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Bioengineering at the nanoscale

Nanotechnology has become a key player in bioengineering, providing control and functions of bioengineered systems at the scale of cells and biomolecules.

Nanotechnology refers to engineering at the nanoscale. In particular, the reduction of materials to their nanoscale dimensions can lead to tremendous changes in their properties, such as bioadhesion, fluorescence and photothermal properties, which can be exploited for a variety of applications, including drug delivery, biosensing, biomaterials design and diagnostics. Importantly, nanoscale engineering allows the implementation of nanoscale functions in bioengineered platforms and tools to precisely guide their interactions with cells and biomolecules.

Many biological mechanisms occur on the nanoscale; for example, the interaction of bacteria and viruses with host cells, recognition events in our immune system or the ability of certain animals and plants to adhere to surfaces. These nanoscale interactions are defined by various properties of the interacting surfaces, including size, charge, functionalization, chirality and topography.

In particular, 3D nanotopography regulates multiple cellular functions, such as membrane-associated mechanisms, proliferation and differentiation. For example, viruses have optimized their surface topographies to achieve efficient host infection, which can be mimicked to increase the cellular uptake or targeting of nanomaterials. In this issue, Tejal A. Desai and colleagues discuss how bioinspired nanotopographical design of drug carriers can modulate their interaction with biological systems inside the body and increase their efficiency. Similarly, taking inspiration from gecko and pollen grains, bioadhesive nanomaterials can be designed that stick to tissues to extend their residence time and prolong drug release. These examples illustrate the power of nanoscale engineering in drug delivery design.

In addition to nanotopography, chirality impacts nanoscale interactions, for example, in protein synthesis and cellular movement. In this issue, Nicholas A. Kotov, Luis M. Liz-Marzán, Ki Tae Nam and team discuss the bioinspired design of chirality in inorganic nanomaterials, highlighting how chiral engineering at the nanoscale can be applied to various biomaterials and biomedical applications, including biosensing and immunomodulation.

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Indeed, nanoscale engineering plays a key role in the design of therapies aimed at modulating the immune system, for example, for the treatment of infectious diseases, cancer or autoimmunity. To target bioengineered platforms, such as vaccines and immunotherapeutics, to specific receptors of immune cells and tissues, the chemical and biological surface properties of nanomaterials can be modulated. In this issue, Darrell J. Irvine and team outline such immune cell- and organ-specific targeting strategies; however, they also emphasize that multi-step chemistries and complex surface modifications at the nanoscale may lead to challenges in achieving regulatory approval of these materials and devices.

Nanoscale engineering can also be applied for the design of biomaterials and nanomedicine platforms that seek to modulate the immunosuppressive tumour microenvironment in immunotherapy. In this issue, Yu Chao and Zhuang Liu examine how nanomaterials can be engineered to regulate the microenvironment of solid tumours, for example, by altering its pH or by relieving hypoxia. Such nanoscale engineering strategies could be applied in conjunction with immune checkpoint blockade and chimeric antigen receptor (CAR) T cell therapy, to increase the efficacy of these immunotherapies.

Furthermore, nanoscale design plays a major role in the development of vaccines that rely on nanoparticle-based delivery systems. In a Comment in this issue, Katharina Maisel, Gregg A. Duncan and colleagues present nanoscale engineering strategies that would allow the intranasal and pulmonary delivery of vaccines, suggesting device designs that closely mimic human respiration and mucosal barriers – which goes back to the same idea of mimicking biological nanoscale interactions in bioengineered platforms.

Nanoscale engineering is at the heart of many bioengineering strategies that aim to precisely target and/or control cells and tissues, as, ultimately, cell- and tissue-level biology happens at the nanoscale. However, a thorough understanding of the impact of nanoscale engineering on the behaviour, interactions and fate of materials in vivo will be key for the clinical translation of nanobioengineered systems.

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