Biofouling Resistance: Role of Nanostructure, Dynamics & Hydration

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Non-specific biomolecular adsorption is ubiquitous and a highly complicated phenomenon occurring throughout nature, technology and medicine. Unwanted protein adsorption can mediate the attachment of larger biological entities at solid/liquid interfaces resulting in biofilm formation, the implications of which in bioengineering and nanomedicine can be both toxic and costly. Functionalizing surfaces and nanoparticles with organic ligands, e.g. PEG, is considered the gold standard for the development of biocompatible (nano)materials. Current understanding of protein adsorption resistance is still dominated by two early theories on the underlying mechanism of this resistance: hydration and steric repulsion. More recent discoveries indicated that natural self-cleaning surfaces such as cicada and butterfly wings possess a specific surface nanostructure that enable their fouling resistance. However, a detailed knowledge of the mechanisms through which proteins adsorb or are repelled at various solid/liquid interfaces is still lacking. This limits the capacity to improve the design of nanomaterials for biomedical applications that combat non-specific protein adsorption but possess the enhanced specific recognition capacity, functionality and durability.

We use molecular simulations to elucidate the fundamental mechanism/s underlying the biofouling resistance of natural and engineered surfaces and nanoparticles.[1] By combining high resolution dynamic AFM imaging with all-atom molecular dynamics simulations we recently revealed the interfacial aqueous layer structure surrounding ligand-protected nanoparticles possessing remarkable biofouling resistance.[2] We demonstrated that suitably spaced flexible chains with hydrophilic terminal groups that interact with water molecules to produce a confluent, quasi-stable yet dynamic interfacial hydration layer provide a basis for antifouling performance of ultrathin hydrophilic surface chemistries. Further, we simulated protein adsorption on ligand-functionalized surfaces to identify in the atomistic detail how the interfacial hydration and/or ligand dynamics work against protein adsorption.

All-atom dynamic models of different proteins interacting with various ligands in solution and when grafted to nanostructured surfaces demonstrated synergetic effect of hydration and steric repulsion as a key factor for antifouling performance. These molecular level studies integrated with machine learning to account for the chemical variation of antifouling ligands[3] allowed us to propose new design rules for effective exploitation of short-chain hydrophilic chemistries on nanostructured surfaces in the development of stealth nanomaterials for applications in biomedicine and industry.

References

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