Hydrophobicity of Denture Base Resins: A Systematic Review and Meta-analysis

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Objectives: The aim of this article is to review the factors that attract *Candida albicans* to denture base resin (DBR) and to verify the influence of different surface treatments, chemical modification, or structural reinforcements on the properties of DBR. Materials and Methods: Searches were carried out in PubMed, Scopus, WOS, Google Scholar, EMBASE, and J-stage databases. The search included articles between 1999 and 2020. This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement. The keywords used during the search were “*Candida albicans*,” “Denture base,” “PMMA,” “Acrylic resin,” “Surface properties,” “hydrophobicity/hydrophilicity,” “contact angle,” and “surface free energy.” English full-text articles involving *in-vitro* studies with different acrylic resin modifications were included, whereas abstracts, dissertations, reviews, and articles in languages other than English were excluded. A meta-analysis was performed where appropriate. Results: Out of the 287 articles, 21 articles conformed to inclusion criteria. Sixteen articles were subjected to meta-analysis using random-effects model at 95% confidence interval. Results showed that DBR coatings/plasma coatings were effective methods to modify surface properties with estimated contact angle (CA) of 59.37° [95% confidence interval (CI): 53.69, 65.04]/55.87° (95% CI: 50.68, 61.06) and surface roughness (*Rₐ*) of 0.55 µm (95% CI: 0.52, 0.58)/0.549 µm (95% CI: 0.5, 0.59), respectively. Antifungal particle incorporation into poly(methylmethacrylate) DBR also produced similar effects with an estimated *Rₐ* of 0.16 µm (95% CI: 0.134, 0.187). Conclusion: The three properties responsible for *C. albicans* adhesion to DBR were *Rₐ*, CA, and surface free energy in terms of hydrophobicity. Therefore, the correlations between the hydrophobicity of DBR and *C. albicans* adhesion should be considered during future investigations for *Candida*-related denture stomatitis.

Keywords: *Candidiasis*, PMMA denture base, surface properties

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**INTRODUCTION**

*Candida*-associated denture stomatitis (DS) infection depends mainly on the denture base (DB) properties and the ability of *Candida albicans* (*C. albicans*) (the most common pathogen in DS) to adhere to the denture surface.¹,² Reports have confirmed that *Candida* adhesion to acrylic is associated with hydrophobic interactions between the two.²,³ Because *C. albicans* are hydrophobic, they can easily adhere to the hydrophobic poly(methylmethacrylate) (PMMA) DB.⁴ Therefore, hindering this interaction may help prevent various infections including DS. Achieving

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Higher microbial adhesion is linked to $R_s$ and hydrophobicity of the DB material,$^7$ in which roughness is capable of providing more surface area and protective hideout spot for microorganisms away from denture cleaning forces.$^7$ To limit the microbial colonization, $R_s$ of DB should not exceed 0.2 $\mu$m.$^7,8$

The chemical composition of PMMA which includes carboxylate, methyl ester groups, as well as other additives, cross-linking agents, fillers, and colorants affects the hydrophobicity and SFE of the DB.$^9$ Studies have reported that SFE and wettability of different denture base resins (DBRs) are related to variations in these additives.$^{10}$ In recent years, several nanoparticles such as ZrO$_2$, SiO$_2$, TiO$_2$, and diamond nanoparticles have been incorporated within the PMMA in an attempt to enhance the physio-mechanical properties of the material. These fillers were also found to increase the resistance of the material to microbial adhesion.$^{10,11}$

Researchers have used surface coating, chemical modifications, or synthesized and incorporated fillers with antimicrobial properties within PMMA to solve the issue of Candida adhesion. However, reviews of the effect of these treatment modifications on PMMA properties with correlation to hydrophobicity are not yet available. The aims of this study were to (1) systematically review literature pertaining to the modifications of DBR and (2) to correlate the variables to Candida adhesion/biofilm formation. The null hypothesis of this study was that alteration of the DB in the form of filler addition, chemical composition modification, or surface coating will not affect the hydrophobicity of the resin surface and therefore will not affect Candida adhesion.

**Materials and Methods**

**Search strategy**

This systematic review was completed according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA). Focus question was generated through the PICO(S) approach and research strategy (Table 1) to systematically review the available literature. Two PICO questions were formulated as follows: first, do the modifications of DB alter the hydrophobicity and Candida adhesion thereafter? Secondly, what factors will influence the hydrophobicity of modified DBR? An electronic search of English-language dental literature on PubMed, Scopus, WOS, Google Scholar, EMBASE, and J-stage databases was conducted for articles published between January 1999 and March 2020 [Figure 1]. To identify all relevant articles, a list of keywords was used for the search. These included “Denture base,” “PMMA,” “Surface properties,” “hydrophobicity/hydrophilicity,” “contact angle,” “surface energy,” and “C. albicans.”

The inclusion criteria included full-text articles in the English language, with in-vitro design, investigating heat-polymerized DBR, C. albicans adhesion, contact angle (CA), surface wettability, $R_s$, and/or SFE with different DB modifications (antimicrobial additives, surface coating, chemical composition modification). In contrast, papers in languages other than English, in-vivo clinical study, case reports, abstracts, short communication, letters to the editors, reviews, and dissertations and materials other than heat-polymerized acrylic resin or resin not used for DBs were excluded.

**Eligibility criteria**

Two investigators (MMAG and RA) reviewed the articles independently according to the same parameters. Studies that (1) measured the effect of incorporated antifungal agents, surface coating, or chemical composition modifications of heat-polymerized PMMA, (2) evaluated the C. albicans adhesion and one of the following properties: CA, SFE, $R_s$, or hydrophobicity/hydrophilicity, (3) reported

| Focus questions | What are the influencing factors of the hydrophobicity of modified denture base resin? |
|-----------------|---------------------------------------------------------------------------------------|
| PICOS           |                                                                                       |
| P: Participant  | Modified denture base materials                                                      |
| I: Interventions| Incorporating antifungal agents                                                      |
|                | Surface coatings                                                                      |
|                | Chemical composition modification                                                     |
| C: Comparison  | Unmodified heat-polymerized/microwave-polymerized acrylic resin                      |
| O: Outcomes    | Effectiveness of modifications on surface free energy/hydrophobicity                  |
| S: Study design| Networking meta-analysis                                                              |
sample size, mean, and standard deviation values, and (4) included brand names and specifications of tested materials were included in this review. DB modifications were categorized as follows: control (unmodified PMMA), antifungal additive, surface coatings, and chemical composition modifications.

**DATA MANAGEMENT, SCREENING, AND SELECTION**

Two independent investigators (MMG and RA) used a standardized Excel sheet to extract the data of the studies. The search was conducted in three steps. First, the titles were reviewed according to the inclusion/exclusion criteria. Secondly, the abstracts of the selected titles were screened to select those of interest for full-text analysis. At the third step, all full-text articles were analyzed. At all stages, any discrepancies between investigators were resolved by discussion. The extracted data included: the authors’ names, year of publication, materials of the study, processing method, *Candida* species, tests employed, presence of control group,
number and dimensions of specimens, type of resin modification, results, statistical analysis and significance, and conclusions. Studies with similar methodology were selected to undergo meta-analysis. Among the scopes of this systematic review is to conduct a meta-analysis taking into consideration the diverse designs (resin modifications) of the studies and the various properties tested and to assess their effect qualitatively (surface properties) and quantitatively (number of Candida colony-forming units) [Tables 2 and 3].

**Assessment of Risk of Bias**

A modification of the method used in previous systematic reviews was used by two authors (MMAG and RA) to independently assess the quality and risk of bias of each study. The characteristics were tabulated (n=21) and the parameters were reported as “+ve” if the parameter was described in the text or “−ve” if the information was missing or unclear. The parameters assessed were: sample size calculation, the use of a control group, stating the treatment method, statistical analysis performed, reliable analytical methods, blinding of the evaluators, and correlation of the reported properties with hydrophobicity. The risk of bias was classified according to the sum of “+ve” marks obtained as follows: 1 to 3 = high-, 4 to 5 = medium-, 6 to 7 = low-risk of bias.

Meta-analysis was performed for each treatment modality separately. Moreover, due to the variability of outcomes and methodology per treatment method, quantitative meta-analysis was done for 16 studies, whereas the rest of the studies were descriptively analyzed.

**Data Analysis**

Comprehensive meta-analysis (version 3, NJ, USA) was used for analysis. Visual inspection of forest plots and \( \chi^2 \) tests were used to evaluate the presence of heterogeneity. Random-effects model was used when the data were found to be heterogenic, whereas the fixed-effects model was used otherwise. Egger’s and Begg’s tests were used to check for the possibility of publication bias. \( P \)-values less than 0.05 were considered statistically significant.

**Results**

**Data Selection**

Twenty-one studies met the inclusion criteria [Figure 1] and submitted for data extraction and result analysis. Tables 2 and 3 summarize the studies’ details, methods, results, and outcomes.

**Risk of Bias**

Figure 2 presents the risk of bias for the included studies. Out of the 21 studies, 19 showed medium risk of bias and two showed low risk of bias. The risk of bias was mainly linked to the absence of sample size calculation and non-blinding of investigators.

Applying the inclusion criteria, out of the 21 included articles, 16 used surface coating, 4 added antimicrobial fillers, and 1 modified the chemical composition of PMMA (refer to Tables 2 and 3 for details). In addition to that, several included studies compared between smooth and rough surfaces of the modified specimens. Results revealed that hydrophobicity of DBRs was affected by surface coating, antimicrobial additives, or chemical composition modifications. Therefore, the results of this study were categorized based on the effects of these modifications on the hydrophobicity of DBR and its correlations with CA, \( R_s \), and \( C. albicans \) adhesion.

**Meta-Analysis**

In coating vs. CA (Supplementary Appendix 1), after exclusion of outliers, 74 groups underwent meta-analysis. Due to the considerable heterogeneity found (\( F > 75\%, P < 0.001 \)), random-effects model was used and the average CA after coating was found to be 59.37° [95% confidence interval (CI): 53.7–65.0]. The trim and fill method suggested inclusion of 33 more groups to remove publication bias after getting significant results of Begg’s and Egger’s tests (\( P=0.002 \) and \( P=0.001 \), respectively).

In the plasma coating vs. CA (Supplementary Appendix 2) and coating vs. \( R_s \) (Supplementary Appendix 3), a total of 38 and 91 observations were, respectively, included in the analysis. Due to significant heterogeneity (\( F > 70\%, P < 0.001 \)) in both the groups, random-effects model was used. The average CA and \( R_s \) were found to be 55.87° (95% CI: 50.68–61.06) and 0.552 \( \mu m \) (95% CI: 0.524–0.58), respectively. In plasma coating vs. CA, Begg’s and Eggers’ tests provided insignificant results; hence, the trim and fill method was not used. However, in coating vs. \( R_s \), the trim and fill method provided insertions of 32 more observations to avoid publication bias.

In plasma coating vs. \( R_s \) (Supplementary Appendix 4) and filler vs. \( R_s \) (Supplementary Appendix 5), 27 and 13 observations were included in the analysis. Both data sets reflected the presence of heterogeneity (\( F > 70\%, P < 0.001 \)) and hence the random-effects model was used for both. The estimated average \( R_s \) for plasma coating and filler addition were 0.549 \( \mu m \) (95% CI: 0.504–0.593) and 0.161 \( \mu m \) (95% CI: 0.134–0.187), respectively. Significant \( P \)-values for Eggers’ and Begg’s tests proved the presence of publication bias for both data sets. Hence, the trim and fill method suggested to insert 12 and 7 observations, respectively, to remove the publication bias.
| Author, year | Acrylic brand, composition, Candida species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|--------------|-------------------------------------------|-----------------------------------|--------------|-----------------|---------|-------------|
| Yildirim et al., 2005 | Denture acrylic, Meliodent (Bayer Dental, Newbury Berkshire, UK) | *Heat-cured | *One surface polished, the other was not (ground with 500 grid sandpaper) | *Contact angle | *O₂ surface modification sig. improved wettablity (lowered contact angle) compared with control | *O₂ gas is effective in increasing wettability of PMMA even with salivary pellicle. |
| Yildirim et al., 2005 | | *Control *102 discs (17×1 mm) *n=60 for wettability *n=30 for Candida adhesion *n=12 for surface analysis | *Plasma surface treatment for 15 min at the O₂ level of 0, 50, or 100 W. n=34 *Saliva contact | *Candida adhesion | *The reduction in contact angle is directly related to plasma power | *Candida adherence increased as hydrophilicity increased |
| Nevzatoglu et al., 2007 | ACRON Shade No. 3, GC | *Heat-cured | *Polishing up to 1000 grit *Buff polished | *Candida adherence | *Candida count was lowest in the coated specimens < buff polished < control | *Straight silicone coating is capable of improving surface properties of denture base material so that it becomes difficult for C. albicans to adhere |
| Zamperini et al., 2010 | Vipi Wave; Vipi | *Microwave-cured | *Processing technique (against glass or against stone) | *Surface roughness | *Surface roughness of specimens processed against glass was lower. No difference between all groups regarding surface roughness in each investigation. | *Adherence of C. albicans was sig. reduced by ArO₂/70 W and ArSF6/70 W plasma, regardless of the presence or absence of salivary and surface roughness (smooth or rough). |
| Author, year | Acrylic brand, composition, Candida species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|-------------|-------------------------------------------|----------------------------------|--------------|----------------|---------|-------------|
| Industria e Comercio Exportacao e Importacao de Produtos Odontologicos Ltda, Pirassununga, SP, Brazil | *Control<br>* 180 discs (13.8x2 mm) in 10 groups<br>*n=18 | *Plasma treatment for 5 min:*<br>1: argon atmosphere at 50 W<br>2: argon/oxygen atmosphere at 70 W<br>3: atmospheric air at 130 W<br>4: argon atmosphere, followed by sulfur hexafluoride atmosphere at 70 W<br>*Saliva exposure (30 min unstimulated whole human saliva) | *Contact angle | *Groups 2 and 4 were not sig. different from each other and showed sig. lower absorbance reading. | *Hydrophobicity was altered by the plasma treatments and water immersion* |
| *Control<br>* Processed against glass or stone | *Candida adhesion* | | | | |
| Zamperini et al., 2010*19* | Vipi Wave; VIPI | *Microwave-cured* | *Processing technique (against glass or against stone)* | *Surface roughness* | *Surface roughness of specimens processed against glass was lower.* |
| Industria e Comercio Exportacao e Importacao de Produtos Odontologicos Ltda, Pirassununga, SP, Brazil | *Control<br>* 180 discs (13.8x2 mm) in five groups<br>*n=18 | *Plasma treatment for 5 min:*<br>1: argon atmosphere at 50 W<br>2: argon/oxygen atmosphere at 70 W<br>3: atmospheric air at 130 W | *Contact angle* | *Contact angle for all groups changed after water immersion except control. All test groups showed an increase in contact angle after water immersion except group 4 which showed a reduction.* | *Contact angle was altered by the plasma treatments. However, mean contact angles of treated specimens were similar to those of control specimens, after 48 h of immersion in water.*<br>*Adherence of C. albicans was not sig. reduced by plasma treatments, surface roughness, or presence of saliva* |
| | *Processed against glass or stone* | 2: argon/oxygen atmosphere at 70 W<br>3: atmospheric air at 130 W | *Candida adhesion* | | |

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*Author, year* indicates the year of publication for each study. *Acrylic brand, composition, Candida species* refers to the type of acrylic material used and the specific Candida species tested. *Processing method/sample dimensions* describes the conditions under which the acrylic samples were processed. *Modification* details the treatments applied to the samples, such as plasma treatment or water immersion. *Tested properties* outlines what specific properties were measured, such as contact angle or Candida adhesion. *Results* presents the findings of the study, including statistical significances and trends. *Conclusions* summarizes the implications of the results.
| Author, year | Acrylic brand, composition, *Candida* species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|-------------|---------------------------------------------|----------------------------------|-------------|-----------------|---------|-------------|
| Wady et al., 2012 [20] | *C. albicans* (ATCC 90028) | *Microwave-cured* | 4: argon atmosphere, followed by sulfur hexafluoride atmosphere at 70 W *Saliva exposure* | *Surface roughness* | *No sig. difference in contact angle between 0 and 7 days or 90- and 180-day storage periods.* | *AgNPs had no effect on *C. albicans* adherence and biofilm formation regardless of concentrations* |
| | Vipi Wave; VIPI | *Control* | *AgNPs solution mixed with 75g acrylic powder at concentrations of (1000, 750, 500, 250, 30, 0 ppm), dried, sieved, ball milled | *Contact angle* | *After 90 and 180 days, contact angles were sig. higher than that at 0 and 7 days* | |
| | Industria e Comercio Exportacao e Importacao de Produtos Odontologicos Ltda Pirassununga, SP, Brazil | *Different storage periods (0, 7, 90, 180 days) (n=18)* | | *Adherence biofilm formation* | *Contact angles were lower than control for all experimental groups* | |
| | *468 discs (13.8×2 mm) in 13 groups* | *Processed against glass (smooth) or against stone (rough)* | | *Surface roughness* | *Sig. increase in surface roughness for all rough specimens* | |
| Lazarin et al., 2013 [21] | Vipi Wave; VIPI | *Microwave-cured* | | | *Experimental S and HP coatings showed sig. reduction of short-term attachment (90 min) of *C. albicans* to PMMA* | }

Table 2: Continued
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| Author, year | Acrylic brand, composition, Candida species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|--------------|---------------------------------------------|------------------------------------|--------------|------------------|---------|-------------|
| Lucitone 550; Dentsply Ind. Com. Ltda, Petropolis, Brazil | *Heat-cured *45 discs (10×5mm) in three groups | 2. hydroxypropyl methacrylate (HP) (HPMA) (cured for 4 min) 3. 2-tri-methylammonium ethyl methacrylate chloride (T) (TMAEMC) (cured for 4 min) 4. sulfobetaine methacrylate (S) (oven at 80°C for 2 h) *Concentrations of coatings at 0%, 25%, 30%, and 35% of the total composition in mmol. Additional components in the coating: MMA, TEGDMA, bis-GMA, 4-methyl benzophenone. Also, amino propyl methacrylate for group 4 *± saliva (non-stimulated) for 30 min at room temp. | *Candida adhesion | *Generally, no sig. difference of surface free energy b/w saliva-coated and uncoated specimens *For smooth specimens, no sig. difference b/w all groups | *For rough surfaces, S30, S35, and HP30 had sig. lower absorbance values than control | *DLC thin films significantly diminished C. albicans biofilm formation |
| Queiroz et al., 2013 | Lucitone 550; Dentsply Ind. Com. Ltda, Petropolis, Brazil | *Heat-cured *45 discs (10×5mm) in three groups | 2. hydroxypropyl methacrylate (HP) (HPMA) (cured for 4 min) 3. 2-tri-methylammonium ethyl methacrylate chloride (T) (TMAEMC) (cured for 4 min) 4. sulfobetaine methacrylate (S) (oven at 80°C for 2 h) *Concentrations of coatings at 0%, 25%, 30%, and 35% of the total composition in mmol. Additional components in the coating: MMA, TEGDMA, bis-GMA, 4-methyl benzophenone. Also, amino propyl methacrylate for group 4 *± saliva (non-stimulated) for 30 min at room temp. | *Candida adhesion | *Generally, no sig. difference of surface free energy b/w saliva-coated and uncoated specimens *For smooth specimens, no sig. difference b/w all groups | *For rough surfaces, S30, S35, and HP30 had sig. lower absorbance values than control | *DLC thin films significantly diminished C. albicans biofilm formation |

Queiroz et al., 2013 [22]
Lucitone 550; Dentsply Ind. Com. Ltda, Petropolis, Brazil

Table 2: Hydrophobicity of DBRs
| Author, year          | Acrylic brand, composition, *Candida* species | Processing method/sample dimensions | Modification                                                                 | Tested properties                                                                 | Results                                                                 | Conclusions                                                                 |
|----------------------|-----------------------------------------------|-------------------------------------|------------------------------------------------------------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Gad, et al.          | *C. albicans* (ATCC 18804)                    | *n=15                               | *Surface treatment for 15 min:                                               | *Rutherford backscattering spectroscopy (RBS) and atomic force microscopy (AFM) for film characterization | *Surface roughness did not affect the number of *Candida* adhered           | *The films undoped and doped with silver nanoparticles presented similar behavior. |
|                      |                                               | *Control (no surface treatment)     | 1. no coating (Gc)                                                          |                                                                                 |                                                                            |                                                                               |
|                      |                                               | 2. surface coating with DLC fil (Gdlc) |                                                                                 |                                                                                 |                                                                            |                                                                               |
|                      |                                               | 3. surface coating with DLC doped with Ag-Nps (Gag) DLC = diamond-like carbon |                                                                                 |                                                                                 |                                                                            |                                                                               |
| Al-Bakri et al., 2014 | Urban, Shofu Inc., Kyoto, Japan                | *Heat-cured*                        | *Silane-coated glass fibers (1.5 μm, with 15% w/w fluoride) were added to PMMA at concentrations of 0.5%, 1.0%, 2.5%, 5.0%, 10% | *Contact angle                                                                  | *Surface treatment reduced *Candida* adhesion in groups 2 and 3 compared with control | *No additional reducing effect was seen with Ag addition                        |
|                      |                                               | *50 discs (10×1.5 mm) in 5 groups   |                                                                                 |                                                                                 |                                                                            | *DLC increased hydrophobicity and lowered surface energy.                   |
|                      | *C. albicnas* (GDH 2346)                      | *n=10                               | *Polishing of both sides with 400 grit Al₂O₃                                |                                                                                 |                                                                            |                                                                               |
|                      |                                               | *Control                           |                                                                                 |                                                                                 |                                                                            |                                                                               |
|                      |                                               | 1. no coating (Gc)                 | *Surface free energy (contact angle cosine value)                           | *10% filler produced sig. rougher surface than control and 1.0%                  |                                                                            |                                                                               |
|                      |                                               | 2. surface coating with DLC fil (Gdlc) | *Surface roughness (non-contact)                                              | *Fluoride addition sig. reduced *Candida adhesion to PMMA                        |                                                                            |                                                                               |
|                      |                                               | 3. surface coating with DLC doped with Ag-Nps (Gag) | *Adherent *Candida* count using a light microscope                          | *Coating PMMA with saliva sig. reduced *Candida adhesion                         |                                                                            |                                                                               |
|                      |                                               | DLC = diamond-like carbon           |                                                                                 |                                                                                 |                                                                            |                                                                               |
| Lazarin et al., 2014 | Vipi Wave; VIPI                               | *Microwave-cured*                   | *Processed against glass (smooth) or against stone (rough)                   | *Surface roughness                                                               | *No sig. differences in surface roughness among groups within each fabrication method | *Experimental photopolymerized coatings did not alter hydrophobicity but changed chemical composition. |
Table 2: Continued

| Author, year | Acrylic brand, composition, *Candida* species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|--------------|------------------------------------------------|------------------------------------|--------------|------------------|---------|-------------|
| Industria e Comercio Exportacao e Importacao de Produtos Odontologicos Ltda Pirassununga, SP, Brazil *C. albicans* (ATCC 90028) | *n=36*  
*Control* | *Photopolymerized coatings:* | *contact angle* | *Samples prepared against stone were sig. rougher than those prepared against glass*  
*C. albicans adhesion decreased with coatings sulfobetaine, 2-hydroxypropyl methacrylate, and 2-hydroxyethyl methacrylate* |  
1. 2-hydroxyethyl methacrylate (HE) (HEMA) (cured for 4 min)  
2. hydroxypropyl methacrylate (HP) (HPMA) (cured for 4 min)  
3. 2-tri-methyl-ammonium ethyl methacrylate chloride (T) (TMAEMC) (cured for 4 min)  
4. sulfobetaine methacrylate (S) (oven at 80°C for 2 h)  
*Concentrations of coatings 0%, 25%, 30%, and 35% of the total composition in mmol. Additional components: MMA, TEGDMA, Bis-GMA, 4-methyl benzophenone. Also, amino propyl methacrylate for group 4  
*± saliva (non-stimulated) for 30 min at room temp.* | *Candida adhesion* | *Smooth groups HE30, T25, T30, and T35 had sig. higher contact angle*  
*Candida adhesion for saliva-coated specimens* | *Contact angles for rough surface were not sig. different*  
*No sig. different in Candida adhesion for saliva-coated specimens*  
*Smooth and non-saliva-coated specimens showed sig. lower Candida with S35, HP35, and HE35*  
*Rough specimens ± saliva → no sig. difference between groups regarding Candida adhesion*  
*Rough S25, S30, HP35, HE30, HE35, T35 with no saliva showed higher Candida adhesion than same smooth groups*  
*XPS showed increase in C, O, Si after HE, HP, and T coating, and S for S coating* |
| Author, year, Acrylic brand, composition, Candida species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|----------------------------------------------------------|-----------------------------------|--------------|------------------|---------|-------------|
| Yodmongkol et al., 2014[21] | Rodex (Australia) | *Heat-cured | *Silane-SiO₂ nanocomposite dip-coating evaporating solvent at 65°C for 20 min and then heating to 110°C for 2 h | *Candida adhesion after 1 h using optical microscope (n=6) | *Sig. higher cell adhesion was seen on uncoated specimens than coated | *Silane-SiO₂ nanocomposite films can make acrylic resin more hydrophobic, which decreases C. albicans adhesion. |
| C. albicans (ATCC 10231) | *Rectangular specimens (1.5×1.5×1 mm) *Control *Roughness (n=5) *Contact angle and SFE (n=3) | | | | |
| | | | | | |
| Sawada et al., 2014[26] | Natural Resin, Nissin Co., Kyoto, Japan | *Heat-cured | *Addition of 5 wt.% | | |
| C. albicans (ATCC 1002) | *Rectangular 64×10×33 mm | —FAp-TiO₂ (100 nm) —HAp-TiO₂ (100 nm) | *Contact angle of three liquids were used: deionized water 18 MΩ/cm, diiodomethane, and glycerol (n=3) → SFE SEM | *Surface roughness (contact) (n=5) | *Surface roughness was the same for coated and uncoated |
| | *n=12 *Control (pure PMMA) | —TiO₂ (25 nm) | | | |
| Compagnoni et al., 2014[27] | Lucitone 550 | *Heat-cured | *Polishing up to 2000 grit polishing paper *Modification with PTBAEMA (0% or 10%) | *Contact angle measurement using 1.0 µL deionized water drop | *Surface roughness increased with PTBAEMA addition | *PTBAEMA slightly increases wettability and roughness of acrylic resin |
| | | | | | |
| Author, year | Acrylic brand, composition, Candida species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|-------------|-----------------------------------------------|-----------------------------------|--------------|-----------------|--------|-------------|
| Gad, et al. | Dentsply International Inc., York, PA, USA C. albicans (ATCC 90028) | *Control (unmodified) | PTBAEMA= polymer poly (2-tert-butyaminoethyl) Methacrylate | *Atomic force microscopy observations of 100 and 400 µm² *Adherence assay using CFU counts after 90 min at 37°C | *Contact angles of PTBAEMA-modified acrylic is lower than controls | *PTBAEMA into acrylic resins did not have an effect against C. albicans at 10% |
| Pan et al., 2015[28] | Vertex Rapid Simplified, Vertex-Dental, Zeist, The Netherlands C. albicans (ATCC 10231) | *Heat-cured | *Polishing to 600 or to 2000 grit silicon carbide | *Contact angle of 2 µL ultrapure water drop (n=18) | *Contact angle decreased as roughness increased | *Ar/O₂ plasma treatment improved surface wettability of PMMA without degrading physical properties |
| Pan et al., 2015[28] | Vertex Rapid Simplified, Vertex-Dental | *Heat-cured | Polished to silicon carbide grit 1000 | *X-ray photoelectron spectroscopy analysis (XPS) *Optical emission spectroscopy (OES) *Contact angle (after plasma TX, 48 h, 15 days, 30 days) | *XPS revealed fluorine on the surface of plasma treated and reduction of C/O *OES revealed abundance of O and OH as active components *Contact angle decreased after plasma treatment | *Cold plasma treatment resulted in increased hydrophilicity and reduced Candida adhesion |
| Qian et al., 2016[29] | Vertex Rapid Simplified, Vertex-Dental | *Heat-cured | | | | |
| Author, year | Acrylic brand, composition, Candida species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|--------------|--------------------------------------------|------------------------------------|--------------|------------------|---------|-------------|
| BV, Zeist, The Netherlands | *45 discs (12×1 mm) in five groups | *Plasma surface treatment with argon 98%/oxygen 2% for 0, 30, 60, 90, and 120 s | *Surface roughness non-contact (n=9) | *No difference between plasma-treated groups (immediately) | *Prolonged plasma treatment did not improve wettability but affected durability. |
| C. albicans (ATCC 10231) | *Control *n=9 | *Candida adhesion by CFU analysis (n=9) | *Contact angle increased after water immersion, 48 h, 15 days | *Reduction in the ratio of C/O, direct relation with treatment time |
| | | *XPS | | *No relation between surface roughness and Candida adhesion |
| Liu et al., 2017[30] | Lucitone 199; Dentsply Intl Inc. C. albicans (ATCC 18804) | *Heat-cured *Smooth and rough surfaces | *Contact angle of sessile drop of distilled water | *Hydrophobicity increased by TMS coating |
| | *60 discs (10×2 mm) in four groups *n=15 *Control | *Coated with TMS or not coated (trimethylsilane) | *Absorbance of OD (optical density) for Candida | *Candida adhesion was decreased by TMS coating |
| | | | *MTT assay | *Surface roughness alone did not affect Candida adhesion |
| Türkcan et al., 2018[31] | Meliodent | *Heat-cured | *Polished with silicon carbide paper 600 grit | *Surface modification with MPC coating decreased contact angle in 0.25 and 0.75 mol/L MPC groups. |
| Heat Cure, Heraeus Kulzer, Germany | *Disc (6×1.5 mm) in four groups | *Surface coating with MPC (2-methacryloyloxyethyl phosphorylcholine) dissolved in degassed pure water at concentrations of 0.25, 0.5, 0.75 mol/L | *Surface roughness (contact) (n=3) | *Surface roughness alone did not affect Candida adhesion |
| C. albicans (ATCC 90028) | *Contact angle and roughness (n=3) | *FTIR spectroscopy with attenuated total reflection (ATR) equipment (n=2) | *MCP increased hydrophilicity (increased water absorption) | *Surface modification with MPC decreases C. albicans adhesion onto PMMA surface. |
| Author, year | Acrylic brand, composition, *Candida* species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|--------------|---------------------------------------------|-----------------------------------|--------------|------------------|---------|-------------|
| Hirasawa *et al.*, 2018[32] | Natural resin, Nissin Co., Kyoto, Japan | *Candida* adhesion (*n* = 10) | *Control* | *Candida* adhesion assay using CFU (*n* = 10) | *Reduction in *Candida* adhesion as concentration increased, no difference between 0.5 and 0.75 mol/mL | *Coating with cross-linkable co-polymers containing SBMAm significantly reduced the initial adhesion of *C. albicans* |
| *C. albicans* (JCM2085) | *Heat-cured* | *Polished on both sides to 8000 grit* | *SEM* (*n* = 2) | *XTT reduction assay* (*n* = 10) | *Significant difference among all groups for XTT and CFU* |
| *n* = 10 | *In laboratory-made co-polymer coating plasma cleaning → primer → drying → immersion (10 s) in prepared polymer at concentrations SM0%, SM15%, SM30%, and SM50% → UV (27s) | *CFU* (*n* = 10) | *Significant reduction in biofilm for all test groups compared with controls* |
| *Control* | | | *SEM* (*n* = 10) | *Surface roughness was less than 0.005 µm for all groups (no difference)* |
| Darwish *et al.*, 2019[33] | Lucitone 199 (Dentsply Intl, York, PA, USA) | *Heat-cured* | *Polished to 4000 grit silicon carbide paper* | *Contact angle using sessile drop of 5 µL deionized water (*n* = 10) | *Contact angle of coated was lower than that of non-coated* |
| *Rectangular specimens (20×20×1 mm)* | *Titanium oxide coating improved wettability, surface smoothness, and increased resistance to microbial adherence.* | *Contact angle of 1 mL purified water drop* | *Surface roughness of coated specimens was less than that of non-coated* |
| | | *Surface roughness (non-contact)* | *Film thickness was less than 5 µm for all groups—thicker for SM30% than SM0% and SM50%* |
| | | *Film thickness (spectroscopic ellipsometer)* | *All coated groups had lower contact angle than control, SM15% had lowest contact angle and highest hydrophilicity* |
| Author, year | Acrylic brand, composition, *Candida* species | Processing method/sample dimensions | Modification | Tested properties | Results | Conclusions |
|--------------|---------------------------------------------|-----------------------------------|-------------|-----------------|---------|-------------|
| Acosta *et al.*, 2019<sup>[34]</sup> | Lucitone 199 (Dentsply Sirona) and ProBase Hot (Ivoclar Vivadent AG) | *Roughness and contact angle (n=10)*<br>*Candida adhesion (n=5)*<br>*Control*<br>*Heat-cured* | Acrylic acid or itaconic acid coatings | *Candida adhesion (n=5) after 12 h at 37°C*<br>*Biofilm formation (n=5)* | *Sig. reduction in viable attached *Candida* cells to coated surfaces*<br>*Sig. reduction in viable *Candida* biofilm on coated surfaces* | Affected surface roughness<br>PMMA acrylic resin base material was superficially modified through the incorporation of carboxylic acid groups by using PAA and PIA coatings that reduced the adherence of *C. albicans* biofilm by 90%. |
| Fouda *et al.*, 2019<sup>[35]</sup> | Major.Base.20 Resin | *Discs (13–14×4–5 mm)*<br>*n=30*<br>*Control*<br>*Heat-cured* | Nano-diamond at 0.5%, 1.0%, and 1.5% | *Contact angle using sessile drop of 5 µL deionized water (n=30)*<br>*Candida biofilm adhesion* | Increased surface wettability<br>PMMA disks modified with PIA or PAA showed a 90% reduction of *C. albicans* | PMMA/ND composites could be valuable in the prevention of denture stomatitis which is considered one of the most common clinical problems among removable denture wearers |
| *C. albicans* | | *Square (10×10×3 mm)*<br>*n=30*<br>*Control* | | *Contact angle using sessile drop of 5 µL deionized water (n=30)*<br>*C. albicans adhesion* | Decreased *C. albicans* adhesion | No significant effect was observed on the contact angle. |
### Discussion

The results of this review revealed that the different treatment modalities (filler incorporation, surface coating, and chemical composition modification) affected the $R_a$, CA, and hydrophobicity of the DBR resulting in *Candida* adhesion modification, and therefore, the null hypothesis was rejected.

**Why coating? and what is the outcome?**

In recent years, the DB surface has been modified with various coatings in an attempt to increase its hydrophilicity and to reduce *C. albicans* adhesion.\[3,21\] These coatings can be in the form of plasma-based treatment, photopolymerized coatings, and hydrophilic polymer coatings, among others. In plasma-based treatment, partial ionization of the gas is brought up by electrical discharge which creates an environment that contains reactive species such as electrons, ions, and free radicals. Plasma treatment helps clean debris, generates reactive groups on the surface, and makes the surface more attractive to specific cells depending on the treatment atmosphere.\[16\] The newly formed surface has higher SFE, improved wettability, and diminished CA, which reduces the adherence of *C. albicans*.\[18,19,28,29\]

Plasma treatment of PMMA in the presence of $O_2$ gas improved the wettability of the surface even in the presence of salivary pellicle.\[16\] Similarly, plasma coating in argon, argon-oxygen, and atmospheric air resulted in lower CAs.\[18\] Conversely, TMS coating increased the hydrophobicity, lowered the wettability of the DB surface, and significantly reduced *C. albicans* adhesion.\[30\] Silane-SiO$_2$ nanocomposite films were found to improve the surface, augment the physical properties of PMMA, and increase surface hydrophobicity which decreases *C. albicans* adhesion.\[25\]

Coating with TiO$_2$ created smoother surfaces that are more resistant to wear and less porous, which prevent microorganisms from diffusing into the acrylic resin and colonizing on the surface.\[33\] UV irradiation of TiO$_2$ activates oxidative species that produce irreversible damage to the cells.\[33\] Additionally, TiO$_2$ coating creates a super-hydrophilic surface with “water sheathing” effect. The ability of TiO$_2$ to improve surface wettability is essential to reduce or inhibit *Candida* attachment on DBR.\[33\]

Surface modification with photopolymerized coating of poly(acrylic acid) (PAA) or poly(itaconic acid)
(PIA) followed by UV irradiation has been achieved. The coatings decreased the CA and increased the SFE, which may have resulted from changes in the surface polar groups after coating and the acidic environment in the presence of (-OH) groups. In a similar manner, surface modification by polymerization of 2-methacryloyloxyethyl phosphorylcholine (MPC) polymer provided a statistical decrease in CA and C. albicans adhesion.

Other hydrophilic coatings like 3-hydroxypropyl methacrylate (HPMA) and polymers containing sulfobetaine methacrylate (SBMA) were found to enhance the wettability of the DB surface and to reduce C. albicans adhesion as a result of limited hydrophobic interactions. The CA and C. albicans adhesion were significantly reduced after coating the DBR with nanocoat or Optiglaze. This effect was brought up by changes in the carbon and oxygen content and different types of interactions. Conversely, cyanacrylate coating increased the C. albicans adhesion with no effect on CA.

The main advantage of coating is that it allows surface alteration at a relatively low cost and preserves the properties of the original material. The low viscosity can produce thin films (~50 nm) and <5 μm on the surface that do not interfere with the fit of the denture. Coating PMMA with ceramic materials improves its resistance to abrasion and protects the surface from attacks of different solutions. Cold plasma treatment is performed at room temperature avoiding possible damage or warpage of acrylic resin with thermal treatments. As most of the aforementioned coatings produce hydrophilic surfaces and improve the wettability of the PMMA, their application on the fitting surface of a denture could enhance the retention of the DBs by increasing affinity to saliva/liquid molecules that would create a denture seal. In contrast, some of the coating materials require a certain preservation temperature and consumption within a short duration after preparation. Also, the durability of different coatings needs further investigation.

**Roughness (R_a), hydrophobicity, resin surface chemistry, and candida adhesion**

High R_a may enhance microbial retention because a rougher surface provides more area for microbial adhesion and promotes fungal adhesion and colonization. Hahnel et al. did not find a linear relationship between R_a and C. albicans adhesion. However, many other studies reported that greater C. albicans adhesion is associated with higher R_a. Studies indicated that R_a was not altered following plasma treatment or film deposition process. Thus, these opposing results suggest that the...
reduced *C. albicans* biofilm was due to the chemical modification of the PMMA surface represented by increased hydrophilicity and SFE that was promoted by film coating.[22] Hirasawa *et al.*[32] reported that roughness of different coated specimens was not the main determining factor in *Candida* reduction, rather it was surface hydrophilicity that played the major role.

**Incorporation of antifungal agents within DBR**

Incorporation of antifungal agents within DBR affected *C. albicans* adhesion and the development of DS.[41] The antimicrobial efficiency of the added AgNPs is associated with ingress of water molecules into the material and the outward movement of the silver ions to the aqueous solution.[20] Others suggested that the

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**Figure 2: Risk of bias for the included studies**
The inhibitory effect was due to the greater antimicrobial effect of the smaller particles which provides more surface area in direct contact with the nanoparticles. PMMA containing FAp-TiO₂ exhibited strong photocatalytic activity following irradiation through the production of reactive oxygen species such as (-OH) and (H₂O₂) which inhibit C. albicans attachment.[26] This filler has clinical advantages especially for elderly patients through maintenance of proper denture hygiene.[20]

The addition of nano-diamonds showed an improvement of the specimen surface, which may contribute to the significant reduction in C. albicans adhesion. Regardless of the increase in Rₐ at a high concentration, a reduction in Candida adhesion was detected. Moreover; the inclusion of nano-diamonds within PMMA did not alter the CAs of the modified specimens in comparison to the unmodified specimen.[34] However, the mechanism of antifungal activity of ND was not described clearly and requires further investigations.

**Chemical Composition Modification**

The addition of phosphate into DBR by monomer substitution was reported to improve the surface hydrophilicity.[28,43] The quantity of adherent C. albicans was associated with the wettability properties of the DB, emphasizing the role of acrylic resin chemistry on the initial attachment of C. albicans.[16]

**Clinical Significance**

The literature reported that hydrophobicity and Rₐ of DBs influence the attachment and colonization of C. albicans. Therefore, to reduce Candida adhesion, the surface of the DB must be smooth, hydrophilic, and has no porosities.[5] Improving the hydrophilicity of the DB allows contact with more liquid molecules which helps in forming the seal that keeps the denture tight to air leakage.[28] Additionally, it has been reported that hydrophilic surfaces have fewer adherent C. albicans.[3] Therefore, increasing the surface hydrophilicity would hinder Candida attachment.[36]

Additionally, the intaglio surface provides the best environment for C. albicans adhesion, as it cannot be finished or polished to preserve its accuracy and fit. Therefore, surface coatings can be of great use in such situations in which the coating films are extremely thin and less likely to induce any misfit between the DB and oral tissues, affect the occlusion, or affect the texture of the resin.[24,25,43] The different coating modalities mentioned earlier can reduce C. albicans adhesion and biofilm formation.[25]

The limitations of this review could be attributed to a wide range of different treatments in each section, such as different coating materials, fillers, and minimal studies on chemical modification, which made the comparison more difficult as a result of the wide range of properties of each material and its effect on the studied properties.

**Conclusion**

Based on this review, it could be concluded that the hydrophobicity of DBRs and C. albicans adhesion were affected by the interrelated following factors: wettability (CA), SFE, and surface structure of DBR. Incorporation of antifungal agents or surface coating of DBR affected its hydrophobicity. Future studies evaluating the long-term biocompatibility and antifungal efficacy of different modifications are required to correlate between factors affecting the hydrophobicity and C. albicans adhesion.

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**Conflicts of Interest**

There are no conflicts of interest.

**Authors’ Contributions**

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**Ethical Policy and Institutional Review Board Statement**

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**Patient Declaration of Consent**

Not applicable.

**Data Availability Statement**

Not applicable.

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## Supplementary Material

### Supplementary Appendix 1: Forest plot for coating vs contact angle (°)

| Author, year | Treatment | 48 | 60 | 80 | Mean (95% CI) |
|--------------|-----------|----|----|----|---------------|
| Yildiz et al., 2014 | Control vs saliva | + | + | + | 78.09 (78.38, 80.32) |
| | O3 50 W vs saliva | + | + | + | 72.32 (70.76, 73.88) |
| | Control vs saliva | + | + | + | 74.53 (73.28, 75.78) |
| | O3 30 W vs saliva | + | + | + | 26.21 (23.52, 28.89) |
| | Control vs saliva | + | + | + | 20.64 (19.05, 22.23) |
| | Ar 50 W vs smooth | + | + | + | 40.48 (40.48, 40.48) |
| | Ar 30 W vs smooth | + | + | + | 40.48 (40.48, 40.48) |
| | Ar 100 W vs smooth | + | + | + | 40.48 (40.48, 40.48) |
| | Control vs smooth | + | + | + | 40.48 (40.48, 40.48) |
| | Ar 50 W vs smooth | + | + | + | 55.85 (55.85, 55.85) |
| | Ar 30 W vs smooth | + | + | + | 55.85 (55.85, 55.85) |
| | Ar 100 W vs smooth | + | + | + | 55.85 (55.85, 55.85) |
| | Control vs smooth | + | + | + | 55.85 (55.85, 55.85) |
| | Ar 50 W vs smooth | + | + | + | 86.17 (86.17, 86.17) |
| | Ar 30 W vs smooth | + | + | + | 86.17 (86.17, 86.17) |
| | Ar 100 W vs smooth | + | + | + | 86.17 (86.17, 86.17) |
| | Control vs smooth | + | + | + | 86.17 (86.17, 86.17) |
| | Ar 50 W vs smooth | + | + | + | 94.10 (94.10, 94.10) |
| | Ar 30 W vs smooth | + | + | + | 94.10 (94.10, 94.10) |
| | Ar 100 W vs smooth | + | + | + | 94.10 (94.10, 94.10) |
| | Control vs smooth | + | + | + | 94.10 (94.10, 94.10) |

6h; immediate reading after plasma treatment
48h; reading after 48 hours in water
Ar50W; Argon atmosphere at 50 W
Ar30W; Argon/oxygen atmosphere at 30 W
S; wettability monomer (sulfobetaine methacrylate)
HP; 2-hydroxypropyl methacrylate (HPMA)
HE; 2-hydroxyethyl methacrylate (HEM)
T; 2-ethylammonium ethyl methacrylate chloride (TMAEMC)
(SM0%); sulfobetaine methacrylate; N,N’-(4,7,10-trioxa-1,13-tridecanediamine) diacrylamide in ratio 1:0.5
**Supplementary Appendix 2: Forest plot for plasma surface treatment vs contact angle (°)**

| Author, year | Treatment | 35 | 55 | 75 | Mean (95% CI) |
|--------------|-----------|----|----|----|---------------|
| Zamperini et al., 2010 (a) | Control- smooth- 0h |  |  |  |  |
| | Ar/ 50 W- smooth- 0h |  |  |  |  |
| | ArO₂/70 W- smooth- 0h |  |  |  |  |
| | ArSF₆/70 W- smooth- 0h |  |  |  |  |
| | Control – rough- 0h |  |  |  |  |
| | Ar/ 50 W- rough- 0h |  |  |  |  |
| | ArO₂/70 W- rough- 0h |  |  |  |  |
| | ArSF₆/70 W- rough- 0h |  |  |  |  |
| | Control- smooth- 48h |  |  |  |  |
| | AAt/130W- smooth- 48h |  |  |  |  |
| | Ar/ 50 W- smooth- 48h |  |  |  |  |
| | ArO₂/70 W- smooth- 48h |  |  |  |  |
| | ArSF₆/70 W- smooth- 48h |  |  |  |  |
| | Control- rough- 48h |  |  |  |  |
| | AAt/130W- rough- 48h |  |  |  |  |
| | Ar/ 50 W- rough- 48h |  |  |  |  |
| | ArO₂/70 W- rough- 48h |  |  |  |  |
| | ArSF₆/70 W- rough- 48h |  |  |  |  |
| Zamperini et al., 2010 (b) | Control- smooth- 0h |  |  |  |  |
| | Ar/ 50 W- smooth- 0h |  |  |  |  |
| | ArO₂/70 W- smooth- 0h |  |  |  |  |
| | ArSF₆/70 W- smooth- 0h |  |  |  |  |
| | Control – rough- 0h |  |  |  |  |
| | Ar/ 50 W- rough- 0h |  |  |  |  |
| | ArO₂/70 W- rough- 0h |  |  |  |  |
| | ArSF₆/70 W- rough- 0h |  |  |  |  |
| | Control- smooth- 48h |  |  |  |  |
| | AAt/130W- smooth- 48h |  |  |  |  |
| | Ar/ 50 W- smooth- 48h |  |  |  |  |
| | ArO₂/70 W- smooth- 48h |  |  |  |  |
| | ArSF₆/70 W- smooth- 48h |  |  |  |  |
| | Control- rough- 48h |  |  |  |  |
| | AAt/130W- rough- 48h |  |  |  |  |
| | Ar/ 50 W- rough- 48h |  |  |  |  |
| | ArO₂/70 W- rough- 48h |  |  |  |  |
| | ArSF₆/70 W- rough- 48h |  |  |  |  |
| Pan et al., 2015 | Control |  |  |  |  |
| | ArO₂ |  |  |  |  |

Overall ($I^2$=99%, $P$=0.00)

0h; immediate reading after plasma treatment
48h; reading after 48 hours in water
(Ar/50W)- Argon atmosphere at 50 W
(ArO₂/70W)- Argon/oxygen atmosphere at 70 W
(AAT/130W)- Atmosphere air at 130 W
As/SF₆/70W)- Argon atmosphere then plasma treatment in Sulphur hexafluoride atmosphere at 70W
### Supplementary Appendix 3: Forest plot for surface coating vs. surface roughness (mm)

| Author, year          | Treatment               | 0.08  | 0.55  | 1.02  | Mean (95% CI)               |
|-----------------------|-------------------------|-------|-------|-------|-----------------------------|
| **Zamperini et al., 2010 (a)** | Control- smooth         |       |       |       | 0.27(0.22, 0.32)            |
|                       | AA/130 W- smooth        |       |       |       | 0.33(0.26, 0.40)            |
|                       | Ar/ 50 W- smooth        |       |       |       | 0.33(0.27, 0.39)            |
|                       | ArO/70 W- smooth        |       |       |       | 0.29(0.23, 0.35)            |
|                       | ArSF/70 W- smooth       |       |       |       | 0.29(0.23, 0.34)            |
|                       | Control- rough          |       |       |       | 1.76(1.22, 2.3)             |
|                       | AA/130 W- rough         |       |       |       | 2.08(1.82, 2.34)            |
|                       | Ar/ 50 W- rough         |       |       |       | 1.86(1.44, 2.27)            |
|                       | ArO/70 W- rough         |       |       |       | 1.75(1.42, 2.08)            |
|                       | ArSF/70 W- rough        |       |       |       | 1.82(1.48, 2.16)            |
| **Zamperini et al., 2010 (b)** | Control- smooth         |       |       |       | 0.30(0.25, 0.35)            |
|                       | AA/130 W- smooth        |       |       |       | 0.28(0.22, 0.33)            |
|                       | Ar/ 50 W- smooth        |       |       |       | 0.30(0.21, 0.36)            |
|                       | ArO/70 W- smooth        |       |       |       | 0.28(0.23, 0.33)            |
|                       | ArSF/70 W- smooth       |       |       |       | 0.28(0.23, 0.33)            |
|                       | Control- rough          |       |       |       | 1.68(1.31, 2.05)            |
|                       | AA/130 W- rough         |       |       |       | 1.95(1.58, 2.32)            |
|                       | Ar/ 50 W- rough         |       |       |       | 1.86(1.52, 2.2)             |
|                       | ArO/70 W- rough         |       |       |       | 1.61(1.32, 1.9)             |
|                       | ArSF/70 W- rough        |       |       |       | 1.79(1.44, 2.14)            |
| **Lazarin et al., 2013** | Control- smooth         |       |       |       | 0.19(0.16, 0.22)            |
|                       | S25- smooth             |       |       |       | 0.17(0.13, 0.21)            |
|                       | S30- smooth             |       |       |       | 0.19(0.15, 0.23)            |
|                       | S35- smooth             |       |       |       | 0.18(0.15, 0.21)            |
|                       | HP25- smooth            |       |       |       | 0.16(0.12, 0.20)            |
|                       | HP30- smooth            |       |       |       | 0.20(0.16, 0.24)            |
|                       | HP35- smooth            |       |       |       | 0.23(0.2, 0.26)             |
|                       | HE25- smooth            |       |       |       | 0.23(0.2, 0.26)             |
|                       | HE30- smooth            |       |       |       | 0.17(0.13, 0.21)            |
|                       | HE35- smooth            |       |       |       | 0.17(0.14, 0.21)            |
|                       | T25- smooth             |       |       |       | 0.17(0.13, 0.21)            |
|                       | T30- smooth             |       |       |       | 0.15(0.12, 0.18)            |
|                       | T35- smooth             |       |       |       | 0.17(0.13, 0.21)            |
|                       | Control- rough          |       |       |       | 1.95(1.7, 2.01)             |
|                       | S25- rough              |       |       |       | 2.13(1.8, 2.5)              |
|                       | S30- rough              |       |       |       | 2.29(1.97, 2.61)            |
|                       | S35- rough              |       |       |       | 1.95(1.61, 2.29)            |
|                       | HP25- rough             |       |       |       | 2.11(1.86, 2.36)            |
|                       | HP30- rough             |       |       |       | 2.05(1.73, 2.37)            |
|                       | HP35- rough             |       |       |       | 1.73(1.48, 1.97)            |
|                       | HE25- rough             |       |       |       | 1.78(1.5, 2.01)             |
|                       | HE30- rough             |       |       |       | 1.90(1.45, 2.26)            |
|                       | HE35- rough             |       |       |       | 2.09(1.81, 2.37)            |
|                       | T25- rough              |       |       |       | 1.93(1.57, 2.29)            |
|                       | T30- rough              |       |       |       | 1.74(1.5, 1.98)             |
|                       | T35- rough              |       |       |       | 1.94(1.57, 2.3)             |
| **Queiroz et al., 2013** | Control                 |       |       |       | 0.14(0.13, 0.15)            |
|                       | GdIc                    |       |       |       | 0.14(0.13, 0.15)            |
|                       | Gag                     |       |       |       | 0.15(0.14, 0.16)            |
|                       | Control- smooth         |       | 0.20(0.16, 0.24) |
|                       | S25- smooth             |       | 0.16(0.12, 0.19) |
|                       | S30- smooth             |       | 0.17(0.14, 0.20) |
|                       | S35- smooth             |       | 0.17(0.13, 0.21) |
|                       | HP25- smooth            |       | 0.17(0.12, 0.21) |
### Supplementary Appendix 3: Continued

| Gad, et al.: Hydrophobicity of DBRs | Lazarin et al., 2014 | Yodmongkol et al., 2014 | Pan et al., 2015 | Qian et al., 2016 | Darwish et al., 2019 | Albin-Ameer et al., 2020 | Overall (I²=99%, P=0.00) |
|------------------------------------|---------------------|-------------------------|-----------------|-----------------|-------------------|------------------------|--------------------------|
| HP30- smooth                       | 0.17 (0.13, 0.21)   | Control                | 0.62 (0.45, 0.79) | Control          | 0.12 (0.11, 0.13) | Control                | 0.55 (0.52, 0.58) |
| HP35- smooth                       | 0.21 (0.18, 0.24)   | Silane-SiO₂             | 0.54 (0.43, 0.65)| 236.21 (0.21, 0.23) | 0.12 (0.06, 0.099) | Nano-coat              | 0.21 (0.17, 0.25) |
| HE25- smooth                       | 0.18 (0.14, 0.22)   | Ar/O₂                  | 0.07 (0.05, 0.09)| Cold plasma/Atmos./ 30 S | 0.12 (0.11, 0.13) | Optiglaze              | 0.15 (0.12, 0.18) |
| HE30- smooth                       | 0.16 (0.12, 0.19)   |                        |                 | Cold plasma/Atmos./ 60 S | 0.12 (0.08, 0.16) | Nano-silica            | 0.12 (0.08, 0.16) |
| HE35- smooth                       | 0.18 (0.14, 0.22)   |                        |                 | Cold plasma/Atmos./ 90 S | 0.19 (0.10, 0.28) | Cyanoacrylate          | 0.29 (0.23, 0.35) |
| T25- smooth                        | 0.20 (0.16, 0.24)   |                        |                 | Cold plasma/Atmos./ 120 S |                |                       |                          |
| T30- smooth                        | 0.17 (0.13, 0.21)   |                        |                 |                 |                   |                       |                          |
| T35- smooth                        | 0.16 (0.13, 0.19)   |                        |                 |                 |                   |                       |                          |
| Control- rough                     | 2.17 (0.19, 0.25)   |                        |                 |                 |                   |                       |                          |
| S25- rough                         | 2.17 (0.18, 2.4)    |                        |                 |                 |                   |                       |                          |
| S30- rough                         | 1.96 (1.68, 2.2)    |                        |                 |                 |                   |                       |                          |
| S35- rough                         | 1.94 (1.64, 2.25)   |                        |                 |                 |                   |                       |                          |
| HP25- rough                        | 1.85 (1.58, 2.1)    |                        |                 |                 |                   |                       |                          |
| HP30- rough                        | 1.68 (1.43, 1.9)    |                        |                 |                 |                   |                       |                          |
| HP35- rough                        | 1.82 (1.5, 2.1)     |                        |                 |                 |                   |                       |                          |
| HE25- rough                        | 1.71 (1.5, 1.9)     |                        |                 |                 |                   |                       |                          |
| HE30- rough                        | 1.74 (1.6, 1.93)    |                        |                 |                 |                   |                       |                          |
| HE35- rough                        | 1.76 (1.4, 2.1)     |                        |                 |                 |                   |                       |                          |
| T25- rough                         | 1.85 (1.66, 2.03)   |                        |                 |                 |                   |                       |                          |
| T30- rough                         | 1.65 (1.46, 1.84)   |                        |                 |                 |                   |                       |                          |
| T35- rough                         | 1.81 (1.64, 1.98)   |                        |                 |                 |                   |                       |                          |

Ar/50W; Argon atmosphere at 50 W  
ArO₂/70W; Argon/oxygen atmosphere at 70 W  
AAT/130W; Atmosphere air at 130 W  
Ar/SF₆/70W; Argon atmosphere then plasma treatment in Sulphur hexafluoride atmosphere at 70W  
S; zwitterionic monomer (sulfo betaine methacrylate)  
HP; 2-hydroxypropyl-methacrylate (HPMA)  
HE; 2-hydroxyethyl methacrylate (HEMA)  
T; 2-trimethylammonium ethyl methacrylate  
Gdcl; diamond-like carbon  
Gag; diamond-like carbon doped with silver nanoparticles  
Silane-SiO₂; silane silica  
Ar/O₂; Argon/Oxygen  
Atmos.; Atmospheric pressure  
S; seconds  
TiO₂; Titanium dioxide
## Supplementary Appendix 4: Forest plot for plasma treatment vs roughness (mm)

| Author, year | Treatment | 0  | 0.55 | 1.1 | Mean (95% CI) |
|--------------|-----------|----|------|-----|---------------|
| Zamperini et al., 2010 (a) | Control- smooth | ✔ | | | 0.27(0.23, 0.31) |
| | AAt/130 W- smooth | | | | 0.33(0.28, 0.38) |
| | Ar/ 50 W- smooth | | | | 0.33(0.29, 0.37) |
| | ArO₂/70 W- smooth | | | | 0.29(0.25, 0.33) |
| | ArSF₆/70 W- smooth | | | | 0.29(0.25, 0.33) |
| | Control- rough | | | | 1.76(1.38, 2.1) |
| | AAt/130 W- rough | | | | 2.08(1.89, 2.26) |
| | Ar/ 50 W- rough | | | | 1.86(1.57, 2.15) |
| | ArO₂/70 W- rough | | | | 1.75(1.5, 2.0) |
| | ArSF₆/70 W- rough | | | | 1.82(1.6, 2.06) |
| Zamperini et al., 2010 (b) | Control- smooth | | | | 0.30(0.27, 0.33) |
| | AAt/130 W- smooth | | | | 0.28(0.24, 0.32) |
| | Ar/ 50 W- smooth | | | | 0.30(0.26, 0.34) |
| | ArO₂/70 W- smooth | | | | 0.28(0.24, 0.32) |
| | ArSF₆/70 W- smooth | | | | 0.28(0.24, 0.32) |
| | Control- rough | | | | 1.68(1.4, 1.9) |
| | AAt/130 W- rough | | | | 1.95(1.69, 2.21) |
| | Ar/ 50 W- rough | | | | 1.86(1.62, 2.1) |
| | ArO₂/70 W- rough | | | | 1.61(1.4, 1.8) |
| | ArSF₆/70 W- rough | | | | 1.79(1.54, 2.0) |
| Pan et al., 2015 | Control | | | | 0.07(0.05, 0.09) |
| | ArO₂ | | | | 0.07(0.05, 0.09) |
| Qian et al., 2016 | Control | | | | 0.22(0.21, 0.23) |
| | Cold plasma/ Atmos./ 30 S | | | | 0.23(0.22, 0.24) |
| | Cold plasma/ Atmos./ 60 S | | | | 0.23(0.22, 0.24) |
| | Cold plasma/ Atmos./ 90 S | | | | 0.21(0.19, 0.23) |
| | Cold plasma/ Atmos./ 120 S | | | | 0.22(0.21, 0.23) |
| Overall (I²=99%, P=0.00) | | | | | 0.549(0.5, 0.59) |

(Ar/50W)- Argon atmosphere at 50 W
(ArO₂/70W)- Argon/oxygen atmosphere at 70 W
(AAt/130W)- Atmosphere air at 130 W
(As/SF₆/70W)- Argon atmosphere then plasma treatment in Sulphur hexafluoride atmosphere at 70W Atmos.- Atmospheric pressure
S- seconds
### Supplementary Appendix 5: Forest plot for fillers vs roughness (mm)

| Author, year       | Treatment     | 0.05 | 0.16 | 0.27 | Mean (95% CI)       |
|--------------------|---------------|------|------|------|---------------------|
| Al-Bakri et al., 2014 | Control       |      |      |      | 0.2 (0.18, 0.22)    |
|                    | 1% glass filler |      |      |      | 0.24 (0.19, 0.29)   |
|                    | 2.5% glass filler |      |      |      | 0.27 (0.23, 0.31)   |
|                    | 5% glass filler |      |      |      | 0.30 (0.26, 0.34)   |
|                    | 10% glass filler |      |      |      | 0.38 (0.33, 0.43)   |
| Sawada et al., 2014 | Control       |      |      |      | 0.1 (0.10, 0.12)    |
|                    | TiO$_2$       |      |      |      | 0.12 (0.11, 0.13)   |
|                    | HAp-TiO$_2$   |      |      |      | 0.13 (0.12, 0.14)   |
|                    | FAp-TiO$_2$   |      |      |      | 0.12 (0.11, 0.13)   |
| Fouda et al., 2019 | Control       |      |      |      | 0.129 (0.125, 0.13) |
|                    | 0.5% ND       |      |      |      | 0.039 (0.036, 0.04) |
|                    | 1% ND         |      |      |      | 0.047 (0.04, 0.05)  |
|                    | 1.5% ND       |      |      |      | 0.102 (0.096, 0.108) |
| Overall (I$^2$=99%, P=0.00) |              |      |      |      | 0.16 (0.134, 0.187) |

Glass filler: silane coated glass filler with 15% w/w fluoride  
TiO$_2$: Titanium dioxide  
HAp-TiO$_2$: Hydroxyapatite-coated titanium dioxide  
Fap- TiO$_2$: Fluoroapatite-coated titanium dioxide  
ND: Nano-diamond