ICM 2025 Question B20: "Does biofilm have different affinities for different surfaces?"

Ferdinando Iannotti, Mojieb Manzary, Rodrigo Jaramillo, Erika Albo, Edward M Schwarz

---

RESPONSE/RECOMMENDATION: Yes. Biofilm exhibits different affinities for different surfaces. However, due to the complex interplay between surface properties and bacterial features, as well as the influence of environmental factors and exposure time, establishing a universally valid correlation or identifying a surface that consistently prevents biofilm formation remains challenging. This is also due to the lack of high-quality in vivo studies. The same material can interact differently with various bacteria since each bacterial strain has different affinities for distinct surfaces.

LEVEL OF EVIDENCE: Strong

DELEGATE VOTE: Agree: [37/97% vote], Disagree: [0/0%], Abstain: [1/3%]

RATIONALE: Biofilms are complex structures that form on biological and implant surfaces following a multi-step process driven by several factors [1]. The transition from bacterial cell adhesion to irreversible binding and early biofilm formation affords a critical window of opportunity for preventing biofilm establishment [2]. Adhesion of planktonic bacteria to the implant surface is influenced by a combination of host factors, microorganism-specific characteristics, exposure time, and implant-related surface properties such as wettability, topography, micro- and nanoscale roughness, surface free energy, and charge[1-3].

To answer this question, a comprehensive literature search was conducted using the search words "biofilm" and "affinity" and "surface" and "infection" within PubMed and Scopus, which identified 145 relevant unique studies for full text review, and 39 were included for evaluation. These articles confirmed that there are three fundamental variables that determine bacterial attachment affinities and the ability of the bacteria to form biofilm on implant surfaces: surface roughness, hydrophobicity, and material type (metal, ceramic, plastic, etc.).

Surface roughness: Substantial evidence suggests that increased implant surface roughness enhances bacterial adhesion and biofilm development[3-5]. Greater roughness at the micro- and macrometric scale increases the contact area, promoting bacterial adhesion, while surface peaks and valleys provide shelter from shear stresses[5; 6]. Rougher surfaces can also promote nutrient sorption, thus improving microbial adhesion[7]. Surface shapes also affect hydrodynamics such that greater attachment is achieve on rougher surface because bacteria tend to align with scratches of similar dimension[8]. Interestingly, under static culture conditions, bacteria exhibit preference for smoother surfaces when the average roughness value is low, ranging between 0.23 and 6.13 nm. Conversely, as these values increase within the range of 6–30 nm, bacteria tend to adhere to rougher surfaces[9; 10]. It has also been reported that *Staphylococcus aureus* and *Staphylococcus epidermidis* biofilm formation can decrease by 80–90% on flat substrates compared to untreated plasma-sprayed porous titanium and by 65–95% for other porous titanium coatings[11]. Similarly, Jackson et al[4]. demonstrated that the plasma-sprayed Ti6Al4V coating exhibits a significant increase in *S. aureus* biofilm growth compared to the grit-blasted surface and a third control surface. They concurred with Moore et al[5]. that surface topography and macroscopic features (including edges, ridges, and tapped screw holes) are critical determinants in bacterial surface colonization, which are not taken into account by standard roughness parameters [12]. Unlike what occurs at the macroscopic scale, increased roughness at the nanometric scale reduces the number of adhesion points[6]. Moreover, peaks with diameters close to bacterial cells exert mechanical stress on the bacterial membrane, resulting in its rupture. Consequently, some authors recommend manufacturing smooth surfaces with nanoscale roughness smaller than the size of the target bacterium. For reference, *Escherichia coli* and *S. aureus*, possess sizes of 1–5 μm and roughly 1 μm, respectively[13; 14]. However, there are exceptions to this, as Ishikawa et al demonstrated that very rough "as fired" silicon nitride implants were more resistant to *S. aureus* adhesion vs. machined smooth-surface silicon nitride implants[15].

Hydrophobicity: Surface chemistry directly affects bacterial adhesion and biofilm formation on implants[16]. The relationship between bacterial characteristics and surface properties is particularly evident when considering wettability, surface free energy, and charge. In general, hydrophobic surfaces often have a higher affinity for bacterial adhesion and biofilm development compared to hydrophilic surfaces[17]. The hydrophobic characteristics of surfaces and microorganisms are determined by factors such as surface energy, chemical composition, and texture. Hydrophobic bacteria show a tendency to adhere more strongly to hydrophobic surfaces, whereas hydrophilic bacteria are more likely to attach to hydrophilic ones. Considering that most bacteria, such as *S. aureus,* present hydrophobic traits, improving surface hydrophilicity could potentially reduce bacterial adhesion[18; 19]. Additionally, surfaces exhibiting superhydrophobic properties (contact angle >150°) have attracted attention due to their capacity to repel water and minimize biofouling [19]. There are differing opinions among authors regarding the effectiveness of various surface types in preventing bacterial colonization. Some argue that hydrophilic, highly hydrated, and uncharged surfaces are effective barriers, while others contend that hydrophobic surfaces with low surface free energy, such as cobalt-chrome, inhibit bacterial growth[20; 21].

Material type: Orthopedic implants are primarily made of metal, ceramic and plastic components, which are known to have different bacterial adhesion properties[22-24]. Considering the numerous variables, it is highly improbable that any single combination of surface characteristics would universally inhibit all bacteria under all conditions. Several comparator studies have been published. Sarfraz et al demonstrated that *S. aureus*, *S. mutans*, and *E. faecalis* showed higher adhesion to Polyetheretherketone (PEEK) than titanium (Ti)[25]. Ishikawa et al demonstrated that *S. aureus* adhesion to PEEK, Ti and stainless steel (SS0 was greater vs. as fired silicon nitride implants[15]. Cho et al.[26] demonstrated that some microorganisms regulated their inherent biofilm-forming ability based on the surface, while others produced consistent levels of biofilm irrespective of the surface material. *P. aeruginosa* exhibited elevated biofilm formation on titanium, whereas it did not on polystyrene. *S. aureus* exhibited moderate adherence on polystyrene and weak on titanium. *Staphylococcus lugdunensis* demonstrated strong biofilm formation on both materials, while *E. faecalis* showed the least adherence on both surfaces. Malhotra et al.[16] found that the highest degree of bacterial adherence occurred on highly cross-linked polyethylene, followed by titanium, stainless steel, and trabecular metal, while cobalt-chromium alloy exhibited the lowest adherence. When analyzed individually, *S. aureus, S. epidermidis,* and *Klebsiella pneumoniae* followed the same trend, whereas *E. coli* exhibited weak adhesion to all materials. *P. aeruginosa* did not adhere to titanium or stainless steel; however, it exhibited weak adherence to cobalt-chromium and strong attachment to trabecular metal and highly cross-linked polyethylene. Despite the presence of some contradictory evidence[17,18], many of the reviewed studies have produced similar findings, indicating that cobalt-chromium possesses the greatest ability to inhibit biofilm[21; 27], while ultra-high molecular weight polyethylene (UHMWPE) and polyetheretherketone (PEEK) demonstrate the least efficacy[15; 28-30].

Microbial adhesion may be reduced by UHMWPE crosslinking and vitamin E (VE) stabilization[31]. Because of the antioxidant properties of VE and its increased hydrophilicity, it has been observed that VE-UHMWPE considerably decreased the adhesion of *S. aureus* and *E. coli* when compared to standard UHMWPE [32]. However, despite VE inclusion's effectiveness against certain strains, many studies found no significant reduction in MRSA or *S. epidermidis* biofilm formation in physiological conditions [33].

Titanium alloys provide a moderate ability to suppress biofilm formation, demonstrating decreased biofilm development by *S. aureus, S. epidermidis, and P. mirabilis* in comparison to stainless steel [27; 34 35-37].

Ceramic materials exhibit surface physicochemical properties that are particularly advantageous in limiting biofilm formation. Ceramics used in arthroplasty are harder than metals and can be polished to a much lower surface roughness. Additionally, they exhibit high hydrophilicity, a negative surface charge, and minimal wear propensity.[38]. Sorrentino et al.[39] reported that ceramic alumina and zirconia-platelet toughened alumina (ZPTA) samples inhibited the adhesion and biofilm formation of *S. aureus* and *S. epidermidis* bacteria more effectively than cobalt-chromium-molybdenum (CoCrMo) and cross-linked polyethylene. Many studies have emphasized silicon nitride's (Si3N4) promising antibacterial qualities, demonstrating its superiority compared to other implant materials like titanium and PEEK in reducing biofilm formation[15; 31; 40]. However, in cemented primary total knee arthroplasty (TKA), Grimberg et al.[41] did not detect a lower risk of periprosthetic joint infection (PJI) linked to ceramic-coated implants. Likewise, no significant differences in PJI risk have been identified among metal-on-polyethylene (MoP), ceramic-on-polyethylene (CoP), and ceramic-on-ceramic (CoC) bearings in total hip arthroplasty (THA)[38]. Slullitel et al. observed no superiority of ceramics compared to other biomaterials utilized in THA for the prevention of bacterial adhesion. The authors concluded that different adhesive potentials among bacteria significantly influence the establishment of infection.

Conclusions: Bacteria exhibit different affinities for different surfaces, which are related to implant surface properties such as roughness, hydrophobicity, topography, surface free energy, and charge. These features are linked to the bacteria's physicochemical properties. A complex array of factors is involved, including environmental conditions and exposure time. All these factors are closely related and should be evaluated collectively to get more consistent and comparable data across studies and to help create new biofilm-resistant implants. Moreover, a greater number of high-level in vivo studies could introduce additional local interaction factors, such as the immune response and the dynamic biological flow. In light of these factors, identifying a surface that consistently prevents biofilm formation remains challenging. Nevertheless, the available evidence indicates that ceramic, cobalt-chromium, and titanium alloy surfaces are generally more effective in preventing the formation of biofilms than polyethylene, stainless steel, and PEEK.

References:

1. Palmer J, Flint S, Brooks J. 2007. Bacterial cell attachment, the beginning of a biofilm. J Ind Microbiol Biotechnol 34:577-588.
2. Davidson DJ, Spratt D, Liddle AD. 2019. Implant materials and prosthetic joint infection: the battle with the biofilm. EFORT Open Rev 4:633-639.
3. Saeed K, McLaren AC, Schwarz EM, et al. 2019. 2018 international consensus meeting on musculoskeletal infection: Summary from the biofilm workgroup and consensus on biofilm related musculoskeletal infections. J Orthop Res 37:1007-1017.
4. Jackson C, Bills P, Allen C, et al. 2023. An investigation into the effects of prosthesis relevant surfaces on the formation of Staphylococcus aureus biofilms. Surf Topogr 11:035018.
5. Moore K, Gupta N, Gupta TT, et al. 2022. Mapping Bacterial Biofilm on Features of Orthopedic Implants In Vitro. Microorganisms 10.
6. Ludecke C, Roth M, Yu W, et al. 2016. Nanorough titanium surfaces reduce adhesion of Escherichia coli and Staphylococcus aureus via nano adhesion points. Colloids Surf B Biointerfaces 145:617-625.
7. Liu X, Fang L, Yan X, et al. 2023. Surface functional groups and biofilm formation on microplastics: Environmental implications. Sci Total Environ 903:166585.
8. Krsmanovic M, Biswas D, Ali H, et al. 2021. Hydrodynamics and surface properties influence biofilm proliferation. Adv Colloid Interface Sci 288:102336.
9. Crawford RJ, Webb HK, Truong VK, et al. 2012. Surface topographical factors influencing bacterial attachment. Adv Colloid Interface Sci 179-182:142-149.

10. Li W, Thian ES, Wang M, et al. 2021. Surface Design for Antibacterial Materials: From Fundamentals to Advanced Strategies. Adv Sci (Weinh) 8:e2100368.
11. Gasik M, Van Mellaert L, Pierron D, et al. 2012. Reduction of biofilm infection risks and promotion of osteointegration for optimized surfaces of titanium implants. Adv Healthc Mater 1:117-127.
12. Gupta N, Gupta TT, Patel K, et al. 2022. The Influence of Patterned Surface Features on the Accumulation of Bovine Synovial Fluid-Induced Aggregates of Staphylococcus aureus. Appl Environ Microbiol 88:e0121722.
13. Calvo-Correa MP, Cortés-Rodríguez CJ, Camargo-López JR. 2024. Surface Roughness Value Recommended for the Manufacture of Antibacterial Metal Surfaces: A Review. Ing Inv 44:e102345.
14. Tardelli JDC, Bagnato VS, Reis ACD. 2023. Bacterial Adhesion Strength on Titanium Surfaces Quantified by Atomic Force Microscopy: A Systematic Review. Antibiotics (Basel) 12.
15. Ishikawa M, de Mesy Bentley KL, McEntire BJ, et al. 2017. Surface topography of silicon nitride affects antimicrobial and osseointegrative properties of tibial implants in a murine model. J Biomed Mater Res A 105:3413-3421.
16. Oh JK, Yegin Y, Yang F, et al. 2018. The influence of surface chemistry on the kinetics and thermodynamics of bacterial adhesion. Sci Rep 8:17247.
17. Krasowska A, Sigler K. 2014. How microorganisms use hydrophobicity and what does this mean for human needs? Front Cell Infect Microbiol 4:112.
18. Cunha Aea. 2016. Femtosecond laser surface texturing of titanium as a method to reduce the adhesion of Staphylococcus aureus and biofilm formation. Applied Surface Science 360:485–493.
19. Quinn J, McFadden R, Chan CW, et al. 2020. Titanium for Orthopedic Applications: An Overview of Surface Modification to Improve Biocompatibility and Prevent Bacterial Biofilm Formation. iScience 23:101745.
20. Gallo J, Holinka M, Moucha CS. 2014. Antibacterial surface treatment for orthopaedic implants. Int J Mol Sci 15:13849-13880.
21. Koseki H, Yonekura A, Shida T, et al. 2014. Early staphylococcal biofilm formation on solid orthopaedic implant materials: in vitro study. PLoS One 9:e107588.
22. Donlan RM. 2002. Biofilms: microbial life on surfaces. Emerg Infect Dis 8:881-890.
23. Bhagwat G, O'Connor W, Grainge I, et al. 2021. Understanding the Fundamental Basis for Biofilm Formation on Plastic Surfaces: Role of Conditioning Films. Front Microbiol 12:687118.
24. Li P, Yin R, Cheng J, et al. 2023. Bacterial Biofilm Formation on Biomaterials and Approaches to Its Treatment and Prevention. Int J Mol Sci 24.
25. Sarfraz S, Mantynen PH, Laurila M, et al. 2022. Comparison of Titanium and PEEK Medical Plastic Implant Materials for Their Bacterial Biofilm Formation Properties. Polymers (Basel) 14.
26. Cho JA, Roh YJ, Son HR, et al. 2022. Assessment of the biofilm-forming ability on solid surfaces of periprosthetic infection-associated pathogens. Sci Rep 12:18669.
27. Castellanos J, Gonzalez-Cuevas A, Sierra JM, et al. 2014. Adherence of S. epidermidis on different metals. A comparative in vitro study. J Appl Biomater Funct Mater 12:141-144.
28. Malhotra R, Dhawan B, Garg B, et al. 2019. A Comparison of Bacterial Adhesion and Biofilm Formation on Commonly Used Orthopaedic Metal Implant Materials: An In vitro Study. Indian J Orthop 53:148-153.
29. Garcia D, Mayfield CK, Leong J, et al. 2020. Early adherence and biofilm formation of Cutibacterium acnes (formerly Propionibacterium acnes) on spinal implant materials. Spine J 20:981-987.
30. Barkarmo S, Longhorn D, Leer K, et al. 2019. Biofilm formation on polyetheretherketone and titanium surfaces. Clin Exp Dent Res 5:427-437.

31. Banche G, Bracco P, Allizond V, et al. 2015. Do crosslinking and vitamin E stabilization influence microbial adhesions on UHMWPE-based biomaterials? Clin Orthop Relat Res 473:974-986.
32. Banche G, Allizond V, Bracco P, et al. 2014. Interplay between surface properties of standard, vitamin E blended and oxidised ultra high molecular weight polyethylene used in total joint replacement and adhesion of Staphylococcus aureus and Escherichia coli. Bone Joint J 96-B:497-501.
33. Williams DL, Vinciguerra J, Lerdahl JM, et al. 2015. Does vitamin E-blended UHMWPE prevent biofilm formation? Clin Orthop Relat Res 473:928-935.
34. McEvoy JP, Martin P, Khaleel A, et al. 2019. Titanium Kirschner Wires Resist Biofilms Better Than Stainless Steel and Hydroxyapatite-coated Wires: An In Vitro Study. Strategies Trauma Limb Reconstr 14:57-64.
35. Adachi K, Tsurumoto T, Yonekura A, et al. 2007. New quantitative image analysis of staphylococcal biofilms on the surfaces of nontranslucent metallic biomaterials. J Orthop Sci 12:178-184.
36. Clauss M, Graf S, Gersbach S, et al. 2013. Material and biofilm load of K wires in toe surgery: titanium versus stainless steel. Clin Orthop Relat Res 471:2312-2317.
37. Arens S, Schlegel U, Printzen G, et al. 1996. Influence of materials for fixation implants on local infection. An experimental study of steel versus titanium DCP in rabbits. J Bone Joint Surg Br 78:647-651.
38. Hexter AT, Hislop SM, Blunn GW, et al. 2018. The effect of bearing surface on risk of periprosthetic joint infection in total hip arthroplasty: a systematic review and meta-analysis. Bone Joint J 100-B:134-142.
39. Sorrentino Rea. 2018. Reduced bacterial adhesion on ceramics used for arthroplasty applications. . Journal of the European Ceramic Society 38:963–970
40. Pezzotti Gea. 2018. In vitro antibacterial activity of oxide and non-oxide bioceramics for arthroplastic devices: I. In situ time-lapse Raman spectroscopy. . Analyst 143:3708–3721
41. Grimberg AW, Grupp TM, Elliott J, et al. 2021. Ceramic Coating in Cemented Primary Total Knee Arthroplasty is Not Associated With Decreased Risk of Revision due to Early Prosthetic Joint Infection. J Arthroplasty 36:991-997.