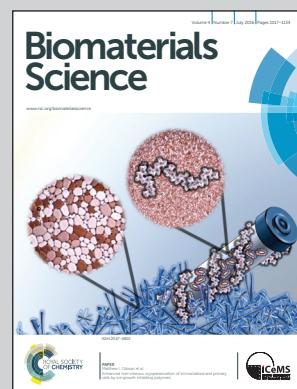


Highlighting research results from the Department of Biofunctional Polymer Materials at Leibniz Institute of Polymer Research Dresden, and the Institute of Manufacturing Technology at University of Technology Dresden, Germany.

The impact of structure dimensions on initial bacterial adhesion

Dimensions of periodical structures play a significant role in bacterial surface colonization and retention: sub-cell sized topographies were found to restrict and cell-sized periodicities maximize initial adhesion irrespective of the contact time (minutes to hours) and the surface chemistry.

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Substrate topography can have profound effects on initial bacterial adhesion during biofilm formation. We applied *Staphylococcus epidermidis* and *Escherichia coli* cells onto periodically structured substrates with different structure dimensions, structure types and wetting properties. We found a strong dependence of cell retention on the structure dimensions of the applied substrates. Periodicities in the range of the cell size increased, whereas smaller periodicities decreased cell retention, independent of contact time (minutes to hours) and hydrophobicity. These novel insights on the role of surface topography on bacterial retention might facilitate the development of non-fouling surfaces in the future.

Adhesion, accumulation and growth of microorganisms on man-made surfaces in contact with aerial or saline environments, designated as biofouling, can have severe negative consequences in various fields including industrial processes (e.g., food processing, textile, pulp and paper manufacturing),^{1,2} medicine (e.g., nosocomial infections)^{3–5} and in seawater-contacting equipment (e.g., pipelines, cooling and filtration systems, fishing nets, ship hulls and bridge pillars).⁶ Biofouling is a complex process that can generally be described by a basic sequence of events. First, a conditioning film is formed on a surface by rapid adsorption of organic molecules (mainly proteins and polysaccharides). Then, a microbial biofilm develops, which involves the attachment of bacterial cells and/or diatoms, growth and proliferation of the attached cells, for-

mation of mature colonies and, finally, partial detachment of cell clusters. In contrast to the strongly adhering mature biofilm, the initial (minutes–hours) adhesion of bacteria onto the surfaces is generally reversible. Therefore, many antifouling strategies rely on the prevention/intervention of initial bacterial adhesion rather than on the removal of the mature biofilms.

Besides the environmental conditions, such as pH, temperature, competing organisms and nutrition, the interactions between the bacteria and the substrate are mainly influenced by interfacial properties such as chemistry, polarity, mechanical properties and structure. The structural features of substrates, such as size, spacing, aspect ratio and roughness can have both deterrent and attractive effects on the settlement of fouling organisms.^{7,8}

On nano-rough surfaces the number of attached cells and the amount of secreted exopolysaccharides (EPS) can be strongly affected by the subtle differences in surface roughness.^{9–14} Bacterial biofilm formation has been observed to be more pronounced on surfaces with the root mean square roughness value of 10 nm compared to that of 5 nm and 15 nm.⁹ For submicron- and micron-sized structures, a permanent increase and an intermediate maximum or minimum of bacterial settlement have been observed depending on feature spacing, period or size.^{15–20} In some reports, a strong impact of feature sizes and/or spacing in the range of the cell size on cell–substrate interactions and colonization has been described.^{8,15,21–23} The structural features of substrates were also reported to influence cell orientation. The regular structures were suggested to influence settlement patterns more than irregular structures and the order of cell pattern was more pronounced on micron- than on nano-sized features, periods and spacings.⁷ In particular, micron-sized grooves and pillar arrays were found to guide cell orientation and proliferation.^{21–25}

A conclusive picture of bacterial retention on structured substrates with graded structural dimensions does not currently exist.^{26,27} The vast knowledge bases on cell retention and orientation on materials with structures spanning the nano- and micro-scale are partially contradictory, perhaps due to the fact that different ranges of structure dimensions as well

^aDepartment of Biofunctional Polymer Materials – Max Bergman Center of Biomaterials, Leibniz Institute of Polymer Research, Hohe Straße 6, D-01069 Dresden, Germany. E-mail: helbig@ipfdd.de

^bFraunhofer Institute for Material and Beam Technology, Winterbergstraße 28, D-01277 Dresden, Germany

^cCUBE - Center for Molecular Bioengineering, Dresden University of Technology, Arnoldstraße 18, D-01307 Dresden, Germany

^dCRTD – Center of Regenerative Therapies Dresden – Center of Excellence, Fetscherstraße 105, D-01307 Dresden, Germany

^eInstitute of Manufacturing Technology, University of Technology, Georg-Bähr Straße 3c, D-01069 Dresden, Germany

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as structure types with periodically arranged or randomly distributed structures were applied. In addition, different bacterial strains and experimental conditions were used. Resolving these contradictions and exploring the role of structure types and dimensions in the initial bacterial adhesion with respect to the colonization patterns are therefore key challenges of current research.

In the current study, cells of a Gram-positive bacterial strain *Staphylococcus epidermidis* (*S. epidermidis*) and a Gram-negative strain of *Escherichia coli* (*E. coli*) were exposed to sets of substrates with micron- and submicron-sized structures. The substrates were prepared by Laser Interference Patterning (LIP).^{28–30} LIP is a mask- and moldless high throughput method that uses a standing wave pattern at the intersection of two or more coherent and collimated laser beams to create micron- and submicron-scaled structures in photo-sensitive materials like photo-resists or by ablation of polymers, ceramics and metals (Fig. S1†). The shape and dimension of the interference patterns can be adjusted by controlling the number of laser beams as well as their geometrical configuration. This method can be applied to large areas and various surface shapes and is not restricted to flat substrates. In order to comprehensively understand the impact of structure dimensions on the bacterial settlement the periodicity of the structures Λ was chosen to be larger, similar or smaller than the cell size of *S. epidermidis* (spherical with a diameter of about 1000 nm) and *E. coli* (rod-shaped with about 1000 nm width and 2000–3000 nm minimal length).

Substrates with comb-like hole patterns were incubated with the bacteria in growth medium for 24 h. Subsequently, the number of adherent cells was quantified. The highest number of *S. epidermidis* cells was found on substrates with a periodicity in the range of the cell size, *i.e.* $\Lambda = 1000$ nm (Fig. 1). Larger periodicities ($\Lambda = 5000$ nm) led to a lower number of attached cells. For *E. coli* no significant difference

in the amount of adherent cells was detected for periodicities of 1000 nm and 5000 nm (Fig. 2). For both strains the lowest number of cells was detected on substrates with $\Lambda = 500$ nm (Fig. 1 and 2).

To investigate the effect of the surface wettability/chemistry on the observed trend, the bacteria were incubated for 24 h on the structures that were hydrophilized or hydrophobized with aminosilane (APTES) or amorphous fluoropolymer TAF, respectively. The wettability, illustrated by water contact angles (Table S1†), is caused by different surface charges. APTES is positively charged,³¹ SU8 is slightly negatively charged (unpublished data) and TAF represents a nonpolar surface. Although the absolute number of adherent cells was different for the tested surface modifications, the relative trends were similar to the initial experiments irrespective of the surface wettability/chemistry (Fig. 1 and 2). The highest number of cells was always found on substrates with $\Lambda = 1000$ nm (both strains) and $\Lambda = 5000$ nm (*E. coli* only), whereas the lowest number of cells was always found on structures with $\Lambda = 500$ nm (Fig. 1 and 2). Irrespective of the structure dimensions, the experiments with *S. epidermidis* revealed a preference for retention on the hydrophilic APTES and a lower settlement on the hydrophobic TAF. Interestingly, *E. coli* cells showed a different trend. The highest number of cells was found on unmodified SU 8 surfaces, whereas few cells adhered to APTES- and TAF-modified surfaces. These results underline the fact that different bacterial strains prefer different surface chemistries, although both the strains possess an overall negative net charge.^{32,33}

Next, we set out to test if the observed trends can be reproduced at significantly shorter contact times and different structure types. Therefore, *S. epidermidis* cells were incubated only for 2 min on SU8 hole structures and the attached cells were quantified. Although less pronounced, the overall trends of these experiments were comparable to the short-term adhesion experiments. The highest amount of cells was found

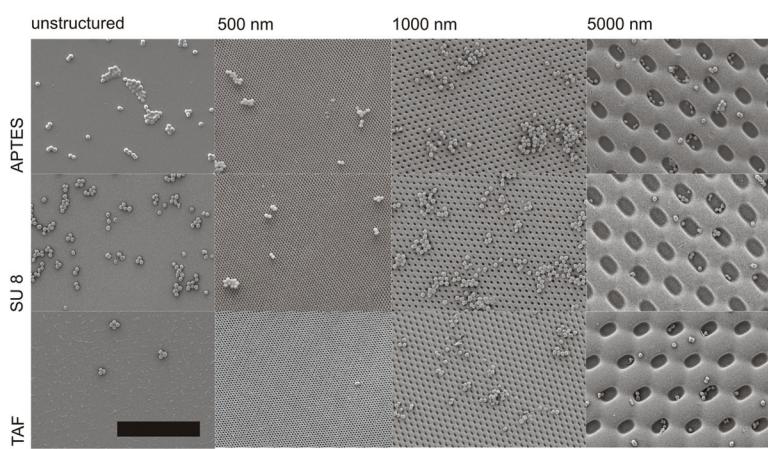


Fig. 1 Bacterial retention on micron- and submicron-scaled hole structures. (Left) Representative SEM images of surface coverage with *S. epidermidis* (scale bar = 10 μ m). (Right) Normalized adherent *S. epidermidis* after 24 h. The structure period Λ is denoted on the x-axis. In all figures, box-whisker plots present half of the data points within the box and 80% within the whiskers. The black continuous lines and black rectangles within the boxes mark the median and mean, respectively. All the values are normalized to the median of unstructured SU8. APTES – (3-aminopropyl) triethoxysilane; SU8 – photoresist, TAF – amorphous fluoropolymer.

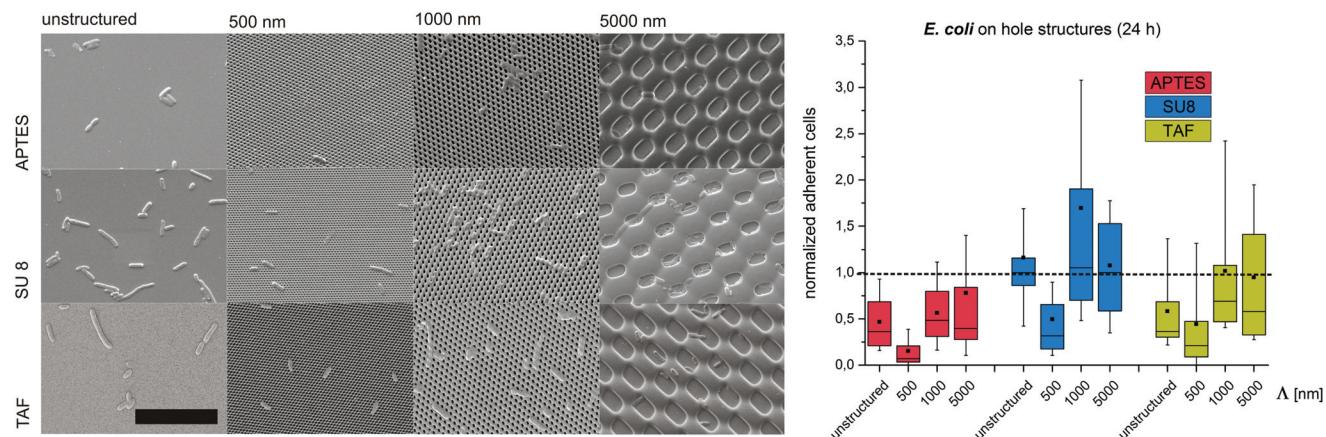


Fig. 2 Bacterial retention on micron- and submicron-scaled hole structures. (Left) Representative SEM images of the surface coverage with *E. coli* (scale bar = 10 μ m). (Right) Normalized adherent *E. coli* after 24 h. The structure period Λ is denoted on the x-axis. In all the figures, box-whisker plots present half of the data points within the box and 80% within the whiskers. The black continuous lines and black rectangles within the boxes mark the median and mean, respectively. All the values are normalized to the median of unstructured SU8. APTES – (3-aminopropyl)triethoxysilane; SU8 – photoresist, TAF – amorphous fluoropolymer.

on structures with a periodicity of 1000 nm, whereas submicron-scaled structures ($\Lambda = 500$ nm) suppress initial cell adhesion (Fig. 3).

Subsequently, we tested if the observed trends depend on the type of structure applied. Therefore, *S. epidermidis* cells

were applied for 2 minutes to SU8 post and line structures with periods smaller, similar and larger than the cell size (wetting parameters in ESI Table S2†). Again, the highest amount of cells was observed for $\Lambda = 1000$ nm whereas the lowest amount of cells was found for $\Lambda = 500$ nm (Fig. 3).

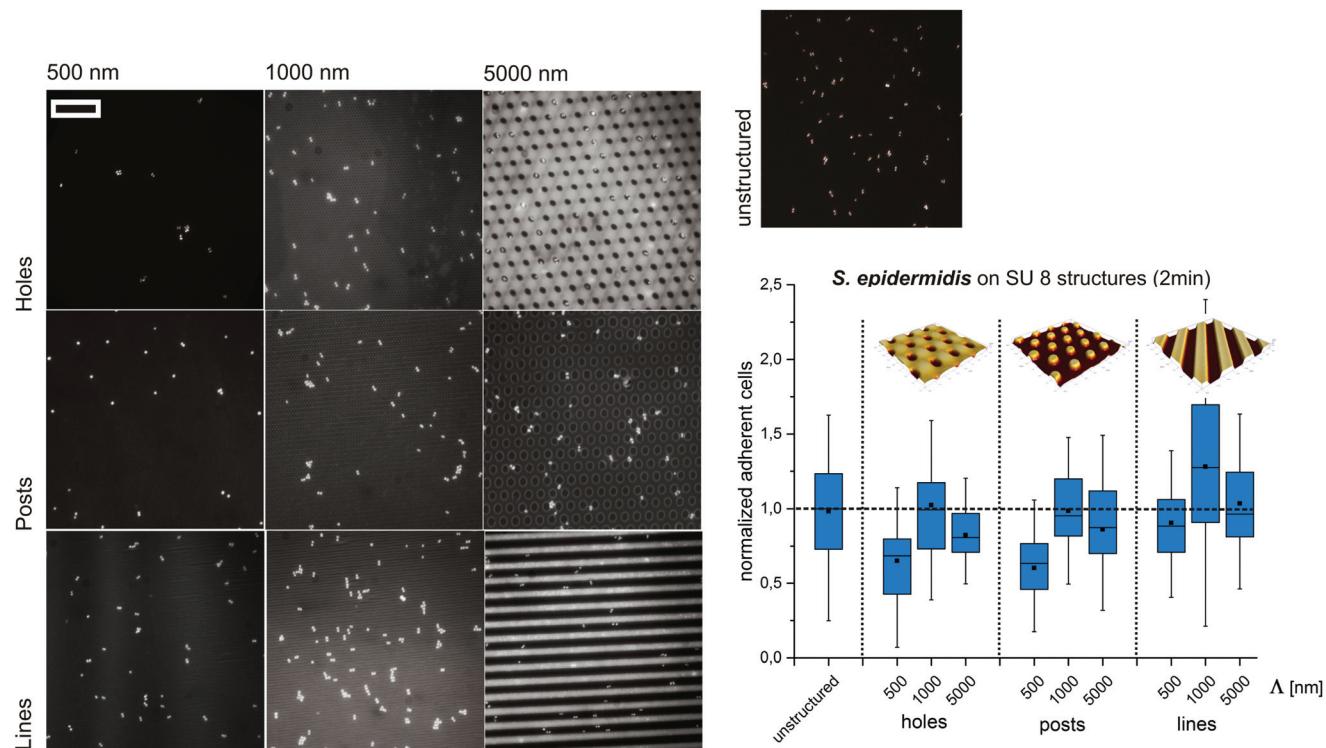


Fig. 3 Bacterial retention on micron- and submicron-scaled hole, post and line structures. Representative fluorescence microscopy images of the surface coverage with *S. epidermidis* (scale bar = 15 μ m) and normalized adherent cells after 2 min of exposure. The structure period Λ is denoted on the x-axis. In all the figures, box-whisker plots present half of the data points within the box and 80% within the whiskers. The black continuous lines and black rectangles within the boxes mark the median and mean, respectively. All the values are normalized to the median of unstructured SU8.

Previous studies suggested a dependence of bacterial cell retention and orientation on the periodicity and dimension of structured surfaces,^{24,25} particularly when feature sizes are in the range of the dimensions of the attaching cells.^{8,15,21,22} Here, we applied a systematic approach to quantify the initial adhesion of two bacterial strains on substrates with graded structure dimensions and additionally tested the effect of contact time, surface chemistry and structure type on cell retention. We suggest that, the maximized cell–substrate contact area on structures with the dimensions in the range of the cell size ($\Lambda = 1000$ nm for *S. epidermidis*, Λ between 1000 nm and 5000 nm for *E. coli*) lead to high cell retention on these structures. In contrast, topographies with structure periods below the size of individual bacterial cells ($\Lambda = 500$ nm) restrict the cell–substrate contact area and therefore lead to reduced cell retention. For topographies with structure periods bigger than the cell size ($\Lambda = 5000$ nm) cell retention strongly depends on the cell morphology. For spherical cells, cell retention was lower (compared to $\Lambda = 1000$ nm), whereas for rod-shaped cells, with the dimension of the long-axis slightly below the dimensions of the structured surface, cell retention was comparable to $\Lambda = 1000$ nm. In future studies it will be interesting to quantify the retention of *E. coli* on the structures with dimensions significantly bigger than the length of this bacterial strain (*i.e.* $\Lambda = 10\,000$ nm). Interestingly, the observed trend was found to be independent of the contact time between the bacteria and the substrate, the structure type and the substrate chemistry, demonstrating that surface topography is indeed a strong trigger influencing cell adhesion.

The presented results demonstrate that the structural properties of surfaces govern the initial adhesion of two important opportunistic pathogens, *Staphylococcus epidermidis* and *Escherichia coli*. Usually, a comprehensive discussion about microbial settlement and biofouling must include considerations of specific and non-specific interactions of bacteria with a substrate, such as cell appendages, specific attachment components, surface free energy, cell membrane charges, surface zeta potential and hydrophobicity. The current work proves that inhibition of bacterial colonization can be supported by sub-cell sized topographies irrespective of the physicochemical properties of the used materials and, therefore, irrespective of different nonspecific cell–substrate interactions. Nevertheless, so far this study cannot claim a long term prevention of biofilm formation which normally takes place after some days of surface colonization, but it might play an important role by inhibiting microbial dispersal in a hospital environment or in food processing areas due to the strong inhibition of the initial attachment on the devices and instruments with sub-micron-scaled structures. The use of sub-cell sized comb or hole structures in opposite to line and post structures should lead to applicable coatings due to the appropriate mechanical properties. Fragile line and post structures were only used to work out the underlying principal. Ongoing studies should aim at exploring the effects of similar surface characteristics on the adhesion of bacteria on respective preconditioned surfaces by hospital relevant proteins, such as albumin, fibrinogen, lysozyme, *etc.* as well as long term *in situ* assays.

Author contributions

The manuscript was written through contributions of all the authors. All the authors have given approval to the final version of the manuscript.

Conflict of interest

The authors declare no competing financial interest.

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