in Speichel und destilliertem Wasser zeigte sich die Wasserlöslichkeit unabhänging vom Lagerungsmedium. Jedoch war eine Abhängigkeit von der Einlagerungszeit und der Materialbeschaffenheit erkennbar [4]. Diese Ergebnisse können folgendermaßen erklärt werden: ein höherer Matrixanteil in Kombination mit einem geringeren Fülleranteil resultiert in einer höheren Wasserabsorption [74]. Derartige Materialien sind anfällig für Verfärbungen durch hydrophile Farbstoffpartikel in wässrigen Lösungen mit zunehmender Tendenz über einen längeren Einlagerungszeitraum [75]. Die Einlagerung in Wasser und eine Temperaturwechselbeanspruchung zeigten hingegen keinen Einfluss auf die Martenshärte der getesteten Kompositmaterialien [76].

Dennoch bleibt die Frage bestehen, wie Verfärbungen am effizientesten von PEEK Restaurationen entfernt werden können. Zunächst muss eine Unterscheidung zwischen drei Hauptanwendergruppen vorgenommen werden. Dabei werden Patienten, welche als individuelle Prophylaxe elektrische oder Handzahnbürsten verwenden, von der Gruppe der Zahnärzte unterschieden, welche sich professioneller Prophylaxemethoden bedienen. Die dritte Gruppe bilden Zahntechniker, welche laborspezifische Reinigungsverfahren anwenden.

Im Hinblick auf die Verfärbungsrate zeigten nur einzelne Reinigunsverfahren einen Effekt. Die Schallzahnbürste, das Sympro-Reinigungsverfahren und Air Flow Plus zeigten die höchste Verfärbungsentfernungskapazität von PEEK im Hinblick auf die einzelnen Benutzergruppen. Gemäß einer weiteren Studie, welche sich mit der Entfernbarkeit extrinsischer Auflagerungen beschäftige, konnte eine klare Überlegenheit von Schallzahnbürsten gezeigt werden [77]. In besonderem Maße auffällig waren die widersprüchlichen ΔE2 und ΔE3 Werte bei der Reinigung von PMMA mittels Korundstrahlen. PMMA besteht hauptsächlich aus Matrixkomponenten mit einem niedrigen Fülleranteil. Es ist anfällig für entstehende Farbveränderungen, welche unter anderem durch verschiedene Getränke ausgelöst werden [78]. Rotwein besitzt einen sauren pH-Wert und kann somit Materialoberflächen angreifen. Indem Aluminiumoxidpartikel auf die Oberfläche eines Materials auftreffen, kann ein hoher Anteil an oberflächlich eingelagerten Rotweinpigmenten entfernt werden. Dabei wird Energie in Form von Wärme freigesetzt. Dieser Prozess kann ebenfalls zu Veränderungen in der Materialopazität führen. Das Ergebnis ist folglich eine deutliche Abweichung von der Ausgangsfarbe des untersuchten Materials, vor allem in Kombination mit verbliebenen, oberflächlich eingelagerten Rotweinpigmenten. Die getesteten Materialien zeigten starke Abweichungen hinsichtlich ihrer Ausgangs L, a und b Werte: PEEK (durchschnittlicher L-Wert 88,2) ist ein dunkleres Material als COMP (durchschnittlicher L-Wert 66,3) und PMMA (durchschnittlicher L-Wert 55,4). Diese Tatsache muss berücksichtigt werden, da hellere Materialien eine tendentiell höhere Verfärbungsneigung zeigen als dunklere Werkstoffe.

Die stark abweichenden ΔE1 Werte in der Gruppe COMP sind auffällig. Das Material COMP weist einen durchschnittlichen Füllkörperanteil von ca. 40% auf. Farbpartikel lagern sich am Übergang zwischen Füllstoff und Matrix ein. Die unregelmäßige Verteilung der eingebrachten Füllpartikel und Farbpigmente korreliert folglich mit einer breiteren Streuung der gemessenen Farbwerte.

Eine bereits durchgeführte klinikinterne Studie testete die Oberflächenrauhigkeit und -benetzbarkeit von PEEK nach Anwendung verschiedener Reinigunsgverfahren. Es konnte nachwiesen werden, dass die geprüften Reinigungsmethoden zu schweren Oberflächenveränderungen in Form von tiefen Kratzern und Mulden führten. Die Verwendung von Air Flow Comfort und Korund, gefolgt von Air Flow Plus, erbrachte höhere Oberflächenrauhigkeitswerte ($> 0,2$ µm) als die übrigen getesteten Reinigungsverfahren ($< 0,2$ µm) [79].

Dabei ist der Schwellenwert von 0,2 µm ein mehr oder weniger willkürlich festgelegter Bereich, bei dessen Überschreiten eine signifikant höhere Biofilmbildung festgestellt werden konnte [14]. Folglich sollte auf die Verwendung solcher Reinigungsverfahren verzichtet werden. Hinsichtlich professioneller Prophylaxemethoden verursacht die Verwendung von Pulverstrahlgeräten und Bikarbonatpulver spezifischer Korngröße bekanntlich Substanzschäden an natürlichen Zähnen. Dennoch besteht das Potential zur effektiven Entfernung extrinsischer Beläge [80]. Der durchschnittliche Substanzverlust, der durch die Anwendung von Reinigungsmethoden entsteht, ist abhängig von der Partikelgröße, der Anwendungsdauer und dem Arbeitsabstand [81].

Hohe Oberflächenrauhigkeitswerte eines Materials korrelieren mit einer erhöhten initialen Bakterienadhäsion und Biofilmbildung. Es ist von großer Bedeutung herauszuarbeiten, welche der genannten Parameter das bakterielle Wachstum und ihre Adhäsion vornehmlich beeinflußen. In Vorgängerstudien konnte die These, dass eine niedrige Oberflächenrauhigkeit ($< 0{,}2$ µm) und -benetzbarkeit mit einem signifikant geringeren bakteriellen Wachstum korreliert, bestätigt werden [41]. Sowohl eine unspezifische Plaqueakkumulation als auch ein Farbveränderungsprozess des entstandenen Biofilms verursachen Farbveränderungen. Der Anwender von Reinigungsmethoden muss folglich eine Gratwanderung zwischen Schaden und letztendlichem Nutzen beschreiten.

4 Zusammenfassung und Ausblick

Auf der Grundlage der hier zusammengefassten Ergebnisse konnte festgestellt werden, dass es bei der Anwendung des Materials PEEK des Wissens seiner Materialeigenschaften bedarf. Nur unter dieser Voraussetzung kann eine effiziente Politur und Reinigung des Werkstoffes durchgeführt werden ohne das Material zu beschädigen und zu einem gegenteiligen Effekt mit Neigung zur erhöhten Plaqueanlagerung zu führen.

Bezüglich der Polierbarkeit des Werkstoffes PEEK kann zusammengefasst werden, dass die Anwendung von Chairside-Politurverfahren zu niedrigeren Oberflächenrauhigkeitswerten führte als die Labside-Methoden. Bei den Labside-Verfahren waren es vor allem die verwendeten Politurpasten (Abraso und Opal L), welche zu Materialoberflächen mit signifikant niedrigeren Rauhigkeitswerten führten. Dabei zeigte die Verwendung der Verfahren Opal L und Ceragum die niedrigsten Oberflächenbenetzbarkeitswerte. Bezüglich der Chairside-Methoden waren es das Super-snap Politursystem und die Prisma gloss Politurpaste, welche zu gleichermaßen signifikant niedrigeren Rauhigkeitswerten führten als das Enhance-Politursystem, wobei letzteres jedoch die niedrigsten Oberflächenbenetzbarkeitswerte aufwies. Prüfkörper, welche mittels Zweikörperverschleißmethoden bearbeitet wurden, zeigten höhere Rauhigkeitswerte als bei der Verwendung von Dreikörperverschleißsystemen.

Hinsichtlich der getesteten Reinigungsverfahren kann festgehalten werden, dass PEEK im Vergleich zu COMP niedrigere Benetzbarkeitswerte zeigte, was mit einer geringeren Tendenz zur Biofilmanlagerung korreliert. Bei näherer Betrachtung der individuellen Prophylaxemethoden kann zusammengefasst werden, dass sich alle in der Studie untersuchten Zahnbürsten für Reinigungszwecke eignen unter Vorbehalt der individuellen, intraoralen Situation des Patienten (z.B. starke Abrasionstendenz). Bezüglich der Labside-Reinigungsverfahren kann geschlussfolgert werden, dass auf die Anwendung von Korund verzichtet werden sollte, da dadurch Oberflächen mit hoher Rauhigkeit und -benetzbarkeit generiert werden. Für Zahnärzte sind professionelle Prophylaxemethoden wie die Anwendung des Perio-Softscaler und Sonicsys empfehlenswert. Der Gebrauch von Pulverstrahlgeräten und Bikarbonatpulvern unterschiedlicher Korngröße kann nur in Kombination mit einem abschließenden Politurvorgang empfohlen werden.

Bezüglich der Entstehung von farblichen Niederschlägen kann die Aussage gemacht werden, dass PEEK nach einer einwöchigen Lagerung in verschiedenen Medien die signifikant geringste Verfärbungstendenz zeigte im Vergleich mit PMMA und COMP. PEEK weist allerdings einen höheren L-Ausgangswert auf und zeigt dadurch einer geringere Verfärbungstendenz als PMMA und COMP. Um eine effiziente Reinigung des Werkstoffes PEEK zu erreichen, sollten Patienten auf die Anwendung von Schallzahnbürsten zurückgreifen, falls es ihre intraorale Ausgangssituation zulässt. Zahnärzte können Verfärbungen gezielt mit der Anwendung von Pulverstrahlgeräten entfernen, dabei sollte jedoch, wie bereits erwähnt, an eine abschließende Politur gedacht werden. Im Rahmen der Labside-Verfahren haben sich vor allem die Anwendung des Reinigungsgeräts Sympro und des Ultraschallbads bewährt.

Unter Vorbehalt der Tatsache, dass es sich bei den durchgeführten Untersuchungen um in-vitro Versuche handelt, müssen zukünftig Studien folgen, welche die erhobenen Ergebnisse validieren. Nur auf diese Weise kann der Werkstoff PEEK unter geeigenten Voraussetzungen mit langanhaltend ästhetisch und funktionell wünschenswerten Ergebnissen als Restaurationsmaterial eingesetzt werden.

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