Effect of different cleaning methods of polyetheretherketone on surface roughness and surface free energy properties

Heimer, Sina <javascript:contributorCitation('Heimer, Sina');>; Schmidlin, Patrick R <javascript:contributorCitation('Schmidlin, Patrick R');>; Stawarczyk, Bogna <javascript:contributorCitation('Stawarczyk, Bogna');>

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) Al2O3-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 (plt;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 (plt;0.001). Within SFE, the cleaning method exerted the highest influence on SFE values (plt;0.001, P2 = 0.246), closely followed by the polymer material (plt;0.001, P2 = 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.

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Effect of different cleaning methods of polyetheretherketone on surface roughness and surface free energy properties

Short title: Cleaning effects on PEEK

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, Switzerland.

Correspondence

Bogna Stawarczyk, Department of Prosthodontics, Dental School, Ludwig-Maximilians University Munich, Goethestrasse 70, 80336 Munich, Germany, Tel. +49-89-4400-59573, Fax. +49-89-4400-59573, e-mail: bogna.stawarczyk@med.uni-muenchen.de

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ABSTRACT (250 words)

Purpose: To determine the effect of different individual, laboratory and professional cleaning methods on 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 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, cleaning method exerted the highest influence on SFE values ($p<0.001$, $\eta P^2=0.246$), closely followed by polymer material ($p<0.001$, $\eta P^2=0.136$). 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 lead to the highest SFE.

Conclusions: With regard to SR, all methods – with exception of the 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 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 as 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 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 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 two main cleaning versions: dry cleaning like using corundum blasting or the wet version like ultrasonic bath or needle cleaning devices in combination with either tap water or specially created cleaning liquids.

The individual prophylaxis can be divided into three main groups: Mechanical and chemical cleaning methods or a combination of thereof (6). Along with the usual using of commercially available manual toothbrushes, there are various further methods cleaning teeth like electric toothbrushes or the use of floss and interdental brushes. In combination with a suitable toothpaste, patients are encouraged brushing their teeth twice a day according to several clinical trials (7-8). The advantage of electric toothbrushes compared with manual ones could be shown in different studies. They are more effective in removing plaque and in this way 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 dentists` professional cleaning spectrum includes both hand instruments (e.g. scalers and curettes) and mechanical ones like ultrasonic scalers and powder jet devices (air-abrasion).

To date, according to the author`s knowledge, 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 ideal surrogate parameter 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 could be determined that a high SR will rather lead to biofilm formation and growing while a high SFE supported a 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. could demonstrate that there are non-favorable conditions for biofilm transformation on PEEK compared with other implant materials, e.g. titanium (16). However, the dependence of material sensitivities and their surface properties like hardness, water absorption and filler degree should be revisited. Especially materials with low hardness surface profiles like PEEK are more vulnerable for cleaning methods using high force and pressure ending in surface changes and mechanical fatigue (17).

This investigation examined the impact of eleven different cleaning protocols (3 individual prophylaxis, 4 laboratory cleaning and 4 professional prophylaxis) on surface roughness

(SR) and surface free energy (SFE) of PEEK and compared these results with two 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 as well as that all tested cleaning methods indicate similar surface properties.

Material and methods

The following materials were used in this study: PEEK (bioHPP, bredent, Senden, Germany), a cold-curing denture polymethylmethacrylate (PMMA) (uni.lign PF 20, bredent) and a veneering resin composite (COMP) (crea.lign, bredent). Details of the three materials are presented in Table 1.

Specimen preparation

Three hundred and thirty 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 mm x 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 into the molds of the silicone model and polymerized in a pressure pot (palamat elite, Heraeus Kulzer, Hanau, Germany) for 20 min, 4.5 bar and at 55°C according to 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 s as recommended by the manufacturer at a wavelength of 370 – 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, Ballerup, Danemark) in the following order: P1200 (3 bar) for 1 min, P4000 (3 bar) for 4 min and P4000 (5 bar) for 4 min under constant water-cooling.

Cleaning protocols

Individual prophylaxis (PPx)

A toothpaste slurry was made using toothpaste (blend-a-med complete, procter & gamble GmbH) mixed with tap water at a ratio of 1:2. The pH values was set and controlled by a pH measuring at a pH value of 7.58. The specimens were cleaned for 4 min with rotary movements. Following brushes were used:

(ST) Soft toothbrush (Dr.Best, GlaxoSmithKline, Munich, Germany).

(MT) A Medium-hard toothbrush (Dr.Best, GlaxoSmithKline).

(SOT) A sonic toothbrush (Oral-B Pulsonic, procter & gamble, Ohio, US).

In order to standardize of contact pressure and surface distance, six 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, Hilzingen, Germany): A high-performance cleaning unit for dentures and orthodontic appliances was used with 75 g of needles and 200 ml Symprofluid (Renfert) for 20 min at a rotation speed of 2.000 U/min.

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

(UB) An ultrasonic bath (USR2200, Dema, Mannheim, Germany) was filled with tap water and specimens were cleaned for 380 s.

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

Professional prophylaxis (PPx)

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

(SO) Sonicsys (KaVo Sonicflex, Biberach, Germany): An contra-angle piece (KaVo) was used for 15 s with rotary movements.

(AFC) Air Flow Comfort (EMS, Nyon, Switzerland): The powder was applied in a PROPHYflex 3 (KaVo). The supragingival sodium bicarbonate air polishing powder (40 µm), was used for 15 s 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- und 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).

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 (Mahr Perthometer SD 26, Mahr, Göttingen, Germany). Six readings with a track length of 6 mm were recorded with a distance of 0.25 mm between the lines. SR was analyzed two times: before storage in the different media and after final cleaning. Using a calibration block the performance of the profilometer was periodically controlled (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 (Kruess Easy Pearl, Kruess, Hamburg, Germany) of water (polar) and diiodomethane (dipolar) at different locations. Data were analyzed by DSA4 software (Kruess, Hamburg, Germany). The surface free energy was calculated.

Surface topography

For scanning electron microscopy (SEM), a representative PEEK specimen of each cleaning group was selected, respectively. Specimens were gold-sputtered (SC7620 Sputter Coater, Quorum technologies) and visualized (SUPRA 55VP, Carl Zeiss AG) 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 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. Non-parametric 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 for 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 (SPSSINC, Chicago, IL, USA).

Results

Kolmogorov–Smirnov test indicated violation of the assumption of normality. Therefore, non-parametric 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 3. 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 (Table 3).

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). By comparison of the cleaning methods, PS, UB and SO showed significantly lower SFE than specimens cleaned using SS, ST and SY. In general, cleaning using SY lead to the highest SFE (Table 4).

Figure 3 presented 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 and on the other hand by Al_2O_3 powder. But also by regarding SEM of AFC and AFP surface impressions are clearly remarkable.

Discussion

The fact that there are currently no reliable data existing regarding the cleaning methods of PEEK and their impact on surface properties like SR and SFE legitimated the present study. Each intraoral inserted dental restoration material is subjected to wear and biofilm formation. It depends on the initial quality regarding polished surface and material properties of a given restoration and the patients` compliance how fast plaque is developing. Patients are usually brushing their teeth twice a day using a toothpaste. Thus, they are thought to be able to reduce the newly built plaque to a minimum. Numerous studies examined differences between manual and electric toothbrushes. Zimmer et co-workers showed that after a period of eight weeks plaque (PI) and gingivitis (PBI) could be significantly reduced by the use of sonic toothbrushes compared with the manual ones (18). On the other hand it could be shown that the use of electric toothbrushes leads to significantly higher abrasion of enamel than brushing with manual toothbrushes (19). Particularly patients with a high consumption of erosive foods or acid indigestion should waive using electric cleaning devices. Concerning individual prophylaxis protocols there are no significant differences in surface roughness between manual and electric brushing even if SR values of sonic toothbrushes showed higher SR values. Because of the short investigation period it is difficult to say, whether SR values of power devices develop proportionally to the period of prohibition or not. Therefore, additional studies have to follow giving clear guidelines and clarifying the question why SFE is in opposite direction to SR values.

Within laboratory protocols there are following features 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 conditioning of restoration materials for reaching a high bonding strength (20). High-sharped corundum particles are accelerated and hit the material surface, where they cause a release of energy. Dents formed like grain impacts could be shown on the surfaces of cleaned PEEK specimens. According to this, surface roughening is higher than using wet cleaning methods, which affect material surfaces not directly. In the latter case, water or liquid are serving as protective barrier helping prevent deep scratches and notches. Sympro cleaning method contains needles beside cleaning liquid whereas SunSparkle and ultrasonic bath require no additional cleaning devices. Regarding surfaces of treated PEEK specimens needle-shaped dents could be found in SEM. A final look at the professional prophylaxis protocols reveals that using AFC leads to significantly higher SR values than the other cleaning ones. The average grain size of AFC is 40 µm and according to manufacturer information suitable exclusively for supra-gingival application. In this way, periodontal damages should be avoided. To allow a subgingival application, manufacturer reduced average grain size on 14 µm (AFP). Thus, SR values could be significantly decreased, but are nevertheless higher comparable to the other chairside methods. This SR increasing effect of prophylactic powders on the enamel could also be observed in another study (21). Analyzing SEM in the present study gives credence to this hypothesis. Furthermore, remaining and attaching bicarbonate particles could be found on specimens` surface what could be confirmed in the study of Eliades et al (22). It has not yet definitely determined if the resting bicarbonate influences surfaces negatively or acts antibacterial by neutralization of bacterial metabolism products. Using sodium bicarbonate as ingredient of toothpastes showed positive clinical results regarding 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 and today`s clinical standard preventing the enumerated problems.

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 could be shown by Zafar and co-workers (24). In conclusion and over all the highest changes in SR could be detected in AFC, AP and AFP what can be explained with surface roughening by used grains 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 material surface by its increase what 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 could confirm 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. What exactly are the unique ingredients of SunSparkle cleaning system powder is company secret. It may be concluded that used liquid combined with vibrations cause surface changes in terms of SFE increase.

A noteworthy aspect is the patients usually use individual prophylaxis devices twice a day for an average time od 2-4 minutes, whereas professional prophylaxis is applied one up to four times per year. Therefore, it can be assumed that the post-cleaning 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 could be achieved in different studies (26). Quyrinen et al. could show that surfaces with lower SFE values accumulate less bacterial colonies than high-energy ones (14) what could be confirmed in further studies (27). Therefore it can be concluded that use of cleaning methods strongly impacting surface properties e.g. 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. Therefore, further studies have to follow evaluating the cleaning efficacy of different methods and a proper balance needs to be struck between surface roughening and removing plaque and discolorations.

Conclusion

Within the limitations of this in vitro study, we conclude that PEEK showed lower SFE values compared to COMP and in this way lower biofilm formation (27). Concerning individual prophylaxis methods, all tested toothbrushes could be recommended dependent on patients` intraoral starting conditions e.g. tooth abrasion. According to laboratory protocols, Al_2O_3 powder should be avoided causing 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.

Conflict of interest

The authors declare no conflict of interest.

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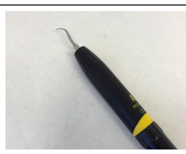
Tables

Table I – Summary of used products, compositions and manufacturer.

Abbrev.	Material	Composition	Manufacturer (LotNo.)
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)

Table II – Manufacturers and cleaning products used.

	Abbrev.		Cleaning method
Individual PPx	ST		Soft toothbrush (Dr.Best, GlaxoSmithKline, Munich, Germany) Duration: 4 min
	MT		Medium-hard toothbrush (Dr.Best, GlaxoSmithKline, Munich, Germany) Duration: 4 min
	SOT		Sonic toothbrush (Oral-B Pulsonic, procter & gamble, Ohio, US) Duration: 4 min
Laboratory protocols	SY		Sympro (Renfert, Hilzingen, Germany): 75 g needles, 200 ml fluid Duration: 20 min, 2000 U/min
	SS		SunSparkle (Sun Dental Laboratories, Düsseldorf, Germany): tap water, half a teaspoon of cleaning powder Duration: 15 min
	UB		Ultrasonic bath (Dema, Mannheim, Germany): tap water Duration: 380 s
	AP		Al_2O_3 (Renfert, Hilzingen, Germany): 50 µm, Distance: 4 mm Duration: 15 s
Professional PPx	PS		Perio-Soft Scaler (Kerr, Karlsruhe, Germany) Duration: 15 s
	SO		Sonicsys (KaVo, Biberach, Germany) Duration: 15 s

	AFC		Air Flow Comfort (EMS, Nyon, Switzerland): 40 µm, Distance: 4mm Duration: 15 s
	AFP		Air Flow Plus (EMS, Nyon, Switzerland): 14 µm, Distance: 4mm Duration: 15 s

Table III - Overview of median, minimum and maximum SR/ΔSR values after different cleaning procedures divided into the different materials (PEEK, PMMA, COMP). Median SR and ΔSR values are listed in µm.

	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.

Table IV - Median, minimum and maximum SFE values after different cleaning protocols. Median SFE values are measured in J/m^2.

	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.

Figures and Tables

Table I - Summary of used products, compositions and manufacturer.

Table II - Manufacturers and cleaning products used.

Table III - Overview of median, minimum and maximum SR/ΔSR values after different cleaning procedures divided into the different materials (PEEK, PMMA, COMP). Median SR and ΔSR values are listed in μm.

Table IV - Median, minimum and maximum SFE values after different cleaning protocols. Median SFE values are measured in J/m^2.

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

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

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