Elena Günther, Nadine Kommerein, Sebastian Hahnel

Biofilms on polymeric materials for the fabrication of removable dentures

Introduction: Oral microorganisms can contribute to the pathogenesis of many diseases in the oral cavity such as caries, periodontitis, peri-implantitis and denture-related stomatitis. Yet, oral microorganisms may also have a considerable influence on the onset of systemic medical conditions such as lung or cardiovascular diseases. Microorganisms are organized in biofilms and they colonize teeth, mucosa, and dental restorations; the extent to which biofilms are accessible during self-performed oral hygiene varies widely.

Discussion: The current demographic trends show that the population is getting older and that an increasing number of elderly and multimorbid patients require nursing care, most of whom already have and/or will receive removable dentures in the future. Impaired motor skills and cognitive abilities often lead to difficulties in self-performed oral hygiene, thus making these patients reliant on others for assistance. The regular accumulation of biofilm on removable dentures, which is not sufficiently removed, may trigger and foster the onset of oral and systemic diseases in immunologically compromised patients. Usually, removable dentures are fabricated from polymeric materials and polymethylmethacrylate is the most frequently used material. In spite of this, many new materials are currently being introduced on the market which can be used to make removable dentures. The range of available materials has become increasingly broad and it includes materials based on polymethylmethacrylate as well as composite-based materials and polymeric materials with a distinct polymer chemistry. Relevant differences exist between the bioadhesion of materials that are processed using classical methods as compared to CAD/CAM-manufacturing.

Conclusion: In this context, the current article aims to describe the importance of biofilms on removable dentures, to outline relevant interactions of oral microorganisms with the surface of polymeric materials, and to present strategies for minimizing bioadhesion on removable dentures.

Keywords: polymeric materials; removable dentures; microorganisms; biofilms; CAD/CAM-manufacturing

Department of Prosthodontics and Dental Materials Science, University Leipzig, Germany: Elena Günther; Prof. Dr. Sebastian Hahnel
Department of Prosthodontics and Biomedical Materials Science, Medical University Hannover, Germany: Dr. Nadine Kommerein
Lower Saxon Centre for Biomedical Engineering, Implant Research and Development (NIFE), Hannover, Germany: Dr. Nadine Kommerein
Translation from German: Christian Miron
Citation: Günther E, Kommerein N, Hahnel S: Biofilms on polymeric materials for the fabrication of removable dentures. Dtsch Zahnärztl Z Int 2020; 2: 142–151
Peer-reviewed article: submitted: 06.12.2019, revised version accepted: 20.03.2020
DOI.org/10.3238/dzz-int.2020.0142–0151

1. The etiology and pathogenesis of biofilm-associated diseases in patients with removable dentures

1.1 The importance of removable dentures

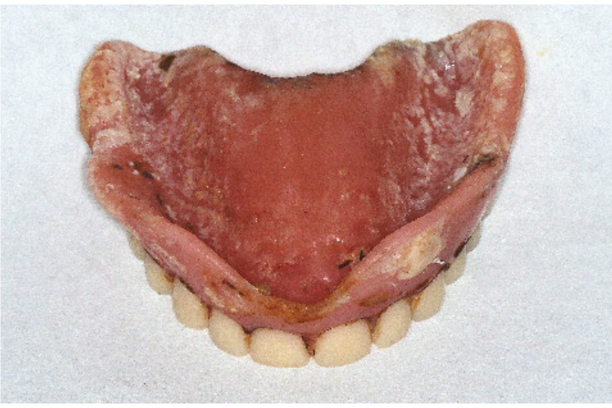
Over the past few decades, both dental care and oral health awareness have notably improved in Germany so that an increasing number of people still have their natural teeth, even at an advanced age [47]. To illustrate this, the number of edentulous patients have halved over the last 20 years; while in 1997 about 25 % of younger seniors between the ages of 65 and 74 years were edentulous, only about 12 % are edentulous nowadays [47]. Nevertheless, almost half of the younger seniors (46 %) wear removable dentures, which underlines their lasting importance in dentistry. For older seniors falling into the age group between 75 to 100 years, and who are also in need of nursing care, the proportion of denture wearers increases up to 86 % [47]. Removable dentures cover large areas of mucous membrane, and thus, provide an extended attachment surface with optimal living conditions for microorganisms; this favors their growth and proliferation together with biofilm formation. Just like for teeth, biofilms that adhere to dentures should be regularly removed. Yet, for older patients in need of nursing care, this is especially difficult to accomplish due to their often limited motor and cognitive abilities (see Fig. 1 and 2). Nearly 30 % of older seniors receiving nursing care claim that they depend on extra assistance for denture and oral hygiene [47]; this emphasizes the importance of instructing nursing care personnel as well as any other caregivers [93]. Regardless of this fact, the time that caregivers have to help seniors with their daily oral and denture hygiene is limited for a number of reasons [23, 48, 78, 79, 107]. One such motive is that nursing staff have high general care workloads, which means that they have very short time frames for assisting patients with oral hygiene. Secondly, it appears that nurses have deficits with regard to dental training, which leads to difficulties in the recognition, insertion, removal, and cleaning of dentures. Studies have also revealed that care receivers' refusal to accept help with oral hygiene is a further problem, as is the fear of contact on the part of the caregiver [7]. In spite of these background challenges, the mechanical cleaning of removable dentures is still the gold standard, as the simple application of chemical cleaners is not always sufficient, and should therefore be viewed as a supportive measure, particularly with regard to the removal of microorganisms [32].

1.2 Materials used to produce removable dentures

For the fabrication of removable dentures, materials are differentiated based on whether they are processed into rigid or flexible dentures. Various polymer systems for the fabrication of removable dentures are available on the market, which can be grouped according to the method of processing [90] (see Table 1). The first group consists of materials that can be cured with the help of pressure, heat (special form: microwaves) or light. A second group of materials includes thermoplastic materials, which do not require curing, but are formed by using heat before they solidify. The third group includes industrially cured or thermoplastically processed materials that are subsequently available as CAD/CAM blocks, from which, dental restorations and dentures can be milled.

Polymethylmethacrylate (PMMA) represents the most important self and warm curing resin. It is the most commonly used denture material in everyday practice. PMMA is appealing due to its low cost as well as its ease of reparation and handling [80]. However, the high rigidity of the material has disadvantages such as increased fracture susceptibility and reduced wearing comfort.

Urethane dimethacrylates belong to the group of light-curing resins that are kneadable during processing before their subsequent curing in special ovens with the aid of light. In the fabrication of partial and complete dentures, this processing technique spares the wax-up step [90]. Other applications of light-curing resins include the manufacturing of individual trays, denture relining or orthodontic appliances. In the finished state, they show increased strength compared to warm curing resins [17], but are more brittle and difficult to repair [92].



Figures 1 and 2 Maxillary and mandibular dentures with extensive biofilm deposits and discoloration due to poor denture hygiene belonging to two patients (91 and 77 years old) in need of care

Curable resins		Thermoplastic polymers	CAD/CAM-polymers
Warm or cold curing resins	Light-curing resins		
Polymethyl methacrylate (PMMA)	Urethane dimethacrylate (UDMA)	Polyamides (Nylon)	Polymethyl methacrylate (PMMA)
		Thermoplastic PMMA	Polyaryletherketone (PAEK)
		Polyoxymethylene (POM)	
		Polyaryletherketone (PAEK)	

Table 1 Overview of different processing forms of polymer materials with examples

The group of thermoplastics represents plastic materials which are shaped by the application of heat during the manufacturing of removable dentures, and which have flexible properties after cooling. Due to the elimination of the curing process, neither bite lock nor the presence of residual monomers occur [90]. This material group is thus the favored one for use in patients with methyl methacrylate allergies. Important thermoplastic materials are polyamide-based plastics, for example, which can be used to manufacture flexible dentures. These have the advantage of being easier to fit in the mouth in patients with limited mouth opening (Microstomia). Moreover, they have minimal fracture susceptibility due to their high elasticity [90]. In addition, these materials also have esthetic advantages, as gingiva-colored clasp components can be produced from the material. Disadvantages of polyamides are their limited capacity to be repaired and polished [92]. Moreover, due to their elasticity, there is discussion regarding unfavorable pressure distribution, which can result in increased atrophy of the alveolar ridge [11]. Industrially cured thermoplastic PMMA materials can also be classified in the group of thermoplastics. Yet, in contrast to their counterparts, which are manufactured using the conservative process, they have a lower residual monomer content, but at the same time, also a reduced repair capacity. Another member of thermoplastic materials is polyoxymethylene (POM) which can be used to produce tooth-colored denture frameworks and clasps. Due to the possibility of designing POM frameworks in gingiva color, the fabrication of complete denture bases from POM is conceivable. However, this material cannot be extended and it requires greater spatial dimensions compared to metal clasps and frameworks [92].

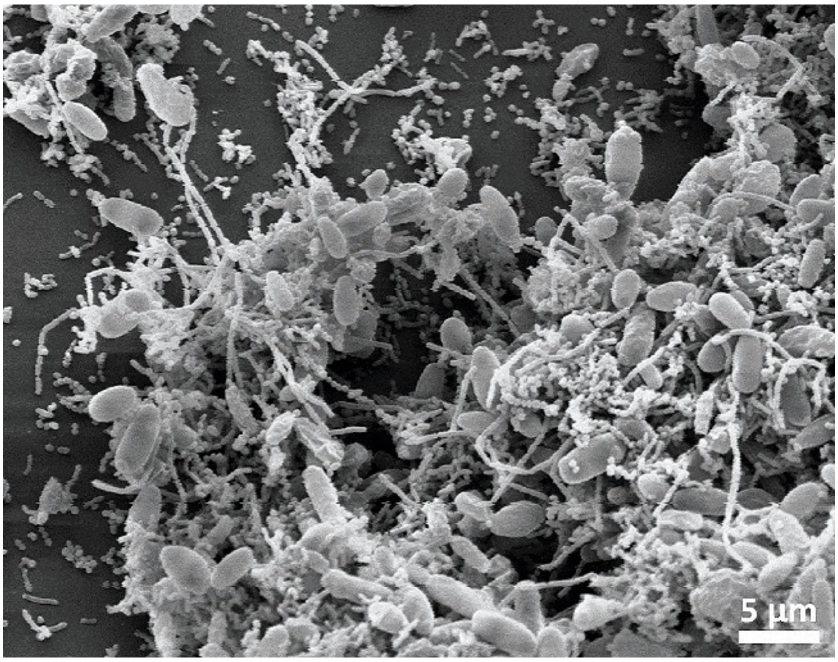
Newer processing methods that employ CAD/CAM-manufacturing enable the milling of denture bases, complete dentures and denture frameworks from industrially prefabricated blocks. Industrially pre-cured PMMA is suitable for the production of denture bases or complete dentures. The absence of polymerization shrinkage and a low residual monomer content are significant advantages compared to conservatively processed PMMA. Moreover, the more homogeneous and pore-free nature of CAD/CAM materials appears to have a positive influence on their mechanical properties [90, 97]. The polyaryletherketones (PAEK) are suitable, stable alternative framework materials that are used in the CAD/CAM-manufacturing of denture frameworks for complex removable dentures for patients with allergies against metals [33]. PAEKs belong to the family of high-performance thermoplastics, which were introduced to the dental market in 2006 [90, 94]; prior to that, they were used during spinal surgery for instance. PAEK materials have improved mechanical properties [73, 97], low weight [33] and a low interaction with biological materials, which contributes to their low allergenic potential [113]. However, the capacity to repair or extend PAEKs is low and they scratch faster than PMMA [41]. Furthermore, to date, there is hardly any clinical data on the long-term performance of these materials in an oral cavity. Regardless of the material, CAD/CAM-manufacturing allows the easy reproducibility of dentures in case of loss or damage thanks to the stored CAD/CAM data. Also, denture modifications such as relining can be made digitally and the dentures can then be manufactured again [90].

Since the supporting alveolar bone for a denture changes in the course of the wearing period, relining to improve mastication and reduce pressure points may be indicated. For this purpose, a distinction is made between rigid relining materials such as cold curing PMMA and soft relining materials based on silicone or acrylate [52, 85]. The latter group of materials is mainly used for removable denture relining in cases of unfavorable morphology of the alveolar process; examples include strongly undermined alveolar ridges, flabby ridges or strongly atrophied alveolar ridges with an exposed inferior alveolar nerve [16]. Moreover, these materials are indicated in situations that require minimal load on the denture supporting tissues such as after surgical interventions (e.g. extractions or implant insertion).

1.3 Biofilm formation

The oral cavity provides habitat for a variety of microorganisms, with bacteria and fungi being the main colonizers of teeth, mucous membranes and dentures (see Fig. 3). Over 700 different types of bacteria have been identified as components of the oral microbiome [50]. Before bacteria or fungi attach themselves to teeth or dental restorations and form biofilms, a so-called acquired pellicle develops on all natural surfaces of the oral cavity and on the surface of dental restorations within seconds to minutes after cleaning [37, 46, 104]. The pellicle consists mainly of proteins (including enzymes), carbohydrates and lipids derived from saliva, gingival sulcus fluid or bacteria [38]. Their formation is initially based on electrostatic interactions. The phosphate ions contained in saliva contribute to the negative charge of teeth and dentures; the positively charged calcium ions, which are also present in saliva, are therefore attracted via electrostatic forces and embed proteins (e.g. phosphoproteins, statorin, histatin) in between the ion layers. Additionally, Van der Waals forces and protein-specific charged functional groups increase the adhesion of the initial pellicle to the surface of teeth and dentures [105, 106]. Furthermore, the subsequent coupling of protein aggregates from saliva via protein-protein interactions with the already immobilized proteins of the initial pellicle follows.

Pellicles display different ultrastructures and thicknesses depending on their location, with these being mostly determined by the salivary biopolymers present at the respective location and the existing shear forces, but less by material-related parameters [36]. However, the material itself influences the composition of the pellicles. For example, fewer statherines and histatines, which are responsible for defense, are found on denture materials [22]. At the same time, the pellicle can hide the properties of the underlying substrate [28, 35]. Other than serving to lubricate and protect



(Fig. 1, 2 and Tab. 1: E. Günther; Fig. 3: N. Kommerein)

Figure 3 Scanning electron microscope image of an oral multi-species biofilm from the plaque of a patient suffering from periodontitis after 72 hours of anaerobic in-vitro cultivation on glass

tooth surfaces, pellicles play an equally important role for microbial attachment to teeth and removable dentures. Components of the pellicle serve as receptors for the attachment of microorganisms. Initially, mainly Gram-positive streptococci (e.g. Streptococcus oralis, Streptococcus sanguinis, Streptococcus mitis) and rods (e.g. Actinomyces naeslundii or oris) colonize the pellicle, thus making them among the early colonizers. As the bacterial biofilm matures, further microorganisms are integrated into the biofilm over a period of days. Gram-negative cocci (e.g. Veillonella spp.) attach themselves to the early colonizers at first. Then, they are followed by Gram-negative, filamentous species such as the bridge germ Fusobacterium nucleatum and late colonizers (e.g. Capnocytophaga sputigena, Porphyromonas gingivalis, Aggregatibacter actinomycetemcomitans, Treponema denticola, Tannerella forsythia, Prevotella intermedia), some of which are leading germs of oral infections [54, 61, 62]. Fungi such as Candida albicans can also interact with bacteria such as Streptococcus gordonii, S. oralis, S. sanguinis [57, 81], A. oris [31] and F. nucleatum [30] and take part in the complex oral biofilm community [112]. Yet, the presence of specific pathogens alone is not sufficient for the development of diseases in the oral cavity. Instead, the dynamic interactions between the microorganisms and the host organism, particularly the host's immune defense, play a decisive role in the development of biofilm-associated diseases. Diseases that can be caused by oral microorganisms include both local manifestations as well as systemic diseases.

1.4 Local diseases caused by biofilms in denture wearers

The fungus C. albicans is of particular importance in this context, as it plays an essential role in the development of denture-related stomatitis [10]. Wearers of complete dentures are more likely to develop denture-related stomatitis than wearers of partial dentures [1], which is most likely resulting from the larger interface. Denture-related stomatitis has a prevalence of up to 75 % [27]; it manifests itself as local redness of the mucosa that is covered by the denture and is often accompanied by burning, discomfort, impaired taste or pain. The development of denture-related stomatitis is dependent on several favoring factors. Inadequate oral and denture hygiene, wearing of the denture all day with the associated reduction in the pH value of the oral mucosa to below 6.5, as well as a weakened immune system can promote the manifestation of C. albicans [27, 63]. In this way, the virulence of C. albicans appears to grow with increasing biofilm maturation, as the fungus undergoes a morphological transformation from predominantly blastospores to hyphae [98]. Studies have revealed that the material surface can also trigger the transformation of blastospores into hyphae [16, 20, 87]. The latter microorganisms are able to invade the affected mucous membrane areas with the help of enzymes and penetrate deeper into mucous membrane layers [10, 59, 98]. Aspartate proteinases, in particular, appear to accelerate the degradation of host proteins and thus promote the invasion of C. albicans [42]. Studies have proven that the activity of proteinases correlates with the severity of denture-related stomatitis [89]. Moreover, C. albicans which were organized in biofilms showed higher aspartate proteinase secretion levels than planktonic C. albicans [68]. This fungus, like other microorganisms, can also degrade material surfaces, which leads to material roughening and the further irritation of the mucosa [87].

1.5 Systemic diseases triggered by biofilms in denture wearers

In recent years, numerous studies have shown that microorganisms in the oral cavity can substantially influence and promote the development of systemic diseases. Oral infections such as periodontitis lead to cell aging (senescence): in comparison to healthy patients, the telomerase activity of affected patients is increased and cannot be reduced, or only slightly reduced, by protective measures such as exercise [67]. Other studies have identified oropharyngeal bacteria in atherosclerotic plaques [5, 21, 69], which suggests that bacteria can enter the bloodstream via the periodontal support apparatus, and thus, promote the development of cardiovascular diseases. With regard to the importance of biofilms on removable dentures, respiratory pathogens have been detected in biofilms on dentures [82, 103], which confirms an association between the occurrence of pneumonia and the wearing of removable dentures [23, 43]. The presence of respiratory pathogens in biofilms on teeth and dentures seems to be related to the pathogenesis of nosocomial pneumonia, but also to the initiation or progression of chronic obstructive pulmonary disease [91]. Pneumonia is one of the most common diseases in the elderly population and, with a mortality rate of 25 %, is one of the most frequent causes of death [76, 95]. In particular, swallowing disorders (dysphagia), wearing dentures at night, inadequate denture hygiene and a weakened immune system favor the development of aspiration pneumonia [71, 91]. Besides aspiration pneumonia, gastrointestinal infections belong to possible disseminated infections caused by the accumulation of oropharyngeal bacteria on denture surfaces [77].

Various studies have shown that improved oral hygiene, with the accompanying lower germ load, has a positive effect on morbidity and mortality from pneumonia: In this manner, 10 % of pneumonia-related deaths in nursing homes could be prevented by improved oral hygiene [95]. Optimized oral hygiene also seems to be more effective in reducing pneumonia-related mortality rates than drug therapy. Besides this, patients with improved oral and denture care experienced a shorter fever duration than patients who did not intensify oral and denture hygiene [109].

2. Modern materials and strategies for modulating biofilm formation and removal from removable dentures

In the development of new dental materials, the optimization of mechanical properties such as flexural strength, resistance to fracture or hardness and the improvement of the esthetic appearance are often the major focus. However, the above-mentioned considerations concerning the prevalence and importance of biofilms on removable dentures show that strategies, which minimize the adhesion of biofilms to removable denture materials, or allow easy removal of these biofilms from the surface of the dentures, could contribute significantly to maintaining the oral and systemic health of denture wearers. For this reason, in addition to optimizing the mechanical and esthetic properties of denture materials, biological considerations should also be taken into account when these materials are further developed.

2.1 Modification of biofilm formation on removable dentures by means of material properties

For the adhesion of biofilms on polymeric materials, it seems that their chemical composition, in particular, as well as their surface roughness, energy and topography are relevant properties. In general, their influence decreases with increasing biofilm thickness [35]; this substantiates the idea that a potentially preventive influence of the material must be maintained by regular mechanical removal of the adhering biofilm. This further implies that innovative material-associated strategies for controlling biofilms on polymeric materials for the production of dentures must have sufficient resistance to withstand the necessary repeated mechanical cleaning.

A high surface roughness generally causes an increased accumulation of microorganisms due to the increased surface area available for adhesion and the furnishing of niches protecting against shear forces, which can in turn be decreased by polishing. Although macrofilled resin composites of earlier generations, especially, were associated with high surface roughness, and thus high plaque accumulation, modern hybrid resin composites show much better behavior in this regard [44]. However, different degrees of biofilm adhesion were observed for different CAD/CAM materials despite comparable surface roughness. The group of polymers showed the lowest biofilm adhesion: Polymer materials such as denture base materials have a larger proportion of organic components, which presumably cause less bioadhesion than inorganic components [4]. To date, there have been very few studies regarding the accumulation of biofilms on modern materials for the CAD/CAM-fabrication of removable dentures. Lower surface roughness values and lower adhesion of C. albicans have been demonstrated for PMMA processed by CAD/CAM than for PMMA produced by conventional methods [72]. Hence, it can be assumed that, in addition to improved mechanical properties, biofilm adhesion is also lower for removable dentures fabricated using CAD/CAM technology as compared to conventional fabrication of polymer materials [83, 97].

The chemical composition of polymeric materials also appears to play an important role in the adhesion of microorganisms. The addition of antibacterial substances to dental materials can be one means of delaying or minimizing biofilm adhesion and growth. Possible antibacterial additives include silver ions [15, 108], zinc oxide nanoparticles [101] and chlorhexidine [60]. The best known antibacterial dental material is amalgam. However, the example of amalgam shows that the development of effective antibacterial materials is always a balancing act between antibacterial [9, 40] and cytotoxic effects [64]. Furthermore, the release of antibacterial substances has the disadvantage of having a temporary effect. Substances which are added, or more specifically, their release can have a negative influence on the mechanical properties [2, 51, 110]. It has been shown that with increasing polymerization time of resin composites, and thus with a presumably decreasing concentration of uncured monomers, the adhesion and proliferation of some bacterial strains also decreases [14]. Consequently, not only for mechanical, but also for biological reasons, the careful curing of the corresponding materials by heat, pressure and/or light based on the manufacturer‘s instructions is strongly recommended. In recent years, the processing and machining of dental materials such as PAEK or PMMA by means of CAD/CAM-processing has become established. Unfortunately, there are only a few studies investigating biofilm formation on PAEK materials [96]. Some studies have presented a lower bioadhesion on PAEK materials than, for example, on conventionally processed PMMA [35,70]. To date, however, it has not been conclusively clarified which mechanism is responsible for this finding. One assumption is the more homogeneous composition and high curing degree of CAD/CAM vs. conservatively processed materials.

Studies on the effect of the surface topography of dental resin composites on the adhesion of microorganisms show that microstructured surfaces are more hydrophobic due to higher water contact angles, thus resulting in increased air inclusions, which in turn reduces the total available contact area between materials and microorganisms [25]. In addition, the topographic barriers lead to a reduction in Quorum Sensing between the microorganisms [25]. For direct dental restorations, this effect can be exploited by using microstructured matrices for filling placement. With the aim of optimizing polymeric materials for indirect dental restorations, special polishing regimes are conceivable that leave a specially structured surface. Studies have shown that different polishing regimes, which produce diverse surface patterns, tend to have different degrees of bioadhesion, even if they have a comparable final roughness [34, 44, 86]. With regard to denture bases that are not polishable, the fabrication of removable dentures using CAD/CAM-processing could be interesting, since these materials appear to exhibit positive properties with regard to biofilm adhesion [72]. While the surface topography of polymers can be modified by polishing and production methods, biomimetic microstructuring of metals is possible with the aid of special lasers and this has shown reduced microorganism attachment [3, 18]. Thus, the surface structuring of metal denture frameworks using laser offers a prospect for the further development of dental biomaterials.

The effects of different denture materials and their surface properties on bacterial adhesion and biofilm formation have not yet been sufficiently characterized. However, the elucidation of the underlying mechanisms could make a significant contribution to the future optimization of denture materials from a biological point of view; the aim would be to reduce the prevalence of biofilm-induced diseases in denture wearers in the long term. For both approaches, elucidation of mechanisms and development of innovative denture materials, reproducible model systems close to clinical practice can be used; the oral multi-species biofilm model can, for example, be used for in-vitro studies under static and under dynamic flow conditions that resemble clinical practice [55, 56]. This model is already being used in dental implant research [19]. Such in-vitro analyzes, which are frequently performed by means of high throughput screening, should be complemented, or validated, by in-situ studies, such as by placing test specimens in splints or dentures. In-situ approaches have the advantage of allowing biofilm formation to occur under the natural conditions of the oral cavity.

2.2 Modification of the adhesion of Candida albicans on removable dentures through material properties

Since denture bases are usually not polished and the denture plastic can be penetrated by C. albicans [66], the rebasing or the new fabrication of the denture is advisable, especially for older dentures and existing denture-related stomatitis, so as to avoid reinfection after antimycotic therapy of the mucous membranes [58]. It is known that C. albicans reacts less sensitively to antifungal therapy, particularly in pores of rough material surfaces [102] and leaves endotoxins in these pores, which further sustain the infection by slow release [16]. A reduced attachment of C. albicans occurs on smooth and hydrophilic surfaces [29, 75, 88, 100, 111]. Additionally, a relationship between the basic part of the surface free energy and the adhesion of C. albicans could be demonstrated [49]. Furthermore, it has been shown that the adhesion of C. albicans to polyamides is higher than to PMMA-based resins [24]. With regard to the different materials available, there are contradictory results concerning the adhesion and proliferation of C. albicans: While some authors demonstrated a significantly higher Candida colonization of PMMA than on silicone-based soft relining materials [80], other authors were able to demonstrate a lower colonization of PMMA with C. albicans as compared to the soft relining materials [6]. A possible explanation for these varying results could be related to the porosity of soft relining materials, which may harbor a large number of Candida cells in their pores and make them inaccessible for analysis, thus conceivably falsifying the results [80]. It could also be shown that materials with high surface energies such as urethane dimethacrylate (UDMA) and silicone displayed higher colonization with C. albicans than materials with comparatively lower surface energies [53]. The proportion of hyphae on silicone-based materials was higher than on UDMA- or PMMA-based materials [98].

In this regard, it is worth considering that most of the present investigations, especially with respect to the analysis of the adhesion of C. albicans to different denture base materials, have been carried out under experimental conditions; this means that the settings are often not very comparable and this is further complicated by the fact that clinical investigations barely exist. In spite of this, based on the available data, it can be concluded that for the production of denture bases, hydrophilic materials should be used as far as possible, as well as materials that have the lowest possible initial roughness after production; in this manner, porosities, and thus niches for biofilm formation, can be minimized in order to reduce biofilm-associated diseases.

3. Microorganisms change materials

Every material that is introduced into the oral cavity is subject to an ageing process as a result of use. The surfaces of removable dentures are no exception and they show signs of ageing and fatigue due to the daily mechanical, thermal and chemical stress during use and cleaning [90]. In the long term, this can lead to surface roughness, discoloration and odor. In addition, the moisture in the oral cavity and the moist extraoral storage environment cause the material to absorb water, which varies in extent depending on the material, and can lead to a reduction in the strength of the material [99]. It appears that thermoplastics absorb less water than cured resin materials [45]. Drying of the denture in turn can lead to distortion and a reduced accuracy of fit, although, shorter drying phases can reduce the formation of bacteria on the surface of the material [90]. In addition, microorganisms play a decisive role in the modification of polymer denture materials [8, 26, 39, 84]. Even pellicle intercalation between the matrix and filler material can cause fillers to dissolve out of the resin composite, and thus, favor the polymer‘s deterioration. Some of the enzymes that are secreted by microorganisms [13], in addition to acids, can degrade material surfaces [12, 65]. This can increase the surface roughness of the materials [74], which on the one hand, promotes bioadhesion, while also simultaneously irritating the mucosa in contact. This phenomenon seems to affect the polymer materials of older generations especially [74]. Therefore, the use of newer generation polymer materials as well as regular professional cleaning and polishing of polymer-based restorations seem to be recommendable. However, no clinical or experimental data is available to date regarding the long-term durability of modern materials that are used for the fabrication of removable dentures such as PAEKs or CAD/CAM-processed PMMA [96].

4. Future prospects

Removable dentures will play an important role in dental prosthetics in the foreseeable future. Due to the current demographic trends, an increasing number of older patients are being treated with dentures. Since regular and adequate removal of biofilms from the surface of removable dentures cannot be ensured in all cases, it would be desirable to develop materials and strategies that make the biofilm accumulation on, and the removal from, denture surfaces manageable and predictable. Currently, the available data from clinical studies regarding the interaction between polymeric materials of removable dentures and biofilms is rather sparse. The first reported results for modern polymeric materials with optimized material properties have been promising. Further strategies that promise the easy removal of adherent biofilms from the surface of denture base materials have so far only been described in very limited laboratory studies, mostly with a different background. At the moment, research regarding clinical applications is still pending.

Conflicts of interest

The authors declare that there is no conflict of interest within the meaning of the guidelines of the International Committee of Medical Journal Editors.

References

1. Abaci O, Haliki-Uztan A, Ozturk B, Toksavul S, Ulusoy M, Boyacioglu H: Determining Candida spp. incidence in denture wearers. Mycopathologia 2010; 169: 365–372

2. Al-Haddad A, Vahid Roudsari R, Satterthwaite JD: Fracture toughness of heat cured denture base acrylic resin modified with Chlorhexidine and Fluconazole as bioactive compounds. J Dent 2014; 42: 180–184

3. Aliuos P, Fadeeva E, Badar M et al.: Evaluation of single-cell force spectroscopy and fluorescence microscopy to determine cell interactions with femtosecond-laser microstructured titanium surfaces. J Biomed Mater Res A 2013; 101: 981–990

4. Astasov-Frauenhoffer M, Glauser S, Fischer J, Schmidli F, Waltimo T, Rohr N: Biofilm formation on restorative materials and resin composite cements. Dent Mater 2018; 34: 1702–1709

5. Atarbashi-Moghadam F, Havaei SR, Havaei SA, Hosseini NS, Behdadmehr G, Atarbashi-Moghadam S: Periopathogens in atherosclerotic plaques of patients with both cardiovascular disease and chronic periodontitis. ARYA Atheroscler 2018; 14: 53–57

6. Bal BT, Yavuzyilmaz H, Yücel M: A pilot study to evaluate the adhesion of oral microorganisms to temporary soft lining materials. J Oral Sci 2008; 50: 1–8

7. Barbe AG, Kottmann HE, Müller D et al.: Evaluation of time and resources required for professional dental cleaning in nursing home residents. Spec Care Dentist 2019; 39: 89–96

8. Beyth N, Bahir R, Matalon S, Domb AJ, Weiss EI: Streptococcus mutans biofilm changes surface-topography of resin composites. Dent Mater 2008; 24: 732–736

9. Beyth N, Domb AJ, Weiss EI: An in vitro quantitative antibacterial analysis of amalgam and composite resins. J Dent 2007; 35: 201–206

10. Bilhan H, Sulun T, Erkose G et al.: The role of Candida albicans hyphae and Lactobacillus in denture-related stomatitis. Clin Oral Investig 2009; 13: 363–368

11. Blankenstein F: Verwendung thermoplastischer Nylon-Kunststoffe als Prothesenbasismaterial. Mitteilung der DGZPW. zm 2009; 99: 42–44

12. Borges MAP, Matos IC, Mendes LC, Gomes AS, Miranda MS: Degradation of polymeric restorative materials subjected to a high caries challenge. Dent Mater 2011; 27: 244–252

13. Bourbia M, Ma D, Cvitkovitch DG, Santerre JP, Finer Y: Cariogenic bacteria degrade dental resin composites and adhesives. J Dent Res 2013; 92: 989–994

14. Brambilla E, Gagliani M, Ionescu A, Fadini L, García-Godoy F: The influence of light-curing time on the bacterial colonization of resin composite surfaces. Dent Mater 2009; 25: 1067–1072

15. Buergers R, Eidt A, Frankenberger R et al.: The anti-adherence activity and bactericidal effect of microparticulate silver additives in composite resin materials. Arch Oral Biol 2009; 54: 595–601

16. Cate JM ten, Klis FM, Pereira-Cenci T, Crielaard W, de Groot, P W J: Molecular and cellular mechanisms that lead to Candida biofilm formation. J Dent Res 2009; 88: 105–115

17. Diaz-Arnold AM, Vargas MA, Shaull KL, Laffoon JE, Qian F: Flexural and fatigue strengths of denture base resin. J Prosthet Dent 2008; 100: 47–51

18. Doll K, Fadeeva E, Schaeske J et al.: Development of laser-structured liquid-infused titanium with strong biofilm-repellent properties. ACS Appl Mater Interfaces 2017; 9: 9359–9368

19. Doll K, Yang I, Fadeeva E et al.: Liquid-infused structured titanium surfaces: antiadhesive mechanism to repel streptococcus oralis biofilms. ACS Appl Mater Interfaces 2019; 11: 23026–23038

20. Douglas L: Candida biofilms and their role in infection. Trends Microbiol 2003; 11: 30–36

21. Eberhard J, Stumpp N, Winkel A et al.: Streptococcus mitis and Gemella haemolysans were simultaneously found in atherosclerotic and oral plaques of elderly without periodontitis – a pilot study. Clin Oral Investig 2017; 21: 447–452

22. Edgerton M, Levine MJ: Characterization of acquired denture pellicle from healthy and stomatitis patients. J Prosthet Dent 1992; 68: 683–691

23. El-Solh AA: Association between pneumonia and oral care in nursing home residents. Lung 2011; 189: 173–180

24. Freitas-Fernandes FS, Cavalcanti YW, Ricomini Filho AP et al.: Effect of daily use of an enzymatic denture cleanser on Candida albicans biofilms formed on polyamide and poly(methyl methacrylate) resins: an in vitro study. J Prosthet Dent 2014; 112: 1349–1355

25. Frenzel N, Maenz S, Sanz Beltrán V et al.: Template assisted surface microstructuring of flowable dental composites and its effect on microbial adhesion properties. Dent Mater 2016; 32: 476–487

26. Fúcio SBP, Carvalho FG, Sobrinho LC, Sinhoreti MAC, Puppin-Rontani RM: The influence of 30-day-old Streptococcus mutans biofilm on the surface of esthetic restorative materials – an in vitro study. J Dent 2008; 36: 833–839

27. Gendreau L, Loewy ZG: Epidemiology and etiology of denture stomatitis. J Prosthodont 2011; 20: 251–260

28. Göcke R, Gerath F, Schwanewede H von: Quantitative determination of salivary components in the pellicle on PMMA denture base material. Clin Oral Investig 2002; 6: 227–235

29. Gomes AS, Sampaio-Maia B, Vasconcelos M, Fonesca PA, Figueiral H: In situ evaluation of the microbial adhesion on a hard acrylic resin and a soft liner used in removable prostheses. Int J Prosthodont 2015; 28: 65–71

30. Grimaudo NJ, Nesbitt WE: Coaggregation of Candida albicans with oral Fusobacterium species. Oral Microbiol Immunol 1997; 12: 168–173

31. Grimaudo NJ, Nesbitt WE, Clark WB: Coaggregation of Candida albicans with oral Actinomyces species. Oral Microbiol Immunol 1996; 11: 59–61

32. Hahnel S, Rosentritt M, Buergers R, Handel G, Lang R: Candida albicans biofilm formation on soft denture liners and efficacy of cleaning protocols. Gerodontology 2012; 29: e383–91

33. Hahnel S, Scherl C, Rosentritt M: Interim rehabilitation of occlusal vertical dimension using a double-crown-retained removable dental prosthesis with polyetheretherketone framework. J Prosthet Dent 2018; 119: 315–318

34. Hahnel S, Wastl DS, Schneider-Feyrer S et al.: Streptococcus mutans biofilm formation and release of fluoride from experimental resin-based composites depending on surface treatment and S-PRG filler particle fraction. J Adhes Dent 2014; 16: 313–321

35. Hahnel S, Wieser A, Lang R, Rosentritt M: Biofilm formation on the surface of modern implant abutment materials. Clin Oral Implants Res 2015; 26: 1297–1301

36. Hannig M: Transmission electron microscopic study of in vivo pellicle formation on dental restorative materials. Eur J Oral Sci 1997; 105: 422–433

37. Hannig M: Ultrastructural investigation of pellicle morphogenesis at two different intraoral sites during a 24-h period. Clin Oral Investig 1999; 3: 88–95

38. Hannig M, Joiner A: The structure, function and properties of the acquired pellicle. Monogr Oral Sci 2006; 19: 29–64

39. 39. Hao Y, Huang X, Zhou X et al.: Influence of dental prosthesis and restorative materials interface on oral biofilms. Int J Mol Sci 2018; 19: 3157

40. Hegde NN, Attavar SH, Hegde MN, Priya G: Antibacterial activity of dental restorative material: An in vitro study. J Conserv Dent 2018; 21: 42–46

41. Heimer S, Schmidlin PR, Stawarczyk B: Effect of different cleaning methods of polyetheretherketone on surface roughness and surface free energy properties. J Appl Biomater Funct Mater 2016; 14: e248–55

42. Hube B, Albrecht A, Bader O et al.: Pathogenitätsfaktoren bei Pilzinfektionen. Bundesgesundheitsbl 2002; 45: 159–165

43. Iinuma T, Arai Y, Abe Y et al.: Denture wearing during sleep doubles the risk of pneumonia in the very elderly. J Dent Res 2015; 94: 28S–36S

44. Ionescu A, Wutscher E, Brambilla E, Schneider-Feyrer S, Giessibl FJ, Hahnel S: Influence of surface properties of resin-based composites on in vitro Streptococcus mutans biofilm development. Eur J Oral Sci 2012; 120: 458–465

45. Jarkas MI: Werkstoffmechanischer Vergleich hypoallergener Prothesenbasiskunststoffe. Dissertation, Halle-Wittenberg 2007

46. Jong HP de, Boer P de, Busscher HJ, Pelt AW van, Arends J: Surface free energy changes of human enamel during pellicle formation. An in vivo study. Caries Res 1984; 18: 408–415

47. Jordan AR, Micheelis W: Fünfte Deutsche Mundgesundheitsstudie (DMS V). 2016

48. Jordan R, Sirsch E, Gesch D, Zimmer S, Bartholomeyczik S: Verbesserung der zahnmedizinischen Betreuung in der Altenpflege durch Schulungen von Pflegekräften. Pflege 2012; 25: 97–105

49. Kang S-H, Lee H-J, Hong S-H, Kim K-H, Kwon T-Y: Influence of surface characteristics on the adhesion of Candida albicans to various denture lining materials. Acta Odontol Scand 2013; 71: 241–248

50. Kilian M, Chapple ILC, Hannig M et al.: The oral microbiome – an update for oral healthcare professionals. Br Dent J 2016; 221: 657–666

51. Kim O, Shim WJ: Studies on the preparation and dental properties of antibacterial polymeric dental restorative composites containing alkylated ammonium chloride derivatives. J Polym Res Taiwan 2001; 8: 49–57

52. Kimoto S, Kimoto K, Gunji A et al.: Clinical effects of acrylic resilient denture liners applied to mandibular complete dentures on the alveolar ridge. J Oral Rehabil 2007; 34: 862–869

53. Koch C, Bürgers R, Hahnel S: Candida albicans adherence and proliferation on the surface of denture base materials. Gerodontology 2013; 30: 309–313

54. Kolenbrander PE, Palmer RJ, Periasamy S, Jakubovics NS: Oral multispecies biofilm development and the key role of cell-cell distance. Nat Rev Microbiol 2010; 8: 471–480

55. Kommerein N, Doll K, Stumpp NS, Stiesch M: Development and characterization of an oral multispecies biofilm implant flow chamber model. PLoS ONE 2018; 13: e0196967

56. Kommerein N, Stumpp SN, Müsken M et al.: An oral multispecies biofilm model for high content screening applications. PLoS ONE 2017; 12: e0173973

57. Koo H, Andes DR, Krysan DJ: Candida-streptococcal interactions in biofilm-associated oral diseases. PLoS Pathog 2018; 14: e1007342

58. Latib YO, Owen CP, Patel M: Viability of Candida albicans in denture base resin after disinfection: a preliminary study. Int J Prosthodont 2018; 31: 436–439

59. Leberer E, Ziegelbauer K, Schmidt A et al.: Virulence and hyphal formation of Candida albicans require the Ste20p-like protein kinase CaCla4p. Curr Biol 1997; 7: 539–546

60. Leung D, Spratt DA, Pratten J, Gulabivala K, Mordan NJ, Young AM: Chlorhexidine-releasing methacrylate dental composite materials. Biomaterials 2005; 26: 7145–7153

61. Listgarten MA: Formation of dental plaque and other oral biofilms. In: Newman HN, Wilson M (Hrsg): Dental plaque revisited-oral biofilms in health and disease. Bioline, Cardiff 2000, 187–210

62. Mantzourani M, Gilbert SC, Fenlon M, Beighton D: Non-oral bifidobacteria and the aciduric microbiota of the denture plaque biofilm. Mol Oral Microbiol 2010; 25: 190–199

63. Marinoski J, Bokor-Bratić M, Čanković M: Is denture stomatitis always related with candida infection? A case control study. Med Glas (Zenica) 2014; 11: 379–384

64. Mary SJ, Girish KL, Joseph TI, Sathyan P: Genotoxic effects of silver amalgam and composite restorations: micronuclei-based cohort and case-control study in oral exfoliated cells. Contemp Clin Dent 2018; 9: 249–254

65. Matsuo H, Suenaga H, Takahashi M, Suzuki O, Sasaki K, Takahashi N: Deterioration of polymethyl methacrylate dentures in the oral cavity. Dent Mater J 2015; 34: 234–239

66. Mayahara M, Kataoka R, Arimoto T et al.: Effects of surface roughness and dimorphism on the adhesion of Candida albicans to the surface of resins: Scanning electron microscope analyses of mode and number of adhesions. J Investig Clin Dent 2014; 5: 307–312

67. Melk A, Tegtbur U, Hilfiker-Kleiner D et al.: Improvement of biological age by physical activity. Int J Cardiol 2014; 176: 1187–1189

68. Mendes A, Mores AU, Carvalho AP, Rosa RT, Samaranayake LP, Rosa EAR: Candida albicans biofilms produce more secreted aspartyl protease than the planktonic cells. Biol Pharm Bull 2007; 30: 1813–1815

69. Mesa F, Magan-Fernandez A, Castellino G, Chianetta R, Nibali L, Rizzo M: Periodontitis and mechanisms of cardiometabolic risk: Novel insights and future perspectives. Biochim Biophys Acta Mol Basis Dis 2019; 1865: 476–484

70. Mishra S, Chowdhary R: PEEK materials as an alternative to titanium in dental implants: A systematic review. Clin Implant Dent Relat Res 2019; 21: 208–222

71. Mojon P: Oral health and respiratory infection. J Can Dent Assoc 2002; 68: 340–345

72. Murat S, Alp G, Alatalı C, Uzun M: In vitro evaluation of adhesion of Candida albicans on CAD/CAM PMMA-based polymers. J Prosthodont 2019; 28: e873–e879

73. Najeeb S, Zafar MS, Khurshid Z, Siddiqui F: Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. J Prosthodont Res 2016; 60: 12–19

74. Nedeljkovic I, Munck J de, Ungureanu A-A et al.: Biofilm-induced changes to the composite surface. J Dent 2017; 63: 36–43

75. Nevzatoğlu EU, Ozcan M, Kulak-Ozkan Y, Kadir T: Adherence of Candida albicans to denture base acrylics and silicone-based resilient liner materials with different surface finishes. Clin Oral Investig 2007; 11: 231–236

76. Niederman MS: Nosocomial pneumonia in the elderly patient. Chronic care facility and hospital considerations. Clin Chest Med 1993; 14: 479–490

77. Nikawa H, Hamada T, Yamamoto T: Denture plaque – past and recent concerns. J Dent 1998; 26: 299–304

78. Nitschke I, Kaschke I: Zahnmedizinische Betreuung von Pflegebedürftigen und Menschen mit Behinderungen. Bundesgesundheitsbl 2011; 54: 1073–1082

79. Nitschke I, Majdani M, Sobotta BAJ, Reiber T, Hopfenmüller W: Dental care of frail older people and those caring for them. J Clin Nurs 2010; 19: 1882–1890

80. O'Donnell LE, Alalwan HKA, Kean R et al.: Candida albicans biofilm heterogeneity does not influence denture stomatitis but strongly influences denture cleansing capacity. J Med Microbiol 2017; 66: 54–60

81. O'Donnell LE, Millhouse E, Sherry L et al.: Polymicrobial Candida biofilms: friends and foe in the oral cavity. FEMS Yeast Res 2015; 15

82. O'Donnell LE, Smith K, Williams C et al.: Dentures are a reservoir for respiratory pathogens. J Prosthodont 2016; 25: 99–104

83. Pacquet W, Benoit A, Hatège-Kimana C, Wulfman C: Mechanical properties of CAD/CAM denture base resins. Int J Prosthodont 2019; 32: 104–106

84. Padovani G, Fúcio S, Ambrosano G, Sinhoreti M, Puppin-Rontani R: In situ surface biodegradation of restorative materials. Oper Dent 2014; 39: 349–360

85. Palla ES, Karaoglani E, Naka O, Anastassiadou V: Soft denture liners' effect on the masticatory function in patients wearing complete dentures: A systematic review. J Dent 2015; 43: 1403–1410

86. Park JW, Song CW, Jung JH, Ahn SJ, Ferracane JL: The effects of surface roughness of composite resin on biofilm formation of Streptococcus mutans in the presence of saliva. Oper Dent 2012; 37: 532–539

87. Pereira-Cenci T, Deng DM, Kraneveld EA et al.: The effect of Streptococcus mutans and Candida glabrata on Candida albicans biofilms formed on different surfaces. Arch Oral Biol 2008; 53: 755–764

88. Pereira-Cenci T, del Bel Cury AA, Cenci MS, Rodrigues-Garcia RCM: In vitro Candida colonization on acrylic resins and denture liners: Influence of surface free energy, roughness, saliva, and adhering bacteria. Int J Prosthodont 2007; 20: 308–310

89. Ramage G, Coco B, Sherry L, Bagg J, Lappin DF: In vitro Candida albicans biofilm induced proteinase activity and SAP8 expression correlates with in vivo denture stomatitis severity. Mycopathologia 2012; 174: 11–19

90. Rosentritt M, Ilie N, Lohbauer U (Hrsg): Werkstoffkunde in der Zahnmedizin. Moderne Materialien und Technologien. Georg Thieme Verlag, Stuttgart, New York 2018

91. Scannapieco FA, Papandonatos GD, Dunford RG: Associations between oral conditions and respiratory disease in a national sample survey population. Ann Periodontol 1998; 3: 251–256

92. Schierz O, Schierz S, Rauch A: Kunst – das neue Metall? ZMK 2018; 34: 378–385

93. Schimmel M, Katsoulis J, Genton L, Müller F: Masticatory function and nutrition in old age. Swiss Dent J 2015; 125: 449–454

94. Silla M, Eichberger M, Stawarczyk B: Polyetherketonketon (PEKK) als Restaurationswerkstoff in der modernen Zahnmedizin: eine Literaturübersicht. Die Quintessenz der Zahntechnik 2016; 42: 176–190

95. Sjögren P, Nilsson E, Forsell M, Johansson O, Hoogstraate J: A systematic review of the preventive effect of oral hygiene on pneumonia and respiratory tract infection in elderly people in hospitals and nursing homes: effect estimates and methodological quality of randomized controlled trials. J Am Geriatr Soc 2008; 56: 2124–2130

96. Skirbutis G, Dzingutė A, Masiliūnaitė V, Šulcaitė G, Žilinskas J: PEEK polymer's properties and its use in prosthodontics. A review. Stomatologija 2018; 20: 54–58

97. Stawarczyk B, Eichberger M, Uhrenbacher J, Wimmer T, Edelhoff D, Schmidlin PR: Three-unit reinforced polyetheretherketone composite FDPs: influence of fabrication method on load-bearing capacity and failure types. Dent Mater J 2015; 34: 7–12

98. Susewind S, Lang R, Hahnel S: Biofilm formation and Candida albicans morphology on the surface of denture base materials. Mycoses 2015; 58: 719–727

99. Takahashi Y, Hamanaka I, Shimizu H: Flexural properties of denture base resins subjected to long-term water immersion. Acta Odontol Scand 2013; 71: 716–720

100. Tari BF, Nalbant D, Dogruman Al F, Kustimur S: Surface roughness and adherence of Candida albicans on soft lining materials as influenced by accelerated aging. J Contemp Dent Pract 2007; 8: 18–25

101. Tavassoli Hojati S, Alaghemand H, Hamze F et al.: Antibacterial, physical and mechanical properties of flowable resin composites containing zinc oxide nanoparticles. Dent Mater 2013; 29: 495–505

102. Tsang CSP, Ng H, McMillan AS: Antifungal susceptibility of Candida albicans biofilms on titanium discs with different surface roughness. Clin Oral Investig 2007; 11: 361–368

103. Urushibara Y, Ohshima T, Sato M et al.: An analysis of the biofilms adhered to framework alloys using in vitro denture plaque models. Dent Mater J 2014; 33: 402–414

104. Vacca Smith AM, Bowen WH: In situ studies of pellicle formation on hydroxyapatite discs. Arch Oral Biol 2000; 45: 277–291

105. Vassilakos N, Arnebrant T, Glantz PO: An in vitro study of salivary film formation at solid/liquid interfaces. Scand J Dent Res 1993; 101: 133–137

106. Vassilakos N, Arnebrant T, Rundegren J, Glantz PO: In vitro interactions of anionic and cationic surfactants with salivary fractions on well-defined solid surfaces. Acta Odontol Scand 1992; 50: 179–188

107. Wårdh I, Hallberg LR-M, Berggren U, Andersson L, Sörensen S: Oral health education for nursing personnel; experiences among specially trained oral care aides: one-year follow-up interviews with oral care aides at a nursing facility. Scand J Caring Sci 2003; 17: 250–256

108. Yamamoto K, Ohashi S, Aono M, Kokubo T, Yamada I, Yamauchi J: Antibacterial activity of silver ions implanted in SiO2 filler on oral streptococci. Dental Materials 1996; 12: 227–229

109. Yoneyama T, Yoshida M, Ohrui T et al.: Oral care reduces pneumonia in older patients in nursing homes. J Am Geriatr Soc 2002; 50: 430–433

110. Yoshida K, Tanagawa M, Atsuta M: Characterization and inhibitory effect of antibacterial dental resin composites incorporating silver-supported materials. J Biomed Mater Res 1999; 47: 516–522

111. Yoshijima Y, Murakami K, Kayama S et al.: Effect of substrate surface hydrophobicity on the adherence of yeast and hyphal Candida. Mycoses 2010; 53: 221–226

112. Zijnge V, van Leeuwen, M Barbara M, Degener JE et al.: Oral biofilm architecture on natural teeth. PLoS ONE 2010; 5: e9321

113. Zoidis P, Papathanasiou I, Polyzois G: The use of a modified Poly-Ether-Ether-Ketone (PEEK) as an alternative framework material for removable dental prostheses. A clinical report. J Prosthodont 2016; 25: 580–584

(Photo: Golden Eyes Fotografie)

ELENA GÜNTHER
Department of Prosthodontics and Dental Materials Science, University Leipzig, Germany
Liebigstr. 12; 04103 Leipzig
elena.guenther@medizin.uni-leipzig.de