Antibacterial coatings

P. Thebault[1,2,3] and **T. Jouenne**[1,2,3]

[1] Univ Rouen, Lab Polymères Biopolymères Surfaces, F-76821 Mont St Aignan, France
[2] UMR 6270 CNRS, F-76821 Mont St Aignan, France
[3] Normandie Univ, Rouen, France

Since a long time, the bacterial contamination of surfaces, leading to biofilm formation, is a major problem in fields as diverse as medical, food or cosmetics even with preventive hygiene protocols. In order to eliminate or reduce bacterial colonization of surfaces and biofilm formation, many prophylactic strategies have emerged. Among them is the elaboration of antifouling surfaces based on antiadhesive coatings such as polyethyleneglycol (PEG) or polysaccharide to repel bacteria and prevent their initial adhesion on surfaces which is a prerequisite in the biofilm formation. Another strategy is the covalent (or not) immobilization of antimicrobial compounds, e.g., antibiotics, quaternary ammonium or silver, to design biocidal coatings able to kill bacteria by release (or not) of the active substances. In this strategy, natural compounds and in particular antimicrobial peptides have appeared as promising candidates by limiting emergence of multiresistant bacteria. This chapter reviews the state-of-the-art of antibacterial coatings developed for combatting bacterial contamination.

Keywords: Bacterial contamination; Biofilm; Antibacterial coatings; Antiadhesive coatings; Biocidal coatings; Antimicrobial peptides

1. Introduction

Bacteria and other microorganisms are well known to be able to adhere to wet surfaces and to colonize them. These contaminations of surfaces can lead to very important problems in various fields such as medical with rejection of implants or chronic wounds [1,2], as food with alterations and poisoning of foodstuffs [3] or as cosmetics with degradation of products and cutaneous problems of consumers [4].

In many cases, once adhered to a surface, microbial population creates a community with other cells, embedded in a biopolymer matrix, called biofilm [5]. The biofilm formation process can be divided into five steps [6]. Briefly, this process begins with an initial reversible attachment of microorganisms on a surface through weak forces such as Van der Waals, followed by an irreversible attachment via for example appendages as pili. This first layer of bacteria allows the colonization by other organisms and the production of exopolymers (exopolysaccharides, DNA, proteins…) which contributes to the matrix formation. The fourth step is the biofilm maturation with bacterial growth and development of the matrix, the consortium reaching its final form. The last step of biofilm formation process is the dispersion of some microorganisms which recover their planktonic status and may re-colonize another surface.

Once under biofilm form, bacteria are drastically more resistant to antibiotics (up to 1000-fold), biocides and hydrodynamic shear forces than their planktonic counterparts [7]. Due to this high resistance, eradication of biofilms needs high concentrations of antimicrobials, causing severe environmental damages and multiresistance emergence. Although some antibiofilm strategies have appeared [8] based on quorum sensing inhibitory or enzymes, prevention of biofilm formation is clearly preferable to any treatment.

This prophylactic strategy is based on the elaboration of antibacterial surfaces [9]. Two main approaches are feasible as shown in Fig. 1. One consists to reduce or inhibit bacterial adhesion through antiadhesive coatings able to repel bacteria; the second one is to kill bacteria or to limit their growth by biocidal coatings. These two coating types will be discussed in this chapter.

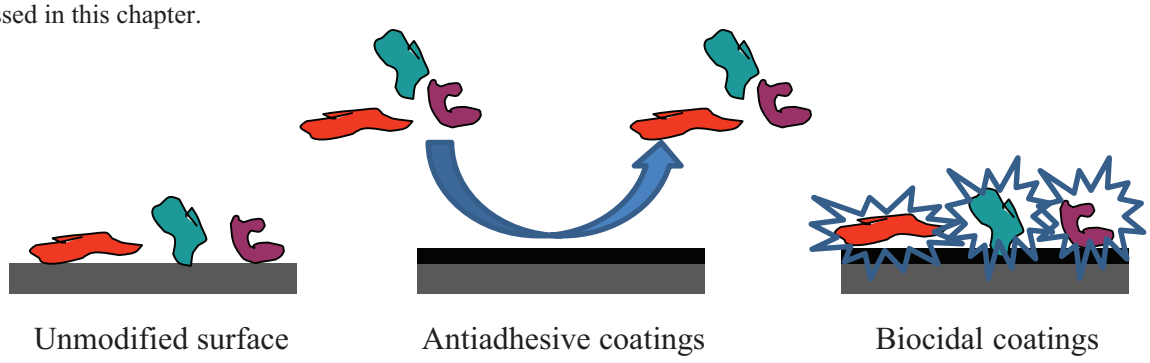

Fig. 1 Antibacterial coatings to prevent biofilm formation.

2. Antiadhesive coatings

The adhesion of bacteria to surfaces is a prerequisite for the formation of biofilm [10]. Consequently, the elaboration of antibiofouling surfaces is a logical strategy to fight against bacterial contaminations. Based on the physico-chemical parameters of the surface, susceptible to modify the bacterial adhesion (e.g., topography, charge, wettability...), many strategies have been proposed to develop these surfaces [11-14]. Some of them are based on physical modification of the surface topography, consisting, for examples, to elaborate smooth or micro-structured surfaces. Another approach consists to chemically modify the surface to create negatively charged or hydrophilic surfaces. One of these chemical strategies is to immobilize hydrophilic polymers to form antiadhesive coatings. In this field, two main families of polymers have been used, i.e., poly(ethylene glycol) (PEG) or its derivatives and polysaccharides.

2.1 Poly(ethylene glycol) coatings

PEG has been extensively used for antiadhesive coatings [15,16], due to its hydrophilicity and steric hindrance effects. Moreover compared to other hydrophilic polymers, the PEG flexibility enhances its activity.

A lot of studied showed that the PEG molecular weight (MW) plays a key role in the repelling feature of PEG coatings Thus, Dong *et al.* [17] modified polyethylene terephthalate (PET) surfaces by PEG with different molecular weights , i.e., from 200 to 4600 g/mol. Surfaces were previously functionalized by silicon tetrachloride ($SiCl_4$) plasma to introduce reactive functions. Antiadhesive properties were tested against *Salmonella enterica serovar typhimurium* and *Listeria monocytogenes*. All modified surfaces exhibited a lower ability to be colonized as compared with unmodified PET.

Increasing the MW of PEG improved the antibiofilm activity, the best one being observed for PEG2000-grafted PET (99.8% decrease). This observation was correlated with water contact angle measurements. Indeed, water contact angle values of modified PET decreased with the MW increase confirming that antifouling properties of PEG are due to its hydrophilic character. Same trend was observed for the inhibition of biofilm formation.

2.2 Polysaccharides coatings

Polysaccharides are natural polymers with intrinsic hydrophilic properties, which lead to highly hydrated layers. A lot of polysaccharides have been studied [18-22], up to now. The most used is hyaluronic acid (HA) [23-25] a linear polysaccharide consisting of alternating units of a repeating disaccharide, β-1,4-D-glucuronic acid-β-1,3-N-acetyl-D-glucosamine. Thus, Morra *et al.* [23] have covalently bond HA to a PEI-Glass slide. They characterized the surface modification by contact angle measurements and showed that it was hydrophilic. This coating reduced the adhesion of *Staphylococcus epidermidis* and *Escherichia coli* by several orders of magnitude, compared to unmodified glass slide. Authors observed same results for surfaces modified by alginic acid (AA).

Other polysaccharides such heparin (HP) [22,26] and dextran [19,27] have shown anti-fouling properties on bacteria or proteins. For example, Shi *et al.* [27] grafted oxidized dextran on functionalized titanium surfaces *via* a first layer of dopamine and demonstrated that *S. epidermidis* and *S. aureus* adhesion was reduced about 2-fold on new surfaces.

Recently, Gadenne *et al.* [28] have immobilized an ulvan which is a sulfated polysaccharide extracted from green algae that invade and contaminate the Brittany coast. Polysaccharide was covalently immobilized, as described in Fig. 2, on titanium surfaces which had been previously functionalized by the aminoundecyltrimethoxysilane (AUTMS). These modified surfaces were able to inhibit the initial adhesion of gram-positive (i.e., *S. epidermidis*) and gram-negative (i.e., *P. aeruginosa*) bacteria. Furthermore, the authors have demonstrated that such polysaccharide coatings affect the spreading of bacteria and could limit the bacterial colonization for a long time.

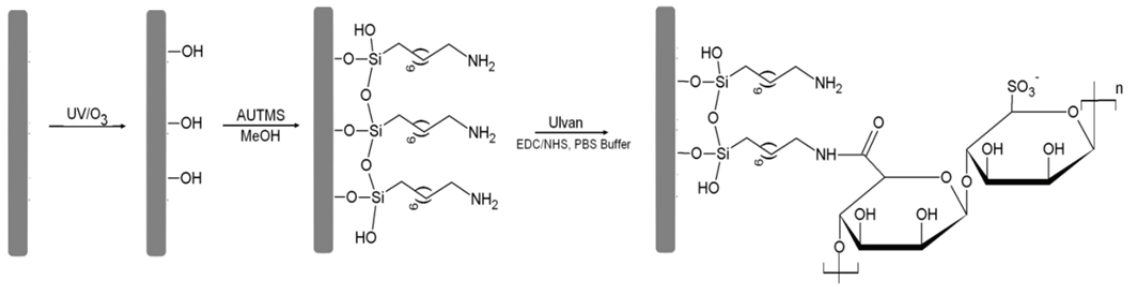

Fig. 2 Scheme of ulvan immobilization on titanium surface (reproduced with permission from ref 28).

The high complexity of the process involved in the bacterial adhesion makes it very complicated to develop a "universal" antiadhesive strategy able to completely inhibiting bacterial adhesion. The approach based on the development of biocidal surfaces which act directly on bacterial integrity seems more attractive.

3. Biocidal coatings

This strategy is based on the immobilization of compounds that have shown bacteriostatic or bactericidal activity in solution [9] such as antibiotics, quaternary ammonium salt or silver ions [29]. To develop biocidal surfaces, two immobilization approaches of antimicrobials on the surface are possible [30]. The covalent one has the advantage to avoid the depletion of inhibitor material and to limit the potential risk of toxicity. The non-covalent immobilization, associates an action mode by contact and by release of the inhibitor. The latter technique avoids the orientation constraints of the molecule during its immobilization. However the continuous release of the inhibitor is a major drawback and may promote the emergence of multiresistant bacteria.

3.1 Non covalent immobilization

To elaborate leaching coatings one strategy consists to incorporate the antimicrobial agents into the bulk. Thus, van de Belt *et al.* [31] have mixed methylmethacrylate powder with a gentamicin solution (a well-known antibiotic) to produce loaded bone cements. *S. aureus* biofilm formation on modified bone cements was compared to that on unloaded cements. All modified bone cement exhibited an antibiofilm activity but with different "window-of-effectiveness". Furthermore, no correlation between gentamicin release and surface properties, e.g., roughness, was observed.

Another strategy to form biocidal surfaces is to entrap antibacterial agents in polyelectrolyte multilayers (PEMs). This approach consists to deposit successive layers of polycations and polyanions onto surfaces. Zan *et al.* [32] have used this PEMs method to functionalize quartz and silicon wafers and to then immobilize silver ions into a coating composed of poly(styrene sulfonate) (PSS) and poly(diallyldimethylammonium chloride) (PDDA). Silver ions were incorporated into PEMs by an ion-exchange process between sodium chloride used as couterion and silver nitrate. Then Silver ions were here reduced in silver nanoparticles.

The antibacterial activity of PEMs enriched with silver ions or nanoparticles, was evaluated against *E. coli* by the Kirby-Bauer method. Polyelectrolyte films with silver ions exhibited a higher antibacterial activity than those with silver nanoparticles in short times (i.e., between 1 and 3 days). For longer times, however, a decrease of the activity of films containing silver ions was observed.

3.2 Covalent immobilization

As mentioned above, in the case of covalent immobilization, orientation but also density and flexibility of the active substances are key factors for the antimicrobial activity of the modified surfaces.

Self-assembled monolayers (SAMs) which allow the formation of a well ordered monolayer bound to the surface is a versatile tool to incorporate reactive functions. Mutin *et al.* [33-34] modified titanium and stainless steel surfaces through this method. Phosphonate functions reacted first with titanium to create a SAM and then terminal functions of phosphonates (e.g., amine or thiol) were used to graft suitable compounds such as quaternary ammonium or silver ions. These new surfaces exhibited an antimicrobial activity. Thus, surfaces modified with silver ions induced a reduction of the bacterial adhesion of *S. aureus*, *S. epidermidis* and *P. aeruginosa*, by 4- to 5-log compared to unmodified titanium.

An alternative is to synthesize biocidal compounds possessing, at one extremity, a function able to react directly with the surface. By using this approach, Thebault *et al.* [35] have synthesized various quaternary ammonium salts with a thiol function in the aim to modify in one-step gold surfaces.

Another strategy is to immobilize antimicrobial polymers such as polyammonium or chitosan. Tiller *et al.* [36] have modified various plastic materials, e.g., high and low density polyethylene (HDPE and LDPE respectively), polypropylene and poly(ethylene terephthalate) by grafting poly(vinyl-N-pyridium bromide) on their surface. All these materials were able to kill bacteria (i.e., *S. aureus* and *Escherichia coli*) between 97 to 99%. But, as shown in Fig. 3, an increase of adhered bacteria was observed on modified surfaces compared to the control, when low density of pyridium group was used. This result pointed out that positive charges of pyridium groups enhanced bacterial adhesion and that high density of pyridium (or ammonium) groups was necessary to lead to an antibacterial surface.

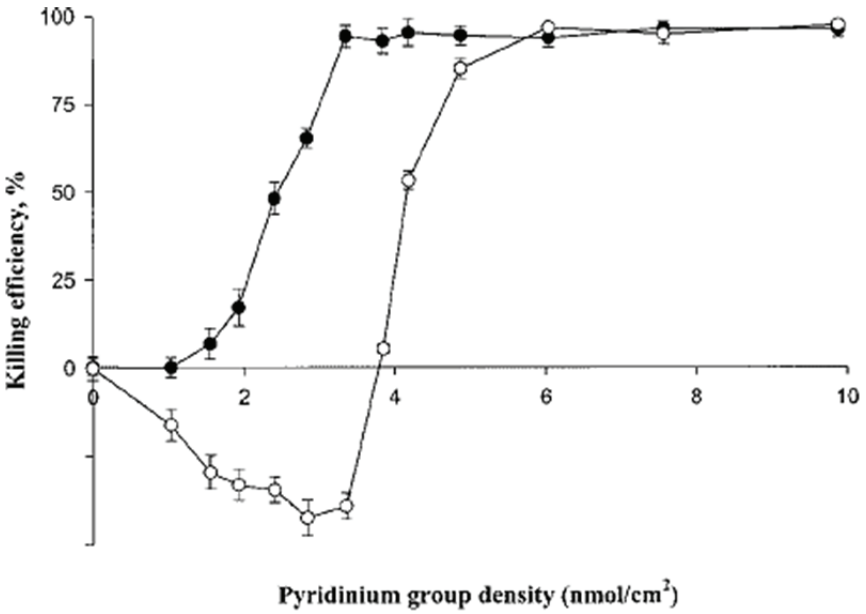

Fig. 3 Killing efficiency of hexyl-PVP derivatized HDPE toward airborne (•) or waterborne (O) *S. aureus* cells deposited on the modified polymer surface as a function of the surface density of the pyridinium groups (reproduced with permission from ref 36).

Whether by non-covalent or covalent immobilization of so called "classical antibacterial substances", the resulting surfaces present some drawbacks such as potential toxicity, not satisfactory efficiency or a bacterial resistance. Consequently, new families of active compounds need to be developed. Based on the nature, which has been fighting against bacterial proliferation over millions of years, bio-inspired strategies have recently emerge [37], some of them using natural molecules, e.g. essential oils or antimicrobial peptides (AMPs). These latter have attracted particular attention in the recent years [38,39].

3.3 Antimicrobial peptides coatings

AMPs are part of the innate immune systems of the most living organisms. They have a broad range of antimicrobial activity, act at very low concentration and do not promote bacterial resistance. AMPs could be immobilized by both non-covalent and covalent strategies depending on the potential application of such modification.

In the case of releasing coatings, entrapment of AMPs in PEMs was the most used strategy [40]. To overcome the main drawback of this approach, i.e., the control of peptides release, Guyomard *et al.* [41] modified an anionic polysaccharide (pullulan) by incorporating hydrophobic alkyl chains. These hydrophobic nanodomains allowed the immobilization of gramicidin A, a highly hydrophobic peptides within PEMs composed of poly(L-lysine) and carboxymethylpullulan layers. The modified surfaces exhibited a biocidal activity against *Enterococcus faecalis*.

To covalently immobilized peptides on surfaces, Humblot *et al.* [42] used functionalized SAMs. Magainin I was immobilized on carboxylated gold surfaces by the formation of an amide bond *via* carbodiimide chemistry. These surfaces exhibited an antibacterial activity against Gram-positive bacteria, e.g., *Listeria ivanovii,* through membrane permeabilization as suggested by viability microscopy analysis (Fig. 4). Furthermore, no release of the peptide in the surrounding solution was observed and the antibacterial activity persisted for up to six months.

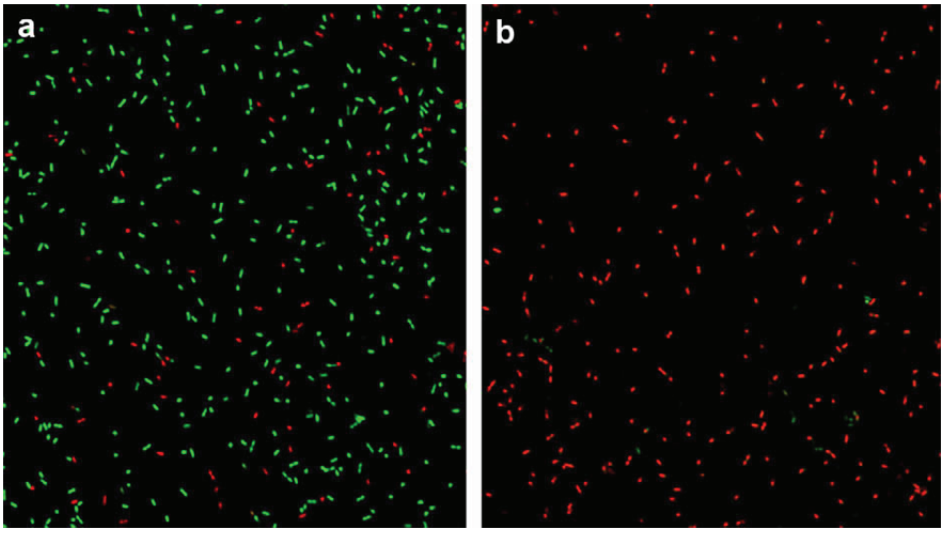

Fig. 4 Viability of *Listeria ivanovii*, stained with LIVE/DEAD® Bacterial Viability Kit, attached to a: functionalized gold surface and b: functionalized gold surface modified by magainin I observed by confocal microscopy (reproduced with permission from ref 42).

Even if biocidal coatings have shown interesting activity, none of them has led to a total inhibition of the biofilm formation, however. It is the reason why combinations of both antiadhesive and biocidal coatings have been proposed.

4. Antiadhesive and biocidal coatings

These coatings are based on two antagonist action modes, i.e., the repulsion and attraction of bacteria. However, a synergic effect is possible by a control of the two phenomena.

Thus, Glinel *et al.* [43] have conjugated repelling properties of PEG with biocidal characteristic of AMPs. They used surface-initiated atom transfer radical polymerization to create, on silicon wafers, copolymer brushes based on oligo(ethylene glycol) methacrylates. This method consists in polymer growth directly from the surface. It allows the elaboration of a well-controlled polymers layer under a brush form. Magainin I was then covalently attached on polymer brushes *via* a maleimide thiol reaction as shown in Fig. 5.

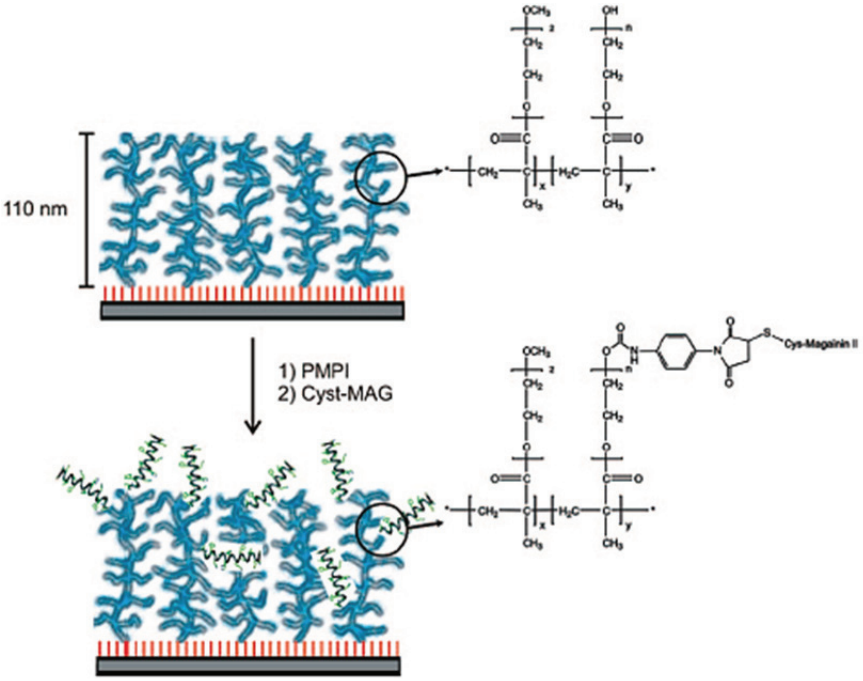

Fig. 5 Oriented grafting of magainin I modified by cysteine derivative on poly(MOE_2MA-*co*-HOEGMA) brushes *via* a PMPI heterolinker (reproduced with permission from ref 43).

The authors showed that grafted magainin I retained its activity against various Gram-positive and Gram-negative bacteria such as *L. ivanovii* and *P. aeruginosa*. Aggregates of dead bacteria were only observed on modified brushes by confocal fluorescence microscopy on modified surfaces, demonstrating the death of bacteria in contact with the AMP.

Based on the same principle, Laloyaux *et al.* [44] immobilized AMPs on thermo-responsive copolymer brushes. These brushes demonstrated a collapse temperature around 35°C. Consequently, the magainin-modified brushes exhibited a bactericidal activity below 35°C and an antiadhesive activity above this collapse temperature.

Another strategy is to use PEMs of chitosan a biocidal cationic polysaccharide, or its derivatives, with anionic hydrophilic (so antiadhesive) polysaccharides e.g., HA, HP, alginate or κ-carrageeenan [45-48]. Thus, Bratskaya *et al.* [48] compared the antibacterial activity against *E. faecalis* between chitosan layer covalently grafted on glass, and PEMs constituted of chitosan and κ-carrageeenan. PEMs exhibited higher antiadhesive activity than the chitosan layer due to electrostatic repulsion between negative charges of κ-carrageeenan. However, biocidal activity of PEMs coating was significantly lower than that of covalently grafted Chitosan.

5. Conclusion

Owing the high resistance of sessile bacteria against antimicrobials, prevention of biofilm formation seems more efficient than the eradication. It is the reason why antibacterial coatings have been extensively developed, through antiadhesive or biocidal coatings. To elaborate antibacterial surfaces, covalent immobilization or release of active substances have been used, depending on the potential application. However, the emergence of multiresistant bacteria, the restriction of some compounds by new norms (in the biomedical or cosmetic fields for example) has led to the research of innovative approaches. In this context, bio-inspired coatings and especially coatings based on AMPs have shown interesting results.

Yet, a new generation of antimicrobial surfaces called "smart antimicrobial surfaces" constitutes a promising way. Based on the response to a stimulus, e.g., the temperature, the pH or an enzymatic degradation, these surfaces allow a better control of the biocidal activity and might limit the emergence of multiresistant bacteria.

It is however a long way to obtain the perfect coating. Indeed, most studies are only based on *in vitro* experiments which are not always consistent with *in vivo* reality and most often the antibacterial property is not the unique property which is looked for.

References

[1] Rosenthal VD, Hu B.J, Maki DG, Mehta Y, Apisarnthanarak A, Medeiros EA, Leblebicioglu H, Fisher D, Alvarez-Moreno C, Abu Khader I, Martinez MDG, Cuellar LE, Navoa-Ng JA, Abouqal R, Garcell HG, Mitrev Z, Garcia MCP, Hamdi A, Duenas L, Cancel E, Gurskis V, Rasslan O, Ahmed A, Kanj SS, Ugalde OC, Mapp T, Raka L, Meng CY, Le TAT, Ghazal S, Gikas A, Narvaez LP, Mejia N, Hadjieva N, Elanbya MOG, Siritt MEG, Jayatilleke K. International Nosocomial Infection Control Consortium (INICC) report, data summary of 36 countries, for 2004-2009. Am. J. Infect. Control. 2012; 40:396-407.

[2] Heuer W, Stiesch M, Abraham WR. Microbial diversity of supra- and subgingival biofilms on freshly colonized titanium implant abutments in the human mouth. Eur. J. Clin. Microbiol. Infect. Dis. 2011; 30:193-200.

[3] Vaillant V, De Valk H, Baron E, Ancelle T, Colin P, Delmas MC, Dufour B, Pouillot R, Le Strat Y, Weinbreck P, Jougla E, Desenclos JC. Foodborne Infections in France. foodborne Pathog. Dis. 2005; 2:221-32.

[4] Giacomel CB, Dartora G, Dienfethaeler HS, Haas SE. Investigation on the use of expired make-up and microbiological contamination of mascaras. Int. J. Cosmetic Sci. 2013; 35:375–380.

[5] Costerton JW, Stewart PS, Greenberg EP. Bacterial biofilms: a common cause of persistent infections. Science. 1999; 284:1318-22.

[6] Khoo X, Grinstaff MW. Novel infection-resistant surface coatings: A bioengineering approach. MRS Bull. 2011; 36:357-66.

[7] Davies D. Understanding biofilm resistance to antimicrobial agents. Nat. Rev. 2003; 2:114-22.

[8] Simoes M, Simoes LC, Vieira MJ. A review of current and emergent biofilm control strategies. LWT-Food Sci. Technol. 2010; 43:573-83.

[9] Bruelhoff K, Fiedler J, Möller M, Groll J, Brenner RE. Surface coating strategies to prevent biofilm formation on implant surfaces. Int. J. Artif. Organs. 2010; 33:646-53.

[10] Donlan RM, Costerton JW. Biofilms: Survival mechanisms of clinically relevant microorganisms. Clin. Microbiol. Rev. 2002; 15:167-93.

[11] Gottenbos B, van der Mei HC, Busscher HJ, Grijpma DW, Feijen J. Initial adhesion and surface growth of Pseudomonas aeruginosa on negatively and positively charged poly(methacrylates). J. Mater. Sci. Mater. Med. 1999; 10:853–5.

[12] Balazs DJ, Triandafillu K, Chevolot Y, Aronsson BO, Harms H, Descouts P, Mathieu HT. Surface modification of PVC endotracheal tubes by oxygen glow discharge to reduce bacterial adhesion. Surf. Interface Anal. 2003; 35:301–9.

[13] Katsikogianni MG, Missirlis YF. Bacterial adhesion onto materials with specific surface chemistries under flow conditions. J. Mater. Sci. Mater. Med. 2010; 21:963–8.

[14] Crawford RJ, Webb HK, Truong VK, Hasan J, Ivanova EP. Surface topographical factors influencing bacterial attachment. Adv. Colloid Interface. Sci. 2012; 179:142–9.

[15] Neoh KG, Kang ET. Combating bacterial colonization on metals via polymer coatings: relevance to marine and medical applications. ACS Appl Mater Interfaces. 2011; 3:2808-19.

[16] Roosjen A, Norde W, van der Mei HC, Busscher HJ. The Use of Positively Charged or Low Surface Free Energy Coatings versus Polymer Brushes in Controlling Biofilm Formation. Progr. Colloid. Polym. Sci. 2006; 132:138–44.

[17] Dong B, Manolache S, Wong ACL, Denes FS. Antifouling ability of polyethylene glycol of different molecular weights grafted onto polyester surfaces by cold plasma. Polym.Bull. 2011; 66:517-28.

[18] Harris LG, Richards RG. Staphylococcus aureus adhesion to different treated titanium surfaces. J. Mater. Sci.-Mater. Med. 2004; 15:311–4.

[19] Martwiset S, Koh AE, Chen W. Nonfouling characteristics of dextran-containing surfaces. Langmuir. 2006; 22:8192–6.

[20] Hu X, Neoh KG, Shi Z, Kang ET, Poh C, Wang W. An in vitro assessment of titanium functionalized with polysaccharides conjugated with vascular endothelial growth factor for enhanced osseointegration and inhibition of bacterial adhesion. Biomaterials. 2010; 31:8854–63.

[21] Xu F, Flanagan CE, Ruiz A, Crone WC, Masters KS. Polyurethane/dermatan sulfate copolymers as hemocompatible, non-biofouling materials. Macromol. Biosci. 2011; 11:257–66.

[22] Farnbacher MJ, Lederer R, Blana A, Schneider HT. Does heparin coating reduce encrustation of biliary plastic endoprostheses? A prospective randomized trial. Scand. J. Gastroenterol. 2012, 47:1141–7.

[23] Morra M, Cassineli C. Non-fouling properties of polysaccharide-coated surfaces. J. Biomater. Sci.-Polym. Ed. 1999; 10:1107–24.

[24] Palumbo FS, Volpe Bavuso A, Cusimano MG, Pitarresi G, Giammona G, Schillaci D. A polycarboxylic/amino functionalized hyaluronic acid derivative for the production of pH sensible hydrogels in the prevention of bacterial adhesion on biomedical surfaces. Int. J. Pharm. 2015; 478:70–7.

[25] Wang B, Lin Q, Jin T, Shen C, Tang J, Han Y, Chen H. Surface modification of intraocular lenses with hyaluronic acid and lysozyme for the prevention of endophthalmitis and posterior capsule opacification. RSC Adv. 2015; 5: 3597–604.

[26] Tenke P, Riedl CR, Jones GL, Williams GJ, Stickler D, Nagy E. Bacterial biofilms formation on urologic devices and heparin coating as preventive strategy. Int. J. Antimicrob. Agents. 2004; 23S1:S67–S74.

[27] Shi Z, Neoh KG, Kang ET, Poh C, Wang W. Titanium with surface-grafted dextran and immobilized bone morphogenetic protein-2 for inhibition of bacterial adhesion and enhancement of osteoblast functions. Tissue Eng. Part. A. 2009a; 15:417–26.

[28] Gadenne V, Lebrun L, Jouenne T, Thebault P. Antiadhesive activity of ulvan polysaccharides covalently immobilized onto titanium surface. Colloid. Surf. B-Biointerfaces. 2013; 112:229–36.
[29] Arciola CR, Campoccia D, Speziale P, Montanaro L, Costerton JW. Biofilm formation in *Staphylococcus* implant infections. A review of molecular mechanisms and implications for biofilm-resistant materials. Biomaterials. 2012; 33:5967-82.
[30] Banerjee I, Pangule RC, Kane RS. Antifouling coatings: recent developments in the design of surfaces that prevent fouling by proteins, bacteria, and marine organisms. Adv. Mat. 2011; 23:690-718.
[31] van de Belt H, Neut D, Schenk W, van Horn JR, van der Mei HC, Busscher HJ. *Staphylococcus aureus* biofilm formation on different gemtamicin-loaded polymethylmethacrylate bone cements. Biomaterials. 2001; 22:1607-11.
[32] Zan X, Su Z. Polyelectrolyte multilayer films containing silver as antibacterial coatings. Thin solid Films. 2010; 518: 5478-82.
[33] Guerrero G, Amalric J, Mutin PH, Sotto A, Lavigne JP. Inhibition of bacterial adhesion and prevention of biofilm formation: use of organic self-assembled monolayers on inorganic surfaces. Pathologie biologie. 2009; 57:36-43.
[34] Amalric J, Mutin PH, Guerrero G, Ponche A, Sotto A, Lavigne JP. Phosphonate monolayers functionalized by silver thiolate species as antibacterial nanocoatings on titanium and stainless steel. J. Mater. Chem. 2009, 19:141-9.
[35] Thebault P, de Givenchy ET, Levy R, Vandenberghe Y, Guittard F, Geribaldi S. Contact-active microbicidal gold surfaces using immobilization of quaternary ammonium thiol derivatives. Eur. J. Med. Chem. 2009; 44:4227-34.
[36] Tiller JC, Lee SB, Lewis K, klibanov AM. Polymer surfaces derivatized with poly(vinyl-N-hexylpyridinium) kill airborne and waterborne bacteria. Biotechnol. Bioeng. 2002; 79:465-71.
[37] Glinel K, Thebault P, Humblot V, Pradier CM, Jouenne T. Antibacterial surfaces developed from bio-inspired approaches. Acta Biomater. 2012; 8:1670-84.
[38] Onaizi SA, Leong SSJ. Tethering antimicrobial peptides: Current status and potential challenges. Biotechnol. Adv. 2011; 29:67-74.
[39] Costa F, Carvalho IF, Montelaro RC, Gomes P, Martins MCL. Covalent immobilization of antimicrobial peptides (AMPs) onto biomaterial surfaces. Acta Biomater. 2011; 7:1431-40.
[40] Etienne O, Picart C, Taddei C, Haikel Y, Dimarcq JL, Schaaf P, Voegel JC, Ogier JA, Egles C. Multilayer polyelectrolyte films functionalized by insertion of defensin: A new approach to protection of implants from bacterial colonization. Antimicrob. Agents Chemother. 2004; 48:3662-9.
[41] Guyomard A, De E, Jouenne T, Malandain JJ, Muller G, Glinel K. Incorporation of a hydrophobic antibacterial peptide into amphiphilic polyelectrolyte multilayers: A bioinspired approach to prepare biocidal thin coatings. Adv. Funct. Mater. 2008; 18: 758-65.
[42] Humblot V, Yala JF, Thebault P, Boukerma K, Hequet A, Berjeaud JM, Pradier CM. The antibacterial activity of magainin I immobilized onto mixed thiols self-assembled monolayers. Biomaterials. 2009; 30:3503-12.
[43] Glinel K, Jonas AM, Jouenne T, Leprince J, Huck WTS. Antibacterial and antifouling polymer brushes incorporating antimicrobial peptide. Bioconj. Chem. 2009; 20:71-7.
[44] Laloyaux X, Fautre E, Blin T, Purohit V, Leprince J, Jouenne T, Jonas AM, Glinel K. Temperature-responsive polymer brushes switching from bactericidal to cell-repellent. Adv. Mater. 2010; 22: 5024-8.
[45] Bratskaya S, Marinin D, Simon F, Synytska A, Zschoche S, Busscher HJ, Jager D. van der Mei HC. Adhesion and viability of two enterococcal strains on covalently grafted chitosan and chitosan/κ-carrageenan multilayers. Biomacromolecules. 2007; 8;2960–8.
[46] Cui D, Szarpak A, Pignot-Paintrand I, Varrot A, Boudou T, Detrembleur C, Jerome C, Picart C, Auzely-Velty R. Contact-killing polyelectrolyte microcapsules based on chitosan derivatives. Adv. Funct. Mater. 2010; 20: 3303–12.
[47] Saito A, Miyazaki H, Fujie T, Ohtsubo S, Kinoshita M, Saitoh D, Takeoka S. Therapeutic efficacy of an antibiotic-loaded nanosheet in a murine burn-wound infection model. Acta Biomater. 2012; 8: 2932–40.
[48] Almodóvar J, Mower J, Banerjee A, Sarkar AK, Ehrhart NP, Kipper MJ. Chitosan-heparin polyelectrolyte multilayers on cortical bone: periosteum-mimetic, cytophilic, antibacterial coatings. Biotechnol. Bioeng. 2013; 110:609–18.

