Effects of various chair-side surface treatment methods on dental restorative materials with respect to contact angles and surface roughness

Candida R.C. STURZ1, Franz-Josef FABER2, Martin SCHEER1,3, Daniel ROTHAMEL1 and Jörg NEUGEBAUER1,4

1 Interdisciplinary Department of Oral Surgery and Implantology, Department of Craniomaxillofacial and Plastic Surgery, University Cologne, Kerpener Str. 60, 50939 Köln, Germany
2 Pre-clinical Departmen of Dental Center, Cologne University, Kerpener Str. 32, 50939 Köln, Germany
3 Department of Craniomaxillofacial and Plastic Surgery, Johannes Wesling Klinikum Minden, Hans-Nolte-Straße 1, 32429 Minden, Germany
4 Praxis für Zahnhelkkunde, Dres. Bayer, Kistler und Elbertzhagen, Von-Kühlmannstr. 1, 86899 Landsberg am Lech, Germany

Corresponding author, Jörg NEUGEBAUER; E-mail: joerg.neugebauer@zahnarzt-rhein-neckar.de; jn@omniplant.de

Available chair-side surface treatment methods may adversely affect prosthetic materials and promote plaque accumulation. This study investigated the effects of treatment procedures on three resin restorative materials, zirconium-dioxide and polyetheretherketone in terms of surface roughness and hydrophobicity. Treatments were grinding with silicon carbide paper or white Arkansas stone, blasting with prophylaxis powder and polishing with diamond paste. Surface roughness was assessed using confocal laser scanning. Hydrophobicity as measured by water contact angle was determined by computerized image analysis using the sessile drop technique. All of the specific surface treatments performed led to significant changes in contact angle values and surface roughness (Ra) values. Median contact angle values ranged from 51.6° to 114°. Ra values ranged from 0.008 µm to 2.917 µm. Air-polishing as well as other polishing procedures increased surface roughness values in all materials except zirconium dioxide. Polyetheretherketone displayed greatest change in contact angle values after air-polishing treatment.

Keywords: Plaque, Inorganic fillers, Polyether ether ketone, Contact angle, Air-polish

INTRODUCTION

In recent years, there has been growing interest in the use of dental resin composites as direct restorative materials in clinical dentistry1-3. The mechanical and physical properties of composites made up of a resin matrix and filler materials have been improved4-6. The application of tooth-colored restorations has greatly increased due to aesthetic demands.

Polyether ether ketone (PEEK) is an advanced biocompatible material used in the field of restorative and prosthetic dentistry that features a natural tooth-colored appearance8. As a result of the trend towards fixed full-arch restorations on a reduced number of implants, a stable framework and different dental resin materials for customized veneering are indispensable9. The application of tooth-colored restorations has greatly increased due to aesthetic demands.

Polyether ether ketone (PEEK) is an advanced biocompatible material used in the field of restorative and prosthetic dentistry that features a natural tooth-colored appearance8. As a result of the trend towards fixed full-arch restorations on a reduced number of implants, a stable framework and different dental resin materials for customized veneering are indispensable9. The application of tooth-colored restorations has greatly increased due to aesthetic demands.

However, plaque accumulation under and around restorations is still a common problem and the main reason for the alteration and replacement of direct restorations1,2,8,9. Especially in the field of prosthetic dentistry, the control and removal of plaque deposits and subsequent polishing seems to be essential for the longevity of restorations. Air-polishing devices (APDs) have become an effective tool for plaque control and are applied routinely in professional dental cleaning10-14. However, adverse effects of APDs on dental restorative materials have been reported. Previous studies have found that the use of APDs increases surface roughness and leads to alteration of the surface integrity of restorative materials15-19. The adhesion of oral microorganisms is also significantly influenced by various substratum properties. Surface roughness of intraoral dental materials seems to be of great clinical importance in terms of bacterial retention, and changes in surface roughness might facilitate the prevention of caries, gingivitis, periodontitis, peri-implantitis and stomatitis. Rough surfaces provide opportunities for bacterial adhesion by increasing the surface area 20-25). In addition, Candida albicans adhesion is enhanced if the roughness of the biomaterial is increased, and this biofilm has been shown to potentially initiate inflammatory diseases of the oral mucosa26). Low roughness and low energy surfaces have been proven to be fundamental properties of restorative materials for reducing bioadhesion in the oral cavity24,25,27,28). Furthermore, surface free energy (SFE), electrical properties and hydrophobicity of the substratum affect the accumulation of biofilm29,30). According to Combe et al., SFE is not desirable if plaque resistance is needed, and restorative materials with low SFE are more likely to resist plaque formation31).

Satou et al. state that the surface contact angles can be measured as an index of hydrophobicity. Their findings indicate that hydrophobic interaction plays a more important role than electrostatic interaction in the adherence of bacteria with pronounced hydrophobic

Color figures can be viewed in the online issue, which is available at J-STAGE.

Received Apr 14, 2014: Accepted Jun 8, 2015
doi:10.4012/dmj.2014-098  JOI JST.JSTAGE/dmj/2014-098
Surface properties are fundamental in dental materials as they influence plaque formation on hydrophilic and hydrophobic materials. Studies have shown that bacterial adhesion is greater on hydrophobic substrates compared to hydrophilic ones. For example, dental plaque formation is greater on rough surfaces compared to smooth ones. Moreover, bacterial adhesion is influenced by the type of dental restorative material. Materials with higher hydrophobicity tend to reduce bacterial adhesion.

In the current study, we hypothesized that the use of different surface treatment methods could affect bacterial adhesion. The study aimed to investigate the impact of various surface treatments on bacterial adherence and biofilm formation. The materials tested ranged across different classes, including inorganic filled polymethyl methacrylate (PMMA-DMA), an inorganic filled polyether ether ketone (PEEK-IOF) and a zirconium dioxide (ZrO) samples.

**MATERIALS AND METHODS**

In total, 160 specimens were investigated. The materials tested included inorganic filled polymethyl methacrylate (PMMA-DMA), an inorganic filled polyether ether ketone (PEEK-IOF), and a zirconium dioxide (ZrO) samples. These materials were tested in three groups:

- **Group 1:** Paper-grinded Surface was ground with 1000 grit silicon carbide paper (Buehler), performing a one-way, straight-line motion.
- **Group 2:** Stone-grinded Surface was equally ground with a cylindrical white Arkansas stone (4 mm diameter, Meisinger, Hafer & Germany) in order to achieve a similar degree of surface roughness.

The specimens were subjected to different surface treatments. Confocal laser scanning and contact angle measurements were performed on all samples prior to further surface treatment. After preparation, the specimens were ultrasonically cleansed with isopropanol (70%) for 15 min to remove any embedded grinding material and washed twice in sterile distilled water before air drying according to the manufacturers instructions of the contact angle measuring device. The specimens were then manually polished using 1000 grit silicon carbide paper (Buehler, Dusseldorf, Germany) in order to achieve a similar degree of surface roughness in all specimens. This was done to reduce possible surface roughness effects, so that the differences in subsequent measurements after modification of the surface would only result from the properties and composition of the specific materials and could be clearly evaluated. Baseline confocal laser scanning measurements and contact angle determination were obtained on all samples prior to further surface treatment.

After preparation, the specimens were ultrasonically cleansed with isopropanol (70%) for 15 min to remove any embedded grinding material and washed twice in sterile distilled water before air drying according to the manufacturers instructions of the contact angle measuring device. The specimens were then manually polished using 1000 grit silicon carbide paper (Buehler, Dusseldorf, Germany) in order to achieve a similar degree of surface roughness. Baseline confocal laser scanning measurements and contact angle determination were obtained on all samples prior to further surface treatment.

**Treatment modalities**

Ten specimens of each group were subjected to each treatment modality. The selected surface treatments were analogous to those routinely applied in laboratory and clinical settings in chair-side dentistry. Sixty contact angle measurements and 10 confocal laser scanning measurements were performed within each group of 10 specimens. The same cleaning and drying procedures were again applied prior to further confocal laser scanning examinations and contact angle measurements.
Table 1  Materials assessed in this study

| Abbreviation | Material | Lot #   | Brand name | Filler                          | Content of fillers |
|--------------|----------|---------|------------|---------------------------------|-------------------|
| PEEK-IOF     | PEEK     | 379805  | BioHPP     | inorganic ceramics and metal oxides | <30%              |
| PMMA-noF     | PMMA, MMA, EGDMA | 374873 | Breformance | No fillers                      | No fillers        |
| DMA-nano     | Bis-GMA, UDMA and aliphatic Dimethacrylate resins | 123765 | CreaLign   | inorganic ceramic fillers        | ~50%              |
| PMMA-DMA     | High molecular PMMA und Dimethacrylate | 3.1/120609 | NovoLign | inorganic ceramic fillers        | <10%              |
| ZrO          | Yttriumoxide, partially stabilized isostatically pressed ZrO₂ | 378421 | Brezirkon  | Alumina                         | 0.2–0.5%          |

Group 3: Air-polished Surface was air-polished with sodium bicarbonate prophylaxis powder (Air Flow Classic, EMS, Nyon, Switzerland, batch # 1210051) using a standard air-polishing unit (EMS handy). The application time was 10 s at an approximate distance of 5 mm. The working pressure was kept at 60 psi. The mean particle size of the sodium bicarbonate particles ejected was 65 µm. The nozzle of the instrument was kept at a 45 degree angle to the specimen surface, and a constant straight line motion was performed. To ensure maximum reproducibility, the instrument powder chamber was refilled after each air-polishing period.

Group 4: High polished Surface was polished to high gloss with a 1 µm diamond paste (ZirPolish, Bredent, Senden, Germany, Ref. # 36010025) using a cotton buff.

All surface treatments were performed by the same trained operator to achieve a homogenous surface.

Surface roughness analysis
Surface roughness and surface area were determined on the prepared surfaces using a confocal laser scanning microscope (µsurf explorer, NanoFocus, Oberhausen, Germany). Analysis was performed on all test objects using the µsoft analysis premium program (NanoFocus), and an area of 320×320 µm was measured on each surface. In this context, roughness does not refer to macroscopic grooves and pits, which might be present on the materials tested, but to microscopic irregularities in the surface structure. To describe the surface structure numerically, Ra, Rz and Sa were used.

Sa gives a three-dimensional description of the arithmetic height deviation from a mean plane and is the parameter corresponding to the two-dimensional parameter Ra, describing the average surface roughness by reading the maximum peak to valley heights of a certain surface profile22. Rz describes the mean roughness depth and is calculated by measuring the vertical distance from the highest peak to the lowest valley within five sampling lengths and then averaging these distances.

Contact angle measurement
The contact angle reflects the interactions of fluids with solid surfaces, which depends on the polarity, hydrophobicity and wettability of the involved components27,58. The hydrophobicity of all test and reference materials was evaluated by measuring water contact angles. The computerized contact angle system EasyDrop DSA 100 (Krüss, Hamburg, Germany) was used in combination with Easy Drop Shape Analysis DSA1 v 1.90 software (Krüss) for image analysis and contact angle calculation. A time frame of 30 s for each measurement was recorded and evaluated. Two measurements (right and left contact angle) were carried out for each droplet. Droplets were generated manually, and contact angles were determined at 23°C using the sessile drop technique. The deionized distilled water used for the measurements was of HPLC (High Pressure Liquid Chromatography) quality (Sigma-Aldrich, St. Louis, USA, Lot # BCBH4122V). The procedure for measuring the contact angle was the same for all groups of specimens and was performed by the same trained operator.

Statistical analysis
The data were analyzed by using descriptive statistics including means and standard deviations. One-way analysis of variance (ANOVA) and post hoc Bonferroni tests were used to determine differences among the material groups and obtained surface treatments. The same level of significance (α=0.05) was used throughout the study. Continuous data were summarized by using medians and interquartile ranges (25th to 75th
RESULTS

For surface roughness analysis, 310 measurements were carried out in total, providing 930 individual values for analysis from the confocal laser morphological image analysis (Figs. 1–20). Paper-grinded PMMA-DMA displayed the lowest Ra value (0.008 µm±0.0025), whereas air-polished PMMA-noF displayed the highest Ra value (2.917 µm±0.4709). The arithmetic means and standard deviations of the surface roughness values (Ra) for the five materials tested, treated with different surface procedures, are reported in Table 2. The results demonstrate a significant increase in surface roughness after polishing procedures in all groups except for the ZrO group, which displayed a significant reduction in surface roughness. PMMA-noF samples and PMMA-DMA samples displayed a highly significant (p<0.001 one-way ANOVA) change in surface roughness (Ra values) after exposure to APD (Figs. 21–24). The highest Sa values were recorded for PMMA-noF samples after APD application (6.197 µm±0.9268). The summary of the ANOVA for surface roughness measurements is presented in Tables 3 and 4. Statistical analysis of the data indicated significant differences in surface roughness between the groups of restoratives (p< 0.001) and the surface treatments (p<0.001).

Table 3a shows differences in surface treatment methods (Ra) within the groups. Post hoc Bonferroni test results for Ra, Rz and Sa are displayed in Tables 4a–c.

For the determination of hydrophobicity, 1,210 measurements were carried out in total, providing 3,630 individual values for analysis. The median values from percentile). Calculations were done using statistical software SPSS 23.0 for Windows (SPSS, Chicago, IL, USA).
Fig. 5  Confocal laser scanning image of a paper-grinded ZrO sample (Ra value 0.0307 μm).

Fig. 6  Confocal laser scanning image of a stone-grinded PEEK-IOF sample (Ra value 0.378 μm).

Fig. 7  Confocal laser scanning image of a stone-grinded PMMA-noF sample (Ra value 2.41 μm).

Fig. 8  Confocal laser scanning image of a stone-grinded DMA-nano sample (Ra value 0.248 μm).

Fig. 9  Confocal laser scanning image of a stone-grinded PMMA-DMA sample (Ra value 0.578 μm).

Fig. 10  Confocal laser scanning image of a stone-grinded ZrO sample (Ra value 0.077 μm).
Fig. 11 Confocal laser scanning image of an air-polished PEEK-IOF sample (Ra value 0.995 µm).

Fig. 12 Confocal laser scanning image of an air-polished PMMA-noF sample (Ra value 3.4 µm).

Fig. 13 Confocal laser scanning image of an air-polished DMA-nano sample (Ra value 0.376 µm).

Fig. 14 Confocal laser scanning image of an air-polished PMMA-DMA sample (Ra value 0.562 µm).

Fig. 15 Confocal laser scanning image of an air-polished ZrO sample (Ra value 0.059 µm).

Fig. 16 Confocal laser scanning image of a high-polished PEEK-IOF sample (Ra value 0.065 µm).
Fig. 17 Confocal laser scanning image of a high-polished PMMA-noF sample (Ra value 1.49 µm).

Fig. 18 Confocal laser scanning image of a high-polished DMA-nano sample (Ra value 0.045 µm).

Fig. 19 Confocal laser scanning image of a high-polished PMMA-DMA sample (Ra value 0.042 µm).

Fig. 20 Confocal laser scanning image of a high-polished ZrO sample (Ra value 0.017 µm).

Fig. 21 Surface roughness of the five tested materials after paper grinding.

Fig. 22 Surface roughness of the five tested materials after stone grinding.
Fig. 23 Surface roughness of the five tested materials after APD treatment.

Fig. 24 Surface roughness of the five tested materials after high polishing.

Table 2 Surface roughness values (µm), mean ± standard deviations

| Material   | Surface treatment | Ra mean | SD  | Rz mean | SD  | Sa mean | SD  |
|------------|-------------------|---------|-----|---------|-----|---------|-----|
| PEEK-IOF   | Paper-grinded     | 0.277   | 0.0664 | 1.589   | 0.2957 | 0.547   | 0.1023 |
|            | Stone-grinded     | 0.364   | 0.0657 | 1.959   | 0.1854 | 1.114   | 0.1356 |
|            | Air-polished      | 0.952   | 0.1359 | 5.613   | 0.2558 | 1.505   | 0.1705 |
|            | High-polished     | 0.073   | 0.0128 | 0.501   | 0.0448 | 0.148   | 0.0384 |
| PMMA-noF   | Paper-grinded     | 0.703   | 0.2867 | 4.003   | 1.3486 | 4.743   | 1.0355 |
|            | Stone-grinded     | 2.567   | 0.4929 | 13.050  | 0.9857 | 5.103   | 0.7687 |
|            | Air-polished      | 2.917   | 0.4709 | 13.930  | 1.1547 | 6.197   | 0.9268 |
|            | High-polished     | 1.260   | 0.3529 | 6.733   | 0.7229 | 3.303   | 0.6909 |
| DMA-nano   | Paper-grinded     | 0.236   | 0.0727 | 1.349   | 0.3917 | 0.357   | 0.0712 |
|            | Stone-grinded     | 0.218   | 0.0588 | 1.261   | 0.2709 | 0.907   | 0.2020 |
|            | Air-polished      | 0.405   | 0.0742 | 2.249   | 0.1588 | 0.632   | 0.1852 |
|            | High-polished     | 0.399   | 0.0038 | 0.245   | 0.0243 | 0.108   | 0.0585 |
| PMMA-DMA   | Paper-grinded     | 0.008   | 0.0025 | 0.800   | 0.0280 | 0.020   | 0.0070 |
|            | Stone-grinded     | 0.633   | 0.0739 | 3.543   | 0.3182 | 1.378   | 0.3055 |
|            | Air-polished      | 0.567   | 0.0725 | 3.200   | 0.1053 | 1.076   | 0.1495 |
|            | High-polished     | 0.050   | 0.0064 | 0.328   | 0.0255 | 0.075   | 0.0117 |
| ZrO        | Paper-grinded     | 0.091   | 0.0449 | 0.519   | 0.1299 | 0.097   | 0.0243 |
|            | Stone-grinded     | 0.073   | 0.0127 | 0.419   | 0.0426 | 0.106   | 0.0157 |
|            | Air-polished      | 0.076   | 0.0148 | 0.464   | 0.0954 | 0.095   | 0.0088 |
|            | High-polished     | 0.103   | 0.0036 | 0.108   | 0.0427 | 0.023   | 0.0079 |
| ZrO reference |             | 0.058   | 0.0173 | 0.352   | 0.1238 | 0.073   | 0.0179 |
Table 3  Summary of ANOVA mean roughness values Ra (µm)

| Group (Material) | Sum of squares | df* | Mean square | F** | Significance |
|------------------|----------------|-----|-------------|-----|--------------|
| **PEEK-IOF**     |                |     |             |     |              |
| Between Groups   | 4.527          | 3   | 1.509       |     | <0.001***    |
| Within Groups    | 0.335          | 56  | 0.006       | 252.513 |              |
| Total            | 4.862          | 59  |             |     |              |
| **PMMA-noF**     |                |     |             |     |              |
| Between Groups   | 51.052         | 3   | 17.017      |     | <0.001***    |
| Within Groups    | 7.690          | 56  | 0.137       | 123.928 |              |
| Total            | 58.741         | 59  |             |     |              |
| **DMA-nano**     |                |     |             |     |              |
| Between Groups   | 0.671          | 3   | 0.224       |     | <0.001***    |
| Within Groups    | 0.234          | 56  | 0.004       | 53.431 |              |
| Total            | 0.906          | 59  |             |     |              |
| **PMMA-DMA**     |                |     |             |     |              |
| Between Groups   | 4.551          | 3   | 1.517       |     | <0.001***    |
| Within Groups    | 0.097          | 56  | 0.002       | 874.641 |              |
| Total            | 4.648          | 59  |             |     |              |
| **ZrO**          |                |     |             |     |              |
| Between Groups   | 0.046          | 3   | 0.015       |     | <0.001***    |
| Within Groups    | 0.062          | 56  | 0.001       | 13.762 |              |
| Total            | 0.108          | 59  |             |     |              |

* df: degrees of freedom  
** F: Variance ratio value  
*** statistically significant

Table 3a  Post hoc Bonferroni tests for Ra

| Material     | Surface       | Surface       | Mean difference | Standard error | Significance |
|--------------|---------------|---------------|-----------------|----------------|--------------|
| Paper-grinded| Stone-grinded | −0.087        | 0.028           | 0.018*         |              |
|              | Air-polished  | −0.675        | 0.028           | 0.000*         |              |
|              | High-polished | 0.203         | 0.028           | 0.000*         |              |
| Stone-grinded| Paper-grinded | 0.087         | 0.028           | 0.018*         |              |
|              | Air-polished  | −0.587        | 0.034           | 0.000*         |              |
|              | High-polished | 0.291         | 0.034           | 0.000*         |              |
| PEEK-IOF     | Paper-grinded | 0.675         | 0.028           | 0.000*         |              |
| Air-polished | Stone-grinded | 0.587         | 0.034           | 0.000*         |              |
|              | High-polished | 0.878         | 0.034           | 0.000*         |              |
| High-polished| Paper-grinded | −0.203        | 0.028           | 0.000*         |              |

| Paper-grinded| Stone-grinded | 1.863         | 0.135           | 0.000*         |              |
|              | Air-polished  | −2.213        | 0.135           | 0.000*         |              |
|              | High-polished | −0.557        | 0.135           | 0.001*         |              |
| Stone-grinded| Paper-grinded | 1.863         | 0.135           | 0.000*         |              |
|              | Air-polished  | −0.350        | 0.165           | 0.235          |              |
|              | High-polished | 1.306         | 0.165           | 0.000*         |              |
| PMMA-noF     | Paper-grinded | 2.213         | 0.135           | 0.000*         |              |
| Air-polished | Stone-grinded | 0.350         | 0.165           | 0.235          |              |
|              | High-polished | 1.656         | 0.165           | 0.000*         |              |
| High-polished| Paper-grinded | 0.557         | 0.135           | 0.001*         |              |
|              | Stone-grinded | −1.306        | 0.165           | 0.000*         |              |
|              | Air-polished  | −1.656        | 0.165           | 0.000*         |              |
| Material   | Surface     | Surface   | Mean difference | Standard error | Significance |
|------------|-------------|-----------|-----------------|----------------|--------------|
| Paper-grinded | Stone-grinded | 0.018     | 0.023           | 1.000          |              |
|            | Air-polished | −0.168    | 0.023           | 0.000*         |              |
|            | High-polished| 0.196     | 0.023           | 0.000*         |              |
| Stone-grinded | Paper-grinded | −0.018    | 0.023           | 1.000          |              |
|            | Air-polished | −0.187    | 0.028           | 0.000*         |              |
|            | High-polished| 0.178     | 0.028           | 0.000*         |              |
| DMA-nano   | Paper-grinded | 0.168     | 0.023           | 0.000*         |              |
|            | Stone-grinded | 0.187     | 0.028           | 0.000*         |              |
|            | High-polished| 0.365     | 0.028           | 0.000*         |              |
| High-polished | Paper-grinded | −0.196    | 0.023           | 0.000*         |              |
|            | Stone-grinded | −0.178    | 0.028           | 0.000*         |              |
|            | Air-polished | −0.365    | 0.028           | 0.000*         |              |
| Paper-grinded | Stone-grinded | −0.625    | 0.015           | 0.000*         |              |
|            | Air-polished | −0.559    | 0.015           | 0.000*         |              |
|            | High-polished| −0.041    | 0.015           | 0.047*         |              |
| Stone-grinded | Paper-grinded | 0.625     | 0.015           | 0.000*         |              |
|            | Air-polished | 0.066     | 0.018           | 0.005*         |              |
|            | High-polished| 0.583     | 0.018           | 0.000*         |              |
| PMMA-DMA   | Paper-grinded | 0.559     | 0.015           | 0.000*         |              |
|            | Stone-grinded | −0.066    | 0.018           | 0.005*         |              |
|            | High-polished| 0.517     | 0.018           | 0.000*         |              |
| High-polished | Paper-grinded | 0.041     | 0.015           | 0.047*         |              |
|            | Stone-grinded | −0.583    | 0.018           | 0.000*         |              |
|            | Air-polished | −0.517    | 0.018           | 0.000*         |              |
| Stone-grinded | Paper-grinded | −0.018    | 0.012           | 0.816          |              |
|            | Air-polished | −0.002    | 0.014           | 1.000          |              |
|            | High-polished| 0.059     | 0.014           | 0.001*         |              |
| Air-polished | Paper-grinded | −0.015    | 0.012           | 1.000          |              |
|            | Stone-grinded | 0.002     | 0.014           | 1.000          |              |
|            | High-polished| 0.062     | 0.014           | 0.001*         |              |
| ZrO        | Paper-grinded | −0.078    | 0.012           | 0.000*         |              |
|            | Stone-grinded | −0.059    | 0.014           | 0.001*         |              |
|            | Air-polished | −0.062    | 0.014           | 0.001*         |              |
|            | Paper-grinded | −0.009    | 0.007           | 1.000          |              |
|            | Air-polished | 0.001     | 0.007           | 1.000          |              |
|            | High-polished| 0.073     | 0.007           | 0.000*         |              |

* statistically significant

the contact angle measurement range from 51.6° to 114° (Figs. 25–28). Air-polished ZrO samples displayed the lowest contact angle values (51.6°±1.16), whereas air-polished PMMA-noF samples displayed the highest contact angle values (114.0°±6.46).

The arithmetic means and standard deviations of the contact angle measurements for the five restorative materials tested, treated with different surface procedures, are presented in Table 5. The air-polished surface treatment revealed the highest contact angles in all groups except ZrO. Furthermore, results show a clear correlation between surface roughness values and
### Table 4  Summary of ANOVA

| Group (Roughness) | Sum of squares | df* | Mean square | F** | Significance |
|-------------------|----------------|-----|-------------|-----|--------------|
| Ra (µm)           |                |     |             |     |              |
| Between Groups    | 27.450         | 4   | 6.863       |     | <0.001***    |
| Within Groups     | 121.672        | 305 | 0.399       | 17.203 |              |
| Total             | 149.123        | 309 |             |     |              |
| Rz (µm)           |                |     |             |     |              |
| Between Groups    | 690.723        | 4   | 172.681     |     | <0.001***    |
| Within Groups     | 2879.603       | 305 | 9.441       | 18.290 |              |
| Total             | 3570.326       | 309 |             |     |              |
| Sa (µm)           |                |     |             |     |              |
| Between Groups    | 60.966         | 4   | 15.242      |     | <0.001***    |
| Within Groups     | 1015.836       | 305 | 3.331       | 4.576  |              |
| Total             | 1076.803       | 309 |             |     |              |

* df: degrees of freedom  
** F: Variance ratio value  
*** statistically significant

### Table 4a  Post hoc Bonferroni tests for Ra

| Materials | Surface | Surface | Mean difference | Standard error | Significance |
|-----------|---------|---------|-----------------|---------------|--------------|
| all       | No treatment | Paper-grinded | −0.204 | 0.206 | 1.000 |
|           |         | Stone-grinded   | −0.712 | 0.218 | 0.013* |
|           |         | Air-polished     | −0.924 | 0.218 | 0.000* |
|           |         | High-polished    | −0.228 | 0.218 | 1.000 |
| all       | Paper-grinded | No treatment    | 0.204  | 0.206 | 1.000 |
|           |         | Stone-grinded   | −0.508 | 0.103 | 0.000* |
|           |         | Air-polished     | −0.720 | 0.103 | 0.000* |
|           |         | High-polished    | −0.024 | 0.103 | 1.000 |
| all       | Stone-grinded | No treatment    | 0.712  | 0.218 | 0.130 |
|           |         | Paper-grinded   | 0.508  | 0.103 | 0.000* |
|           |         | Air-polished     | −0.212 | 0.126 | 0.940 |
|           |         | High-polished    | 0.483  | 0.126 | 0.002* |
| all       | Air-polished | No treatment    | 0.924  | 0.218 | 0.000* |
|           |         | Paper-grinded   | 0.720  | 0.103 | 0.000* |
|           |         | Stone-grinded   | 0.212  | 0.126 | 0.940 |
|           |         | High-polished    | 0.695  | 0.126 | 0.000* |
| all       | High-polished | No treatment   | 0.228  | 0.218 | 1.000 |
|           |         | Paper-grinded   | 0.024  | 0.103 | 1.000 |
|           |         | Stone-grinded   | −0.483 | 0.126 | 0.002* |
|           |         | Air-polished     | −0.695 | 0.126 | 0.000* |

* statistically significant

Contact angle values after treatment with an APD for all materials except ZrO. In contrast, however, other applied surface treatments did not display a generally conclusive association between surface roughness values and contact angle values. Polishing procedures led to a considerable increase in the contact angle values for PEEK-IOF, PMMA-noF and ZrO. Nano-filled PMMA-DMA displays lower contact angle values than nano-filled DMA-nano due to its considerably lower filler fraction. Polishing resulted in a decrease of contact angle values only for DMA-nano and PMMA-DMA.

The summary of the ANOVA for contact angle measurement is presented in Tables 6 and 7. Statistical analysis of the data with a one-way analysis of variance indicated significant differences in contact angle values between the groups of restoratives (p<0.001) and the surface treatments (p<0.001).
Table 4b  *Post hoc* Bonferroni tests for Rz

| Materials | Surface      | Surface       | Mean difference | Standard error | Significance |
|-----------|--------------|---------------|-----------------|----------------|--------------|
| all       | No treatment | Paper-grinded | −1.156          | 1.003          | 1.000        |
|           |              | Stone-grinded | −3.694          | 1.064          | 0.006*       |
|           |              | Air-polished  | −4.738          | 1.064          | 0.000*       |
|           |              | High-polished | −1.230          | 1.064          | 1.000        |
| all       | Paper-grinded| No treatment  | 1.156           | 1.003          | 1.000        |
|           |              | Stone-grinded | −2.538          | 0.501          | 0.000*       |
|           |              | Air-polished  | −3.582          | 0.501          | 0.000*       |
|           |              | High-polished | −0.074          | 0.501          | 1.000        |
| all       | Stone-grinded| No treatment  | 3.694           | 1.064          | 0.006*       |
|           |              | Paper-grinded | 2.538           | 0.501          | 0.000*       |
|           |              | Air-polished  | −1.044          | 0.614          | 0.902        |
|           |              | High-polished | 2.463           | 0.614          | 0.001*       |
| all       | Air-polished | No treatment  | 4.738           | 1.064          | 0.000*       |
|           |              | Paper-grinded | 3.582           | 0.501          | 0.000*       |
|           |              | Stone-grinded | 1.044           | 0.614          | 0.902        |
|           |              | High-polished | 3.507           | 0.614          | 0.000*       |
| all       | High-polished| No treatment  | 1.230           | 1.064          | 1.000        |
|           |              | Paper-grinded | 0.074           | 0.501          | 1.000        |
|           |              | Stone-grinded | −2.463          | 0.614          | 0.001*       |
|           |              | Air-polished  | −3.507          | 0.614          | 0.000*       |

* statistically significant

Table 4c  *Post hoc* Bonferroni tests for Sa

| Materials | Surface      | Surface       | Mean difference | Standard error | Significance |
|-----------|--------------|---------------|-----------------|----------------|--------------|
| all       | No treatment | Paper-grinded | −1.079          | 0.596          | 0.711        |
|           |              | Stone-grinded | −1.648          | 0.632          | 0.096        |
|           |              | Air-polished  | −1.827          | 0.632          | 0.041*       |
|           |              | High-polished | −0.657          | 0.632          | 1.000        |
| all       | Paper-grinded| No treatment  | 1.079           | 0.596          | 0.711        |
|           |              | Stone-grinded | 0.568           | 0.298          | 0.573        |
|           |              | Air-polished  | 0.747           | 0.298          | 0.126        |
|           |              | High-polished | 0.421           | 0.298          | 1.000        |
| all       | Stone-grinded| No treatment  | 1.648           | 0.632          | 0.096        |
|           |              | Paper-grinded | 0.568           | 0.298          | 0.573        |
|           |              | Air-polished  | −0.179          | 0.364          | 1.000        |
|           |              | High-polished | 0.990           | 0.364          | 0.070        |
| all       | Air-polished | No treatment  | 1.827           | 0.632          | 0.041*       |
|           |              | Paper-grinded | 0.747           | 0.298          | 0.126        |
|           |              | Stone-grinded | 0.179           | 0.364          | 1.000        |
|           |              | High-polished | 1.169           | 0.364          | 0.015*       |
| all       | High-polished| No treatment  | 0.657           | 0.632          | 1.000        |
|           |              | Paper-grinded | −0.421          | 0.298          | 1.000        |
|           |              | Stone-grinded | −0.990          | 0.364          | 0.070        |
|           |              | Air-polished  | −1.169          | 0.364          | 0.015*       |

* statistically significant
Table 5  Contact angle values (°), mean ± standard deviations

| Material   | Surface treatment  | Mean  | SD   |
|------------|--------------------|-------|------|
| PEEK-IOF   | Paper-grinded      | 70.8  | 5.85 |
|            | Stone-grinded      | 70.2  | 3.35 |
|            | Air-polished       | 114.0 | 6.46 |
|            | High-polished      | 79.4  | 3.57 |
| PMMA-noF   | Paper-grinded      | 90.7  | 4.29 |
|            | Stone-grinded      | 90.0  | 4.90 |
|            | Air-polished       | 98.6  | 3.91 |
|            | High-polished      | 91.5  | 3.46 |
| DMA-nano   | Paper-grinded      | 76.9  | 4.01 |
|            | Stone-grinded      | 65.0  | 2.16 |
|            | Air-polished       | 77.9  | 4.10 |
|            | High-polished      | 69.1  | 4.13 |
Table 5  continued

| Material       | Surface treatment | Mean | SD   |
|----------------|-------------------|------|------|
| PMMA-DMA       | Paper-grinded     | 73.8 | 2.65 |
|                | Stone-grinded     | 73.9 | 2.47 |
|                | Air-polished      | 86.3 | 4.96 |
|                | High-polished     | 71.9 | 1.55 |
| ZrO            | Paper-grinded     | 55.0 | 2.70 |
|                | Stone-grinded     | 54.2 | 2.45 |
|                | Air-polished      | 51.6 | 1.61 |
|                | High-polished     | 75.0 | 2.63 |
| ZrO reference  |                   | 94.2 | 1.18 |

Table 6  Summary of ANOVA mean contact angles

| Group (surface treatment) | Sum of squares | df* | Mean square | F** | Significance |
|--------------------------|----------------|-----|-------------|-----|--------------|
| 1                        | Between groups | 39,321.631 | 4  | 9,830.408  | <0.001***|
|                          | Within groups  | 4,912.121  | 295| 16.651     | 590.370    |
|                          | Total          | 44,233.752 | 299|            | <0.001***  |
| 2                        | Between groups | 41,393.544 | 4  | 10,348.386 | <0.001***  |
|                          | Within groups  | 3,077.460  | 295| 10.432     | 991.979    |
|                          | Total          | 44,471.004 | 299|            | <0.001***  |
| 3                        | Between groups | 131,648.269| 4  | 32,912.067 | <0.001***  |
|                          | Within groups  | 5,971.336  | 295| 20.242     | 1,625.944  |
|                          | Total          | 137,619.605| 299|            | <0.001***  |
| 4                        | Between groups | 21,155.056 | 5  | 4,231.011  | <0.001***  |
|                          | Within groups  | 3,088.784  | 304| 9.996      | 423.270    |
|                          | Total          | 24,193.840 | 309|            | <0.001***  |

* df: degrees of freedom
** F: Variance ratio value
*** statistically significant

Table 7  Summary of ANOVA mean contact angles

| Group (material) | Sum of squares | df* | Mean square | F** | Significance |
|------------------|----------------|-----|-------------|-----|--------------|
| PEEK-IOF         | Between groups | 77,210.926 | 3  | 25,736.975 | <0.001***  |
|                  | Within groups  | 5,912.516  | 236| 25.053     | 1,027.300  |
|                  | Total          | 83,123.442 | 239|            | <0.001***  |
| PMMA-noF         | Between groups | 2,888.147  | 3  | 962.716    | <0.001***  |
|                  | Within groups  | 4,117.014  | 236| 17.445     | 55.186     |
|                  | Total          | 7,005.161  | 239|            | <0.001***  |
| DMA-nano         | Between groups | 7,042.344  | 3  | 2,347.448  | <0.001***  |
|                  | Within groups  | 3,234.215  | 236| 13.704     | 171.293    |
|                  | Total          | 10,276.560 | 239|            | <0.001***  |
| PMMA-DMA         | Between groups | 7,946.808  | 3  | 2,648.936  | <0.001***  |
|                  | Within groups  | 2,370.979  | 236| 10.047     | 263.667    |
|                  | Total          | 10,317.787 | 239|            | <0.001***  |
| ZrO              | Between groups | 20,960.043 | 3  | 6,986.681  | <0.001***  |
|                  | Within groups  | 1,352.253  | 236| 5.730      | 1,219.340  |
|                  | Total          | 22,312.296 | 239|            | <0.001***  |

* df: degrees of freedom
** F: Variance ratio value
*** statistically significant
DISCUSSION

Dental restorative materials are regarded as artificial predilection sites for the adherence and accumulation of oral microorganisms. Various studies have been carried out with a focus on bacterial adherence on materials used in conservative dentistry, but few studies have been conducted on resin restorative materials used in prosthodontics. Thus, this study was carried out to assess chair-side surface treatment methods of prosthodontically used resin restorative materials by relating possible differences to surface roughness, hydrophobicity and type of matrix.

In the present study, differences in contact angle values and surface roughness values after specific surface treatment did not follow a clear pattern, suggesting that the chemistry of the material itself with respect to differences in matrix composition and filler fraction plays a decisive role. These results are supported by previous studies showing that surface roughness as well as composition of the resin composites (filler size and matrix monomer) influence biofilm formation.

Filled resins (composites) and particularly DMA (organic composites) display several features. The fillers are functionalized differently, either silanized or without functionalization as in thermoplasts, partly also mixed with additives. Those additives are supposed to prevent the agglomeration in the resin during the manufacturing and subsequent processing. This implicates that the mere presence of ceramic or anorganic fillers (displayed by the filler fraction) on the surface is not unequivocally and does therefore not necessarily lead to a conclusive prognosis of the materials hydrophilic or hydrophobic properties. The reason for this is that abrasive surface or compacted surface treatment methods also expose the components differently, respectively only lead to changes in surface structure. Therefore the investigations of different surface treatment methods under lab-technical and clinical conditions are useful. PEEK-IOF is a filled thermoplastic and hence likewise inhomogenous in regard to the properties. Pure cold-curing resins, being low molecular, not filled and cross-linked, display a rather consistent contact angle, but do react with significant changes of surface roughness. PMMA is known to be hardly susceptible to plaque which confirms these theorems. PMMA-DMA composites, being low filled (<10% nanoscale), higher molecular and more net-worked with DMA, displays a significantly better surface stability and provides relatively constant contact angles (<90 / >75). DMA-nano, having a 50% filler fraction (0.05 μm) provides the most constant results with respect to the contact angles, despite different surface roughness. PEEK as a thermoplastic with a filler fraction of <30% and a 0.5 μm medium particle size responds noticeably inhomogenous to the surface treatment with respect to the contact angles, however not as pronounced as PMMA responds to the surface roughness. Changes in contact angles could therefore either result from the polymer (aromatic structure) and/or result from the inhomogenous surface which is caused by the fillers.

Moreover, it has been demonstrated that the physicochemical characteristics of the specific substratum affect the quality of the bacterial adhesion to the surface of the material, but the influence of surface roughness and hydrophobicity is considered dominant in this regard. In contrast, other studies found no relationship between surface roughness values and bacterial adhesion. Those studies attribute firm bacterial adhesion to filler particles of the composite resin surfaces but also to electrical interactions between bacteria and the material surfaces.

Noting that some materials are more plaque-prone than others, Nassar et al. clearly emphasize that the degree of hydrophobicity alone is not a useful discriminant for dental plaque build-up. Their findings indicate that plaque adherence to prosthetic materials depends more directly on the value of the surface free energy of the material than on its relative wettability by water solutions. Within the limitations of the present study, contact angle measurements could therefore only serve as an indication of surface free energy changes. According to Glantz, acrylic resin has a low specific surface energy. However, more plaque was found to adhere in clinical studies. This could be explained by the acrylic resins’ highly porous nature, causing liquid absorption and enabling adhesive forces to rise. In consequence, a greater amount of plaque adheres to this surface than could possibly result from the low values of surface free energy alone. Moreover, smooth low-energy surfaces have shown to attract less plaque than smooth intermediate-energy surfaces. In addition, several studies have been conducted concerning the effect of surface hydrophobicity on bacterial adhesion, supplying evidence that hydrophobic bacteria adhere much more readily to hydrophobic supports, while hydrophilic bacteria display less adhesion to hydrophobic supports. As hydrophobicity can be used as a discriminating to predict bacterial adhesion, the results of the present study have shown that selected chair-side surface treatments do have a significant (p<0.001) impact on substratum hydrophobicity values. Changes in hydrophobic properties can thus be explained by the physicochemical composition of the material.

Furthermore, Bollen et al. clearly state that preferential bacterial retention occurs on rough surfaces since bacteria on such surfaces are better protected against shear forces. These results are confirmed by other investigators who state that increasing surface roughness not only increases plaque retention but also leads to plaque adhering much more rapidly and in larger quantities. Comparing all influencing factors, several studies concluded that surface roughness plays the most important role in initial bacterial adhesion and the influence of surface roughness exceeds the influence of surface free energy. It is thus more prone to accumulate biofilms. They point out that polishing leads to an increased polar and notably basic contribution to the total surface free energy for the
composite resin, whereas unpolished composite resin is weakly basic with a small polar (acid-base) contribution to the total surface free energy.62

Other investigators state that polished composite surfaces supported larger amounts of plaque due to the loss of superficial filler particles during the polishing process.4,25,30,32 These observations contradict those of other authors who found that surface polishing of composite materials rendered the materials more plaque resistant and that the procedure was important to reduce bacterial accumulation.8,37,40 The use of air-polishing devices in oral hygiene and periodontal therapy has proven to be a very effective means in rapidly removing stains and dental plaque. However, numerous studies have shown that air-polishing instrumentation can potentially remove considerable amounts of resins from restorative material13,14, due to the low wear resistance of the resinous matrix material16,18,19. In line with these findings, the present study found significant increases (p<0.001) in surface roughness values (Ra) after APD surface treatment for all tested materials (except ZrO2). An accumulation of agglomerated bicarbonate particles of the jet stream has been found within the filler-matrix interface after air-polishing instrumentation10. It could therefore be assumed that embedded bicarbonate particles may also affect the material surface texture to the extent that the physicochemical surface properties of the material are being masked.

In the present study, PMMA-nof exhibited by far the greatest increase in surface roughness values (Ra) after APD treatment. Its relatively low wear-resistance and agglomeration of bicarbonate particles could account for these results. Furthermore, other studies observed staining and pitting on porcelain surfaces.15,16 The results of the present study confirm earlier work indicating that the use of an air-polishing device on resinous restorative materials leads to a significant increase in surface roughness.12,14,15 Treated surfaces may subsequently become more plaque-retentive, and the use of an APD around the treated restorations should therefore be avoided.

As adhering bacteria play a crucial role in the development of infectious diseases, a low susceptibility of restorative materials to microorganism adherence is of major interest.

According to our results, the hypothesis that the use of different surface treatment methods does have a significant impact on the properties of the materials that were tested could not be rejected. For clinical use different dental resin materials for customized veneering and coating have shown to be indispensable.

The findings of the present investigation indicate that supplementary studies on adsorption patterns and the distribution of adhering bacterial strains by means of fluorescence imaging are necessary to permit drawing conclusions about substratum surface properties and bacterial adsorption.

CONCLUSION

Within the limitations of this study, significant differences were found between the chair-side surface treatment procedures applied on dental restoratives used in prosthetic dentistry. However, no general correlation could be found between changes in surface hydrophobicity and surface roughness values. Air-polishing treatment and polishing procedures with Zirpolish paste resulted in higher surface roughness for all materials except zirconium dioxide. This treatment may facilitate microbial retention and infection. Polyether ether ketone (PEEK-IOP) displayed the greatest change (increase) in contact angle values after air-polishing treatment. However, this effect can be prevented by veneering PEEK-IOP with DMA-nano components. Nevertheless, the use of an air-polishing device around these materials should be considered carefully.

ACKNOWLEDGMENT

This study was supported by the faculty of dental medicine, Cologne, Germany. We are indebted to Bredent Medical, Senden, Germany, for providing the test materials free of charge. The support of the company’s chemical laboratory was greatly appreciated. We are grateful for the assistance of Implant Dental Consult, Landsberg, Germany. The authors declare that they do not have any conflicts of interest.

REFERENCES

1) Busscher HJ, Rinaudo M, Siowomihardjo Wandvan der Mei HC. Biofilm formation on dental restorative and implant materials. J Dent Res 2010: 89: 657-665.
2) Buergers R, Schneider-Bracht W, Hahnel S, Rosenritt MandHandel G. Streptococcal adhesion to novel low-shrink silorane-based restorative. Dent Mater 2009: 25: 269-275.
3) Burgers R, Cariaga T, Muller R, Rosenritt M, Reichl U, Handel G, Hahnel S. Effects of aging on surface properties and adhesion of Streptococcus mutans on various fissure sealants. Clin Oral Investig 2009: 13: 419-426.
4) Weitman RT, Eames WB. Plaque accumulation on composite surfaces after various finishing procedures. J Am Dent Assoc 1975: 91: 101-106.
5) Schmidlin PR, Stawarczyk B, Wieland M, Attin T, Hammerle CH, Fischer J. Effect of different surface pre-treatments and luting materials on shear bond strength to PEEK. Dent Mater 2010: 26: 553-559.
6) Bayer G, Kistler F, Kistler S, Sigmund F, Adler S, Neugebauer J. Versorgungsmöglichkeiten ohne Sinusbodenelevation —6 Jahre Erfahrungen. Implantologie 2012: 20: 195-204.
7) Stawarczyk B, Beuer F, Wimmer J, Jahn D, Sener B, Roos M, Schmidlin PR. Polyetheretherketone-A suitable material for fixed dental prostheses? J Biomed Mater Res B Appl Biomater 2013: 101: 1209-1216.
8) Ono M, Nidaiko T, Ikeda M, Imai S, Hanada N, Tagami J, Matin K. Surface properties of resin composite materials relative to biofilm formation. Dent Mater J 2007: 26: 613-622.
9) Lee BC, Jung GY, Kim DJ, Han JS. Initial bacterial adhesion
on resin, titanium and zirconia in vitro. J Adv Prosthodont 2011; 3: 81-84.
10) Petersilka GJ, Schenck U, Flemmig TF. Powder emission rates of four air polishing devices. J Clin Periodontol 2002; 29: 694-698.
11) Weaks LM, Lescher NB, Barnes CM, Holroyd SV. Clinical evaluation of the Prophy-Jet as an instrument for routine removal of tooth stain and plaque. J Periodontal Res 1984; 1: 486-488.
12) Giacomelli L, Salerno M, Derchi G, Genovesi A, Paganin PP, Covani U. Effect of air polishing with glycine and bicarbonate powders on a nanocomposite used in dental restorations: an in vitro study. Int J Periodontics Restorative Dent 2011; 31: e51-e56.
13) Pelka MA, Altmaier K, Petchelt A, Lobhauer U. The effect of air-polishing abrasives on wear of direct restoration materials and sealants. J Am Dent Assoc 2010; 141: 63-70.
14) Barnes CM, Hayes EF, Leinfelder KF. Effects of an airabrasive polishing system on restored surfaces. Gen Dent 1987; 35: 186-189.
15) Elades GC, Tsoutzas JG, Vougiaulkakis GJ. Surface alterations on dental restorative materials subjected to an air-powder abrasive instrument. J Prosthodont Res 1991; 5: 27-33.
16) Cooley RL, Lubow RM, Brown FH. Effect of air-powder abrasive instrument on porcelain. J Prosthodont Dent 1988; 60: 440-443.
17) Lubow RM, Cooley RL. Effect of air-powder abrasive instrument on restorative materials. J Prosthodont Res 1986; 35: 482-485.
18) Cooley RL, Lubow RM, Patrissi GA. The effect of an air-powder abrasive instrument on composite resin. J Am Dent Assoc 1986; 112: 362-364.
19) Carr MP, Mitchell JC, Seghi RR, Vermilyen SG. The effect of air polishing on contemporary esthetic restorative materials. Gen Dent 2002; 50: 238-241.
20) Bollen CM, Lambrechts P, Quirynen M. Comparison of surface roughness of oral hard materials to the threshold surface roughness for bacterial plaque retention: a review of the literature. Dent Mater 1997; 3: 258-269.
21) Lee SP, Lee SJ, Lim BS, Ahn SJ. Surface characteristics of orthodontic materials and their effects on adhesion of mutants streptococci. Angle Orthod 2009; 79: 353-360.
22) Carlen A, Nikol K, Wennerberg A, Holberg K, Olsson J. Surface characteristics and in vitro biofilm formation on glass ionomer and composite resin. Biomaterials 2001; 22: 481-487.
23) Mei L, Busscher HJ, van der Mei HC, Ren Y. Influence of surface roughness on streptococcal adhesion forces to composite resins. Dent Mater 2011; 27: 770-778.
24) Teughels W, Van Assche N, Sliepen I, Quirynen M. Effect of material characteristics and/or surface topography on biofilm development. Clin Oral Implants Res 2006; 17 Suppl 2: 68-81.
25) Nassar U, Meyer AE, Ogle RE, Baier RE. The effect of restorative and prosthetic materials on dental plaque. Periodontol 2000 1995; 8: 114-124.
26) Burgers R, Schneider-Brachert W, Rosentritt M, Handel G, Hahnel S. Candida albicans adhesion to composite resin materials. Clin Oral Investig 2009; 13: 293-299.
27) Hannig C, Hannig M. The oral cavity—a key system to understand substratum-dependent bioadhesion on solid surfaces in man. Clin Oral Investig 2009; 13: 123-139.
28) Tanner J, Robinson C, Soderling E, Vallittu P. Early plaque formation on fibre-reinforced composites in vivo. Clin Oral Investig 2005; 9: 154-160.
29) Quirynen M, Bollen CM. The influence of surface roughness and surface-free energy on supra- and subgingival plaque formation in man. A review of the literature. J Clin Periodontol 1995; 22: 1-14.
30) Quirynen M, Marechal M, Busscher HJ, Weerkamp AH, Darius PL, van Steenberge D. The influence of surface free energy and surface roughness on early plaque formation. An in vivo study in man. J Clin Periodontol 1990; 17: 138-144.
31) Combe EC, Owen BA, Hodges JS. A protocol for determining the surface free energy of dental materials. Dent Mater 2004; 20: 262-268.
32) Satou J, Fukunaga A, Satou N, Shintani H, Okuda K. Streptococcal adherence on various restorative materials. J Dent Res 1988; 67: 588-591.
33) van Dijk J, Herzkstroter F, Busscher H, Weerkamp A, Jansen H, Arends J. Surface-free energy and bacterial adhesion. An in vivo study in beagle dogs. J Clin Periodontal 1987; 14: 300-304.
34) Quirynen M, Van der Mei HC, Bollen CM, Van den Bossche LH, Doornbusch GI, van Steenberge D, Busscher HJ. The influence of surface-free energy on supra- and subgingival plaque microbiology. An in vivo study on implants. J Periodontol 1994; 65: 162-167.
35) Muller R, Ruhl S, Hiller KA, Schmalz G, Schweikl H. Adhesion of eukaryotic cells and Staphylococcus aureus to silicon model surfaces. J Biomed Mater Res. Part A 2008; 84: 817-827.
36) Verran J, Maryan CJ. Retention of Candida albicans on acrylic resin and silicone of different surface topography. J Prosthodont 1997; 77: 535-539.
37) Kawai K, Urano M. Adherence of plaque components to different restorative materials. Oper Dent 2001; 26: 396-400.
38) Hahn R, Weiger R, Netuschil L, Bruch M. Microbial accumulation and viability on different restorative materials. Dent Mater 1993; 9: 312-316.
39) Adamczyk E, Spieschowicz E. Plaque accumulation on crowns made of various materials. Int J Prosthodont 1999; 3: 285-291.
40) Givi T, Morrier JJ, Benay G, Barsotti O. Effect of hydrophobicity on in vitro streptococcal adhesion to dental alloys. J Mater Sci Med Mater 2000; 11: 637-642.
41) Weerkamp AH, van der Mei HC, Busscher HJ. The surface free energy of oral streptococci after being coated with saliva and its relation to adhesion in the mouth. J Dent Res 1985; 64: 1204-1210.
42) Absolom DR, Lamberti FV, Policova Z, Zingg W, van Oss CJ, Neumann AW. Surface thermodynamics of bacterial adhesion. Appl Environ Microbiol 1983; 46: 90-97.
43) Busscher HJ, Weerkamp AH, van der Mei HC, van Pelt AW, de Jong HP, Arends J. Measurement of the surface free energy of bacterial cell surfaces and its relevance for adhesion. Appl Environ Microbiol 1984; 48: 980-983.
44) Smales RJ. Plaque growth on dental restorative materials. J Dent 1981; 9: 133-140.
45) Ikeda M, Matin K, Nakaod T, Foxton RM, Tagami J. Effect of surface characteristics on adherence of S. mutans biofilms to indirect resin composites. Dent Mater J 2007; 26: 915-923.
46) Poggi C, Arciola CR, Rostii F, Scribante A, Saino E, Visai L. Adhesion of Streptococci mutants to different restorative materials. Int J Artif Organs 2009; 32: 671-677.
47) Imazato S, Ebi N, Takahashi Y, Kaneko T, Ebisu S, Russell RR. Antibacterial activity of bactericidal-immobilized fller for resin-based restorative. Biomateriais 2003; 24: 3605-3609.
48) Weiman W, Thalerger C, Guggenberger R. Siloranes in dental composites. Dent Mater 2005; 21: 68-74.
49) Eick JD, Kotha SP, Chappel CC, Kilway KV, Giese GJ, Glaras AG, Pinzino CS. Properties of silorane-based dental resins and composites containing a stress-reducing monomer. Dent Mater 2007; 23: 1011-1017.
50) Yamamoto K, Ohashi S, Taki E, Hirata K. Adherence of oral streptococci to composite resin of varying surface roughness. Dent Mater J 1996; 15: 201-204.
Influence of resin monomers on growth of oral streptococci. J Dent Res 2004; 83: 302-306.

52) Dummer PM, Harrison KA. In vitro plaque formation on commonly used dental materials. J Oral Rehabil 1982; 9: 413-417.

53) Burgers R, Eidt A, Frankenberger R, Rosentritt M, Schweikl H, Handel G, Hahnel S. The anti-adherence activity and bactericidal effect of microparticulate silver additives in composite resin materials. Arch Oral Biol 2009; 54: 595-601.

54) Rosentritt M, Hahnel S, Groger G, Muhlfriedel B, Burgers R, Handel G. Adhesion of Streptococcus mutans to various dental materials in a laminar flow chamber system. J Biomed Mater Res B Appl Biomater 2008; 86: 36-44.

55) Hahnel S, Rosentritt M, Handel G, Burgers R. In vitro evaluation of artificial ageing on surface properties and early Candida albicans adhesion to prosthetic resins. J Mater Sci Mater Med 2008; 19: 2619-2627.

56) Hahnel S, Rosentritt M, Burgers R, Handel G. Surface properties and in vitro Streptococcus mutans adhesion to dental resin polymers. J Mater Sci Mater Med 2009; 20: 249-255.

57) Pratten DH, Johnson GH. An evaluation of finishing instruments for an anterior and a posterior composite. J Prosthet Dent 1988; 60: 154-158.

58) Glantz PO. On wettability and adhesiveness. Odontol Revy 1969; 19: 10-21.

59) Stawarczyk B, Bahr N, Beuer F, Wimmer T, Eichberger M, Gernet W, Jahn D, Schmidlin PR. Influence of plasma pretreatment on shear bond strength of self-adhesive resin cements to polyetheretherketone. Clin Oral Investig 2014; 18: 163-170.